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Systematic Approach to the Structural Diagnosis of Reinforced Concrete

Approche systématique pour la détermination de l'état de structures en béton armé

Systematische Vorgehen zur Beurteilung des Zustandes von Stahlbeton

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SUMMARY

The assessment of the conditions of RC and PRC structures calls for the combined use of several non-destructive or partially destructive techniques. After a brief examination of the deterioration processus affecting concrete and steel properties, available investigation methods are systematically examined and new techniques currently being developed are illustrated pointing out their applicability within a systematic structural diagnosis procedure.

RESUME

L'évaluation de l'état des structures en béton armé et précontraint doit se faire au moyen des plusieurs techniques non destructives ou partiellement destructives. Après une brève description des processus de détérioration du béton et de l'acier, on passe en revue les méthodes d'essai disponibles et on présente quelques techniques nouvelles actuellement en cours d'expérimentation. Les techniques indiquées font partié d'un procedé systéematique pour le diagnostic des structures.

ZUSAMMENFASSUNG

Die Zustandsermittlung von Beton- und Spannbetonbauwerken erfordert eine ganze Reihe von zerstörungsfreien und teilzerstörenden Techniken. Nach einem Ueberblick über die Zersetzungsvorgänge bei Beton und Stahl werden die verschiedenen Prüfmethoden besprochen. Die Anwendung neuer, noch in Entwicklung stehender Techniken bei systematischen Untersuchungen wird beschrieben.

INTRODUCTION

Non destructive diagnoses can be applied both to new structures and to works that have been in service for a long time. In the first case, the diagnosis serves as a quality control of the execution, in the other, it can be used to identify execution defects as well as damages which may have been produced later on.
In this report these two aspects will be examined together as a number of the available techniques are applicable to both, whilst others are more suited to either the one or the other.
It should be pointed out that in the case of newly erected structures, the current approach to durability tends to define various classes of exposure and to lay down different criteria for each. Hence, quality control will consist of checking whether these requirements have been met.
In this connection we attach Tables 1 and 2 taken from a proposal developed jointly by the CEN and by the editorial committee of the Eurocode.
As for structures that have been in service for a long time, the aim is to identify the deterioration processes they have been subjected to as well as the ones under way.
These processes are also strictly tied up with the exposure classes referred to above, and naturally enough, with the design and execution of the structure.

1. A FEW OBSERVATIONS ON DETERIORATION PROCESSES

1.1. Physical processes

The physical processes leading to the deterioration of concrete properties are:
- cracking
- freezing and thawing effects
- erosion

While the last two are usually easy to identify, cracking calls for an accurate study aimed at identifying its causes.

1.2 Chemical processes

1.2.1 Carbonation

The carbon dioxide (CO_2) present in the air penetrates into the concrete pores and may react with the calcium hydrowide ($Ca(OH)_2$) present in the cement mix via a process which can be simplified in these terms:

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

This reaction begins on the outer surfaces exposed to the air and penetrates inward at a rate governed essentially by the permeability of concrete.
The phenomenon lowers the pH of the material, from the habitual values of 12.5 ÷ 13.5 to 8.3 ÷ 9, enabling reinforcement corrosion to take place.
From the viewpoint of the mechanical characteristics of concrete it has no negative repercussions, as a rule, actually this phenomenon gives rise to an increase in surface hardness; thus, it should be regarded as a deterioration process solely as concern the durability of metal reinforcement.

Table 1: Exposure classes related to environmental conditions

Exposure class		Environmental conditions
1 dry environment		e.g.: interior of buildings for normal habitation or offices
2 humid environment	a without frost	e.g.: - interior of buildings where humidity is high (≥ 60 %) - exterior components - components in non-aggressive soil and/or water
	b with frost	e.g.: exterior components exposed to frost or non-aggressive soil and/or water
3		Humid environment with frost[1]) and de-icing agents e.g.: exterior components exposed to frost or non-aggressive soil and/or water and frost and de-icing chemicals
4 seawater environment	a without frost	e.g.: - components in splash zone or partially emerged from seawater - components in saturated salt air (direct coast area)
	b with frost	
The following classes may occur alone or in combination with the above classes:		
5 chemical environment	a	- slightly aggressive (gas, liquid or solid)[2]) - aggressive industrial atmosphere
	b	moderately aggressive (gas, liquid or solid)[3])
	c	highly aggressive (gas, liquid or solid)[4])

[1]) Under moderate European conditions

[2]) ISO-classification (ISO DP 9690): A 1 G, A 1 L, A 1 S

[3]) ISO-classification (ISO DP 9690): A 2 G, A 2 L, A 2 S

[4]) ISO-classification (ISO DP 9690): A 3 G, A 3 L, A 3 S

Table 2: Requirements for reinforced concrete

Exposure class	1	2a	2b	3	4a	4b	5a	5b	5c
max W/C ratio	0.65	0.60	0.55	0.50	0.50	0.55	0.55	0.50	0.45
min cement content in kg/m³	260	280	280	300	300	300	280	300	300
Strength class	If the strength classes below are reached, the values above are assumed to be fulfilled								
	C 16/20	C 20/25	C 25/30	C 30/35	C 25/30	C 30/35	C 25/30	C 30/35	C 30/35
Air content	—	—	+	+	—	+	—	—	—
frost resistant aggregates	—	—	+	+	—	+	—	—	—
Types of cement	CE I 32,5/42,5 CE II 32,5/42,5 CE III 32,5/42,5 CE IV 32,5/42,5	the same as 1	CE I 32,5/42,5 CE II 32,5/42,5 CE III 32,5/42,5 CE I 42,5	CE I 32,5/42,5 CE I 42,5 CE II 42,5	the same as 1	the same as 2b	the same as 1	the same as 1	the same as 1
					however sulfat resistant cement for sulfat contents of: > 500 mg/kg in water > 3000 mg/kg in soil				
water impermeability	—	—	+	+	+	+	+	+	+

1.2.2 Chloride penetration

The penetration of chlorine ions into concrete has a de-passivating effect on the reinforcing steel; this phenomenon is due exclusively to the free Cl^- ions that come into contact with concrete through the water contained in its pores, whilst the ions that are chemically bound with the constituents of the mix play no part in it.

Carbonation enhances this phenomenon, since it reduces the binding capacity of cement constituents for chloride compounds. The de-passivating effect of chloride is counteracted by concrete alkalinity, and, all other conditions being equal, it develops only if the concentration of Cl^- ions exceeds a certain threshold value which depends upon concrete pH.

In this case too, the fundamental parameter influencing this phenomenon is concrete permeability.

The structures most exposed to this type of attack are those located in a sea-water environment and roads on which deicing salt is scattered.

1.2.3 Sulfate attack

Under the attack of the sulfates present in water (high concentration of SO_4^{--} ions) concrete swells and its surface turns whitish, soft and pasty.

The compounds that have the most detrimental effects on concrete are Ammonium, Calcium, Magnesium and Sodium sulfates.

These substances react with hydrated calcium aluminate and with calcium hydroxide that are present in hardned cement, resulting in the formation of Ettringite and of other compounds which crystallize and expand in doing so, creating a considerable pressure which leads to the disintegration of concrete.

The severity of this phenomenon hinges largely on concrete permeability.

1.2.4 Acid attack

This phenomenon can be summarized as follows: when an acid (HCl, H_2SO_4, HNO_3, etc.) penetrates into the interior of hardened concrete through its pores it may react with the calcium-based compounds contained in the material, leading to the formation of salts which are usually highly soluble and therefore can be washed away by water.

1.2.5 ASR induced deterioration

Essentially, ASR is a chemical reaction between some forms of silica contained in the aggregate and the alaklis contained in cement; the outcome of the reaction is a gel that tends to expand and give rise to cracks.

Tle latter may be considerable in terms of both length and width. In general, this phenomenon occurs within a year since the casting, but it has also been observed to occur at a later date. It can only take place, however, under the following concurrent conditions:

- considerable humidity in the environment
- a sufficient quantity of alkalis in the cement
- the presence of a significat amount of reactive aggregate.

The visual outcome is an extensive network of cracks forming a random pattern (like a spider web) independent of static conditions.

1.2.6 Reinforcement corrosion

This is an electro-chemical phenomenon which develops through two processes: an anode and a cathode one.

- Anode process

$$2Fe = 2\ Fe^{++} + 4e$$

(dissolution of iron and release of electrons)

- Cathode process

$$O_2+2H_2O+4e = 4OH^-$$

(consumption of electrons and reduction in the amount of oxygen in contact with the reinforcement)

The overal reaction is as follows:

$$2Fe+O_2+2H_2O = 2Fe^{++}+4OH^- = 2Fe(OF)_2$$

(formation of rust)

The phenomenon is affected by the potential and the pH of the environment in which the reinforcement is placed, as can be seen in fig. 1: hence the importance of the carbonation and chloride penetration phenomena described above which influence both concrete pH and the potential.

1.2.7 Hydrogen embrittlement

This phenomenon has been observed in high yield point type steel (prestressing steel).

It evolves through the extension of the cracks occurring through failure at the root as the adjacent material becomes brittle owing to the migration of atomic hydrogen towards it, this migration being induced by the cathodic reaction complementary to the iron dissolving anode process.

Steel sensitivity to this attack increases with strength and is a function of its composition and structure.

This phenomenon will not take place when the steel is embedded in concrete of a suitable composition, with high pH value, free from chloride, sulfate and thiocyanates.

2. INVESTIGATION METHODS

A visual examination perfomed by a structural specialist is of fundamental importance for the identification of construction flaws and visible deterioration processes; this will be the basis of all subsequent investigations.

It is essentially aimed at:

- the identification of cracks and their causes. There are many different types of cracks and in many cases it is not easy to recognize the phenomena that produced them; in dealing with these deterioration phenomena special importance should be attached to even minor cracks located along the reinforcement or along the path of prestressing tendons. The significance of transverse cracks with an opening of less than 0.3 mm is controversial;
- the identification of rust stains, especially in the areas adjacent to the prestressing tendons. This is one of the crucial tasks of visual inspection;
- the identification of saline efflorescence revealing water permeable areas.

When obvious signs of local corrosion are detected it will be adviseable to proceed to a direct examination of ordinary reinforcement by removing a portion of the concrete cover; for a larger scale investigation, instead, especially where prestressing tendons are concerned, it will be necessary to resort to more complex methods, as described below.

When a structure has an iterative configuration, the visual examination will generally enable the information obtained from one representative element to be extended to the entire structure.
When visual observation suggests the need of a more through investigation, it will be necessary to resort to special testing instruments and techniques.

2.1 Special investigation techniques for concrete

2.1.1 Initial approach tests

Let us consider first of all non-destructive or partially destructive testing methods which might be defined as 'initial approach' tests because of their relative ease of execution: cores, microcores, on-site compressive tests, pull-out, pull-off, Windsor probe, pH measurements.
By means of microcores (Ø = 30 mm) specimens can be obtained from the areas deemed to be most significant for visual examination purposes and subjected to laboratory tests designed to determine the mechanical characteristics of concrete at various points and at different depths. The results should be interpreted taking into account the impact of core drilling which can be considerable. A viable alternative consists of on-site compressive tests (10). This is done by loading in compression, till failure, portions of the reinforced concrete structural members (beams, slabs, etc..) without removing them from the overall structure they are part of. The testing apparatus is shown in figure 2; a basic requirement is to make use of plates sufficiently rigid to reduce to the minimum the risk of uneven distribution of the load and to this end the tierods should be placed as close as possible to the edges of the element being tested.
When interpreting the results, however, it should be kept in mind that a portion of the compressive load effects might have been carried by the adjacent areas.
Other, moderately destructive testing methods, such as pull-out, pull-off, Windsor test, provide an indirect measurement of concrete strength on the surface.
The rebound hammer, an instrument widely used on account of the ease with which it can be applied, yields rather uncertain results, especially when dealing with carbonated concretes having a hardened outer layer.
All these techniques as a whole, however, cannot provide failsafe results, since they are primarily intended for use in comparative assessments. They can be instrumental both for quality control purposes and to evaluate the damages affecting a reinforced concrete structure that has been is service for a long time. Concrete pH measurements, instead, are applicable only to the latter type of investigation, i.e., on pre-existing structures. They can be performed on cores or microcores taken from the structure as well as on fragments chiselled off starting from the outer surface of the structure. The specimens must be tested right away to prevent them from remaining in contact with carbon dioxide for a sustained period ot time, as the CO_2 contained in the air could alter the results (an exposure time of a few hours is acceptable).
The following procedures can be employed:
- spraying with phenolphthalein in ethanol solution
- pH-meter

The alcoholic phenolphthalein solution in 1% ethanol turns pink/purple when it comes in contact with materials having a pH of over 9.8 and stays colourless in the case of lower values (photos 1 and 2).
The pH-meter should be used in doubtfus cases and whenever one wishes to obtain more detailed pH data as a function of depth. It can be applied by taking concrete samples and breaking them up into a powder. When mixed with distilled water the samples will provide an accurate measurement of pH values at various depths.

2.1.2 More rigorous testing methods

Among the so-called "second approximation" tests let us mention ultrasonic pulse velocity tests, tomography and dynamic pulse tests. We shall not describe these techniques in detail as they are illustrated by other reports dealing specifically with this subject.
Finally, there are other tests - still being perfected - that seem very promising. One is the on-site permeability test with which the local permeability of a structure can be assessed and, as we have seen, this is a fundamental parameter influencing almost all deterioration phenomena. In the case of new structures it can be profitably used to evaluate execution quality, since the results provide data not only on the composition of the casting aggregate size and grading, water/cement ratio, cement quantity) but also on on-site compacting methods.
As for older structures, it can be used to substantiate the data provided by pH measurements, especially when the regularity of the diffussion of the chemical phenomenon - that may be interrupted by the formation of calcium carbonate - is doubtful. The testing method, developed within the framework of a joint research project by the Politecnico di Torino and ISMES, is similar to a technique devised a few years ago by Figg (6).
The test we have developed consists of making a small diameter hole in the structure to be examined and introducing in it air, water or gas under pressure: then the reduction in pressure over time is carefully observed.
Fig. 3 provides, as an exemplification, several diagrams illustrating the results of tests performed on various concrete samples. The assessment of concrete permeability must take into account the possibility of an uneven diffusion of the fluid owing to local defects or pore clogging produced while making the hole.
Another method, currently being tried out within the framework of the above mentioned research project, is based on thermographic measurements (7). As is known, thermography can be used to map out surface temperature values, with an accuracy of about 0.1 °C. Thus, in the presence of a heat gradient, this reveals differences in conductivity levels corresponding to different materials or local disuniformity.
A first application may consist of combining visual thermographic inspection with on site permeability tests to check the even diffusion of the fluid inside a structure. Notably, this provides information as to the presence of preferential directions (cracks, etc.). Furthermore, the thermographic procedure can be used to detect local disuniformity in the material or in hygrometric conditions.
Laboratory tests have resulted in the identification of gaps and holes in masonry structures, water infiltrations in concrete slabs, grouting defects in prestressing tendons, segregation areas (photo 3).

In all cases, a thermal gradient was artificially induced in the elements to be checked.

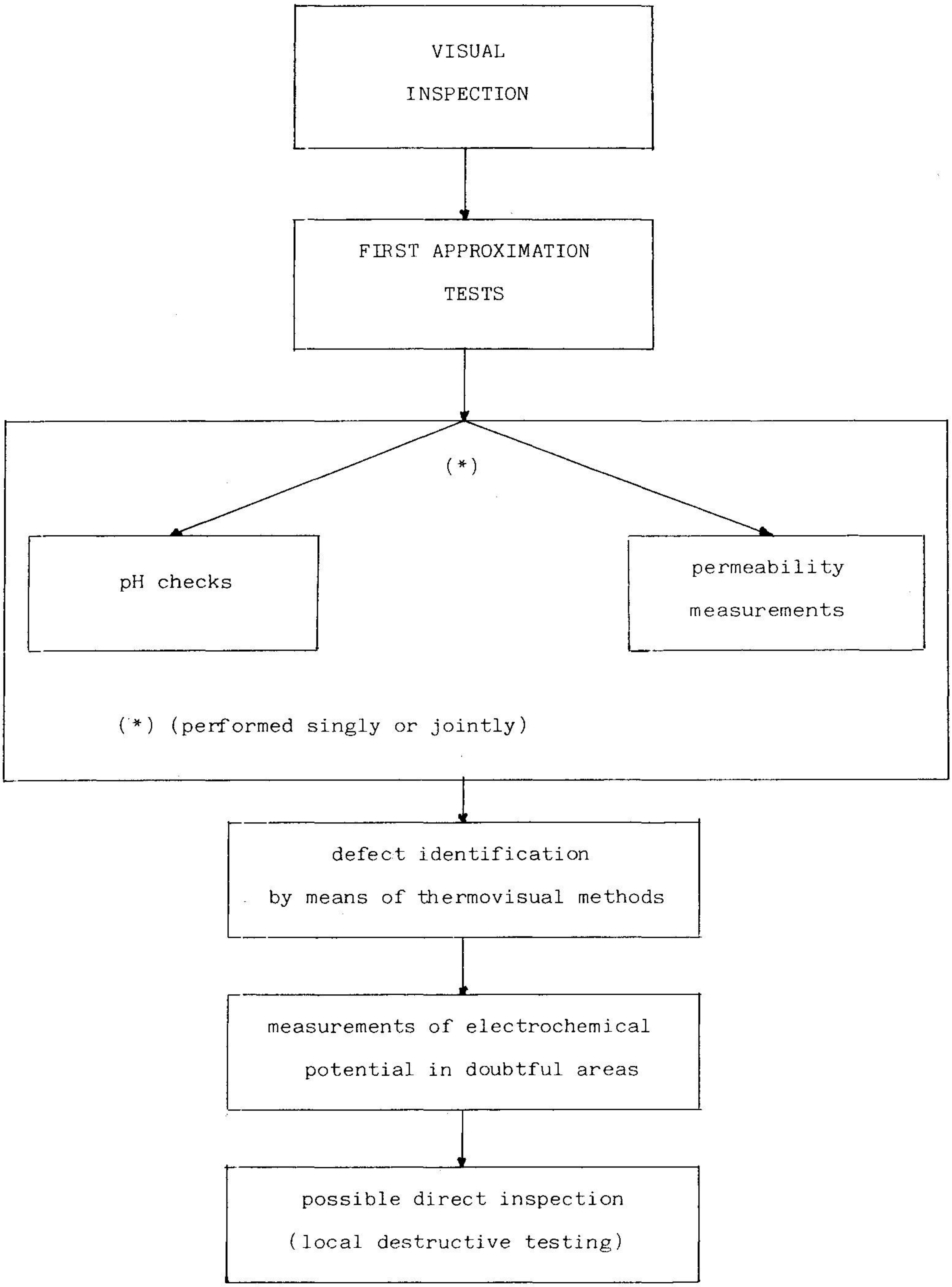
2.2 Special investigation techniques for embedded steel

The non destructive techniques used to assess reinforcement conditions are aimed at determining the geometrical characteristics of the reinforcement and whether corrosion processes are under way.
The determination of reinforcement position, diameter, cover thickness and the presence of joints, is of the utmost importance both when checking the quality of newly built structures and in the assessment of older structures for which no past records are available.
To this end, magnetic detectors can be used (pachometer) but the results can be depended on only when concrete cover is not too thick.
More conclusive results can be obtained by means of thermography, although this requires the prior heating of the reinforcement, either by Joule effect or by means of electromagnetic induction. This technique results in a very clear picture of the way the reinforcement is arranged, and photographic evidence can also be provided.
The corrosion of reinforcing steel can be identified by means of electrochemical potential measurements (3) performed on the concrete surface. This non destructive testing method in based on the consideration that corroded iron portions differ from passivated one because of their different electrochemical potential.
Thus, the measurements are taken by means of a sample electrode of Copper (Cu) in a copper sulfape saturated solution ($CuSO_4$). The electrode's potential, referred to hydrogen, is + 316 mV.
The interpretation scheme for these measurements is given in figure 4.
However, it is important to point out that this method provides insight only on on-going corrosion processes and does not detect older phenomena which may be temporarily inactive: hence, before the tests, the conditions fostering the development of corrosion processes should be restored.

3. Summary considerations on working procedures to be applied in the assessment of existing structures.

In chart 1, reproduced below, we have summed up the logical sequence of steps to be followed when performing the investigations illustrated in the foregoing paragraphs.
It should be kept in mind that no single non destructive test applied in isolation can be regarded as decisive.
As rule, it is adviseable to try to correlate the various experimental approaches, comparing the results in order to enhance the reliability of the assessment.

Chart 1 : Sequence of investigation steps



4. TESTING THE STRUCTURES

The main problem encountered in the interpretation of tests carried out on real structures lies in having to draw conclusions concerning structural behaviour at all limit states, including ultimate LS, through the interpretation of checks performed under serviceability conditions.
The difficulties involved in extrapolating valid data from tests performed under service conditions is clearly borne out by the tests carried out on an overpass that was being torn down (9).
12 beams prestressed by means of sliding tendons were tested in the laboratory till failure. In 6 cases behaviour proved satisfactory and when the beam was demolished, after the tests, corrosion was found to be modest (fig. 5)
In the other 6 cases, instead, failure occurred under applied moments lower than expected and when the beams were taken apart tendon corrosion was found to be exremely severe, with residual sections of less than 50% (ifg; 6).
Yet, from an examination of the moment vs. displacement diagrams in figs. 5 and 6, it can be seen that in terms of dead loads all beams displayed the same stiffness values; hence, any non destructive test based on the assessment of stiffness with no loading would not have revealed the extent of the damages. Furthermore, under service loads, only the beams in the worst conditions of repair manifested cracks and hence service load tests would have detected only the severest cases of deterioration.
Although with the above mentioned reservations, it can be stated that the observation of structural behaviour under service conditions helps to integrate the findings of non destructive tests; especially valuable is the repetition at periodical intervals (e.g., every 5 to 10 years) of tests (such as topographic measurements of displacement, load tests, etc.) aimed at identifying changes in structural response.
Needless to say, a loading test performed till failure on a structural element suitably isolated from the adjacent ones, if practical, would provide much more conclusive data which could then be extented to similar elements by means of non destructive methods. A typical instance of this consists of testing till failure a number of joists belonging to a floor slab made up of a large number of identical elements after having removed the continuous cross members.

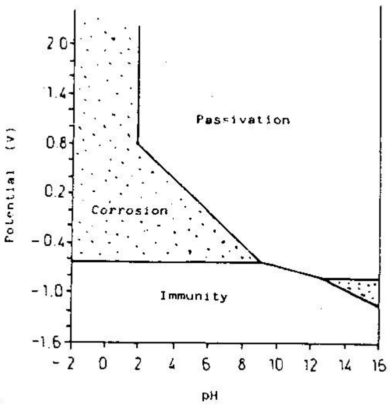
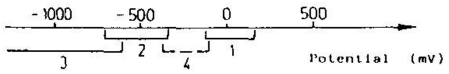


Fig. 1 - Steel corrosion vs. pH value and potential.



1) Perfectly passive steel embedded in aerated concrete
2) Attack through formation of couples
3) Generalized corrosion in carbonated concrete
4) Doubtful case

Fig. 4 - Interpretation scheme for potential measurements.

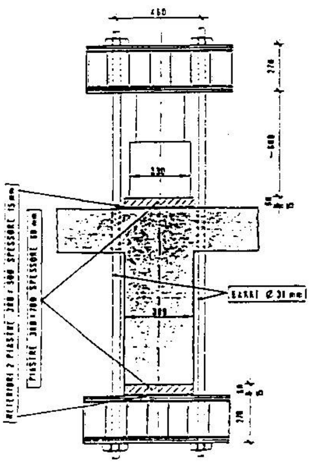


Fig. 2 - Arrangement of on-site compression tests.

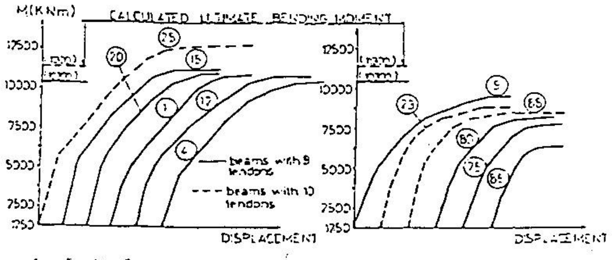
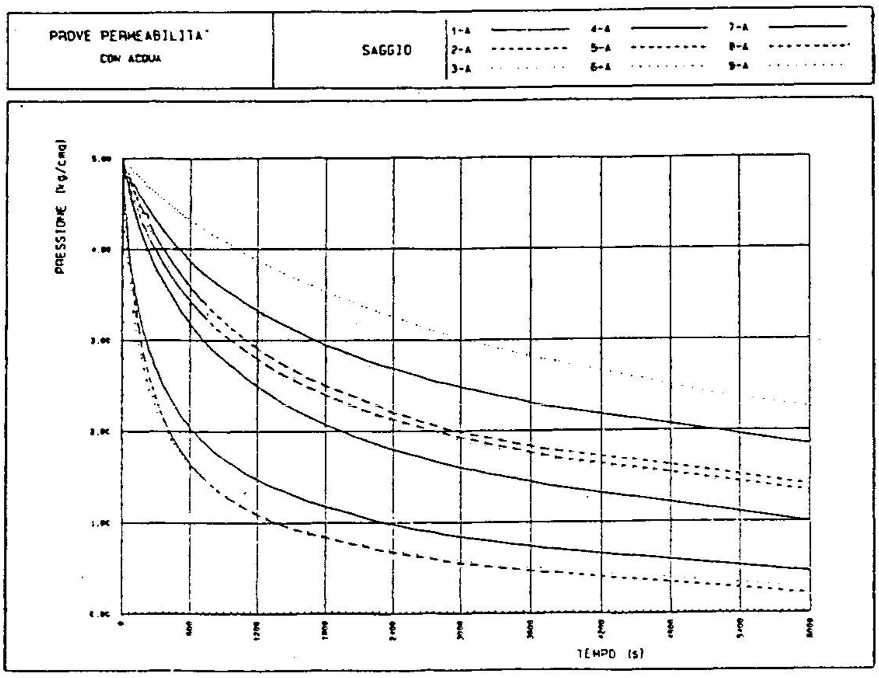
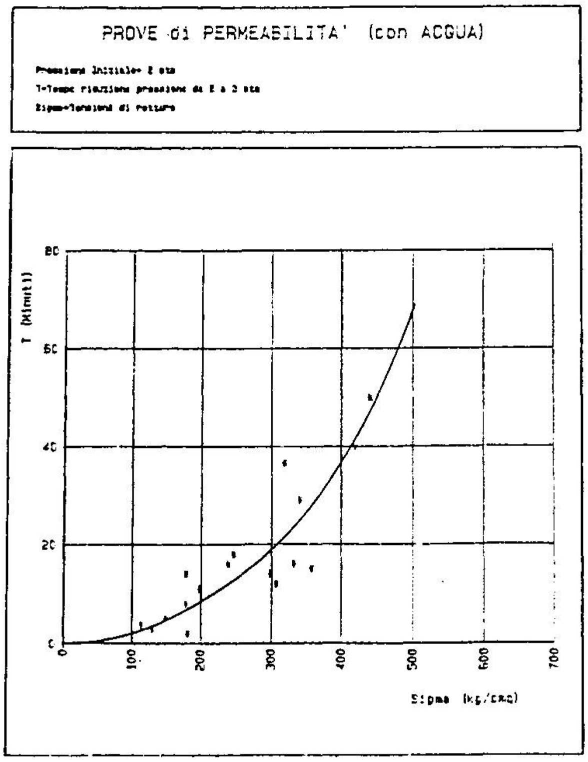


Fig. 5 - Fig. 6: Moment versus displacements diagram of tested beams



(a)



(b)

Fig. 3 - On-site permeability tests:
a) pressure drop times for concretes of different permeability, and b) correlation with strength.

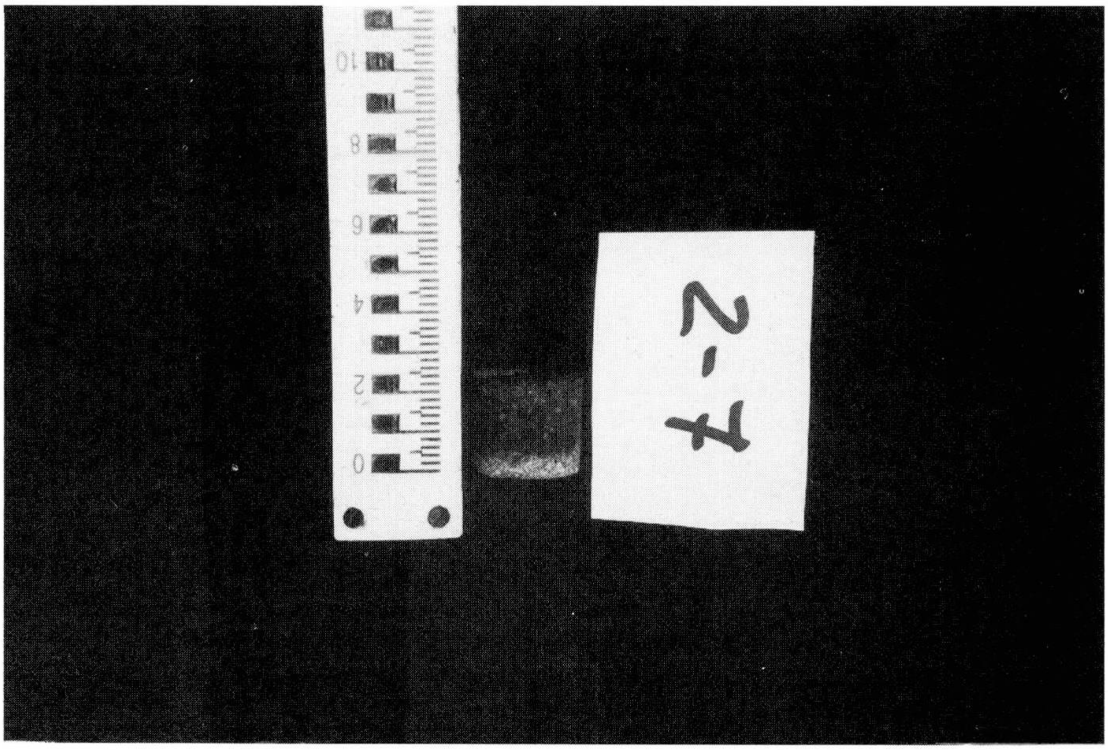


PHOTO 1 - Reaction to phenolphthalein on a microcore: in the colourless area pH$<$9.8

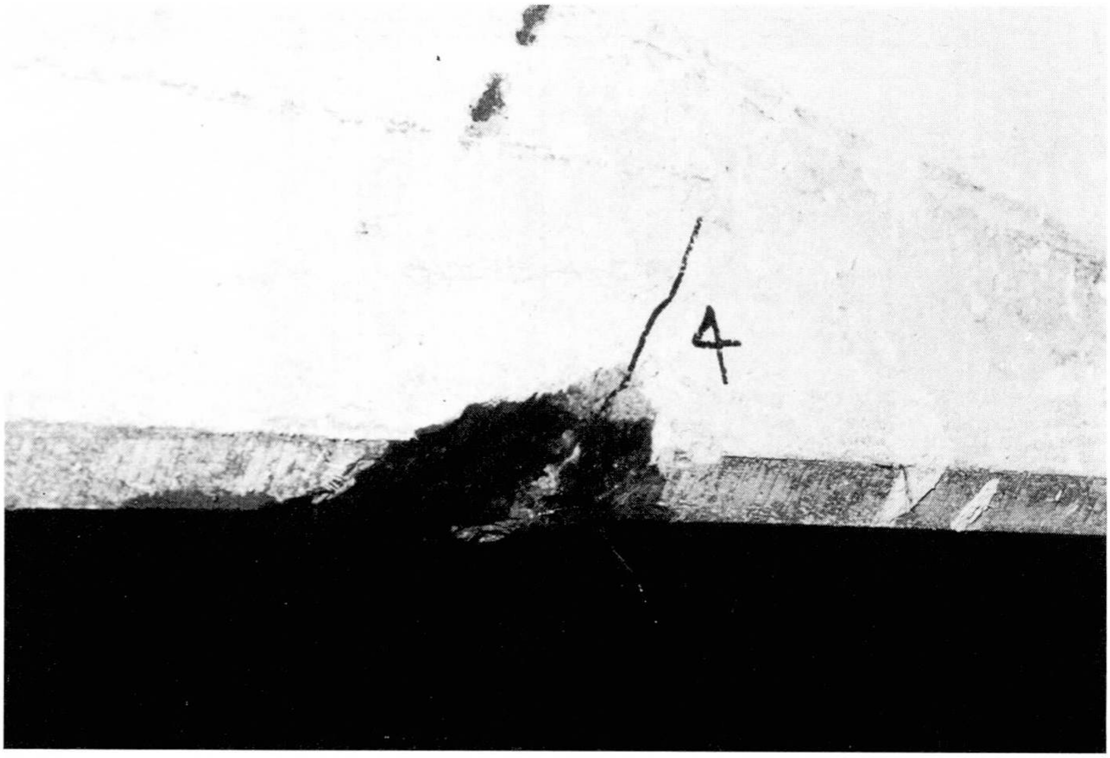


PHOTO 2 - On-site phenolphthalein reaction: the influence of cracks can be observed

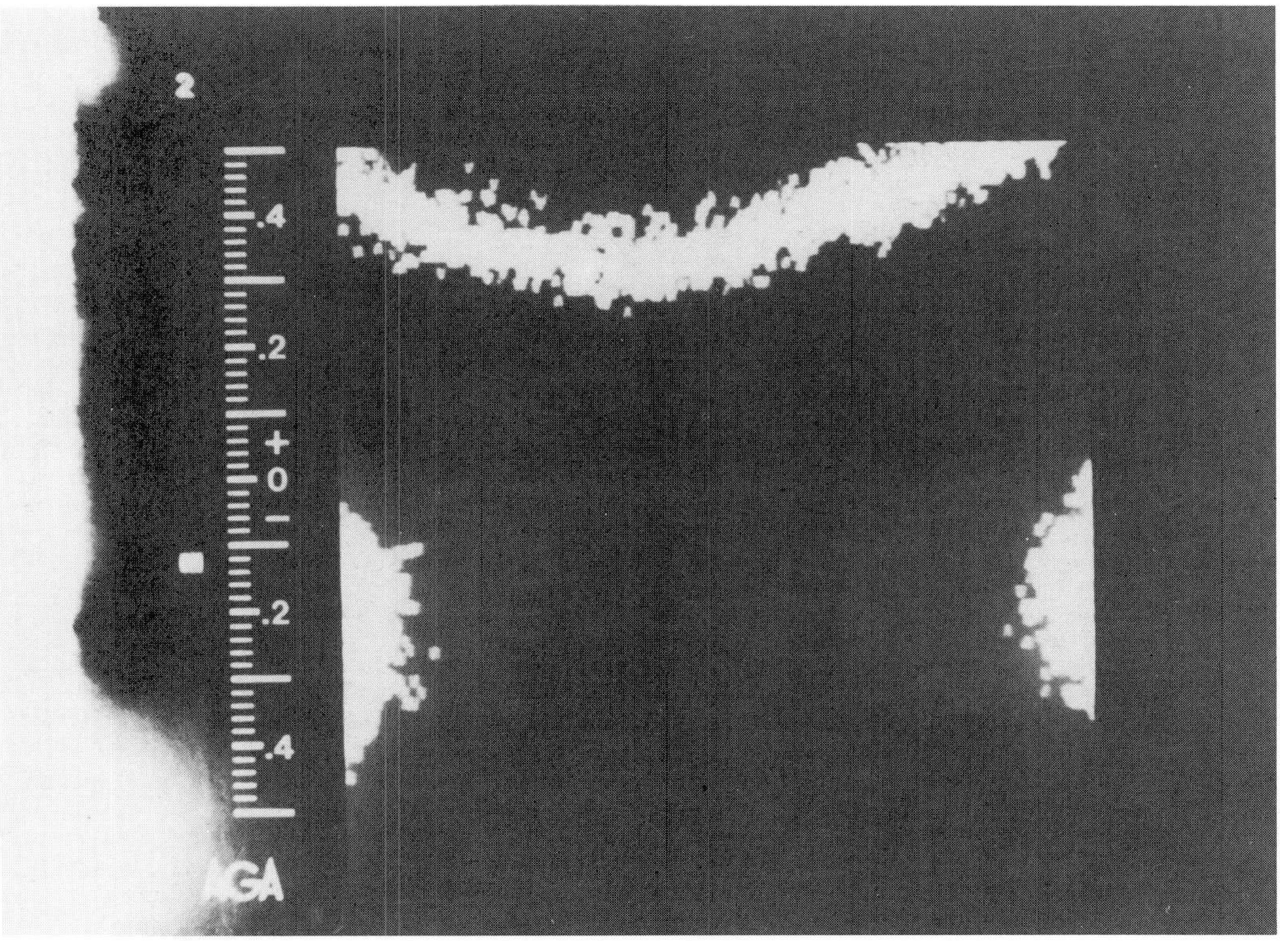


PHOTO 3 - Thermo-visual inspection on a sheath enclosing a pre-heated prestressing tendon: the dark area at centre reveals a grouting defect.

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