

**Zeitschrift:** IABSE reports = Rapports AIPC = IVBH Berichte  
**Band:** 73/1/73/2 (1995)

**Artikel:** Forecasting the condition of a reinforced concrete structure under corrosion  
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**DOI:** <https://doi.org/10.5169/seals-55224>

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## Forecasting the Condition of a Reinforced Concrete Structure under Corrosion

Prévision de l'état d'une construction en béton armé, sous corrosion

Ueberwachung und Zustandsprognose eines korrodierenden Stahlbetontragwerks

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### SUMMARY

For monitoring the effects of rebar corrosion in a structure, some methods have been developed which are minimally or totally nondestructive. To determine the areas where rebars are corroding, a potential map is drawn. The extension of the corroding areas is predicted by using the results of these measurements and those of carbonation depth or chloride profile, as well.

### RÉSUMÉ

Les auteurs exposent les méthodes peu ou non destructives mises au point pour détecter les effets corrosifs sur les armatures d'une construction. Ces procédés permettent d'effectuer un relevé graphique du potentiel électrique des zones d'armatures déjà corro-dées. L'extension des zones de corrosion est prévue en utilisant aussi bien les résultats de ces mesures que ceux de profondeur de carbonatation ou de profil de teneur en chlorure.

### ZUSAMMENFASSUNG

Zur Ueberwachung der Auswirkung von Bewehrungskorrosion in einem Tragwerk wurden einige Methoden entwickelt, die ganz oder weitgehend zerstörungsfrei ablaufen. Um die Fläche zu bestimmen, wo die Bewehrung korrodiert, wird das elektrische Potential kartographiert. Das Ausmass der geschädigten Zonen wird aus diesen Ergebnissen in Verbindung mit der Karbonatisierungstiefe und dem Chloridprofil bestimmt.



## 1. INTRODUCTION

Concrete cover in reinforced concrete structures can undergo several damaging actions. For example, freezing and thawing cycles result in physical effects (temperature gradient) and chemical actions (chloride effects). Reinforcing steel in these structures can also be deteriorated by chemical actions, mainly due to chlorides and carbon dioxide.

The corrosion process of rebar includes two stages. For the first stage, aggressive reagents, such as chlorides, penetrate through the concrete cover but rebars are not yet corroding. The second stage starts when the amount of aggressive reagents contacting steel, reaches a critical value.

So, it is of importance to monitor corroding rebars, by applying non-destructive methods, before significant deteriorations are visible on the concrete surface. If corroding rebars are detected, the deteriorated areas can be well located and eventual repairs can be made at low costs. This principle has been applied to the following procedure which has been developed by Laboratoires des Ponts et Chaussées (LPC - France).

## 2. MONITORING THE CONDITION OF THE STRUCTURE

### 2.1 : Potential mapping

Potential map is drawn by measuring the half-cell potential  $E$  of rebar against a reference electrode, placed at various locations on the structure surface. This monitoring technique is now common. The distance between the nearest checking points is as short as possible. For the French LPC laboratories this length is of about 25 mm. This method is non-destructive when some rebar are no more covered and can be connected to the measurement circuit. If no rebar is visible, a small hole is drilled for connecting the rebar mat to the voltmeter.

The interpretation of the potential  $E$  values can be difficult. For example, it appeared that in a reinforced concrete elements in tidal zone, the rebar half-cell potential depends on the tide height and then the amplitude of potential change is about 100 mV. So, potential maps are used only for determining the areas where rebar half-cell potentials  $E$  are of the same order of magnitude, i.e. for example,  $E$  lower than  $-350 \text{ mV}_{\text{CSE}}$ , or  $E$  higher than  $-200 \text{ mV}_{\text{CSE}}$ . When the  $E$  value is very low, rebar is likely corroding. But, in that case, a small hole is drilled for examining the actual state of this rebar. Thus, it may be asserted that rebars are corroding in such areas. It is of a great importance to determine the locations and the extents of the areas where rebars are corroding, because such areas are more dangerous if they are in tensioned members of the structures.

More commonly, potential maps are used to determine the parts of a structure where repairs are to be made. They give no information on rebar corrosion rate.

Figure 1 gives an example of potential mapping. It deals with a bridge, in mountain area, on which deicing salts have been applied. This map shows that the corroding rebars are also in the lower part of the members, near their ends. The reason of this deterioration was that the waterproof membrane (on the bridge deck) was not effective at its ends.

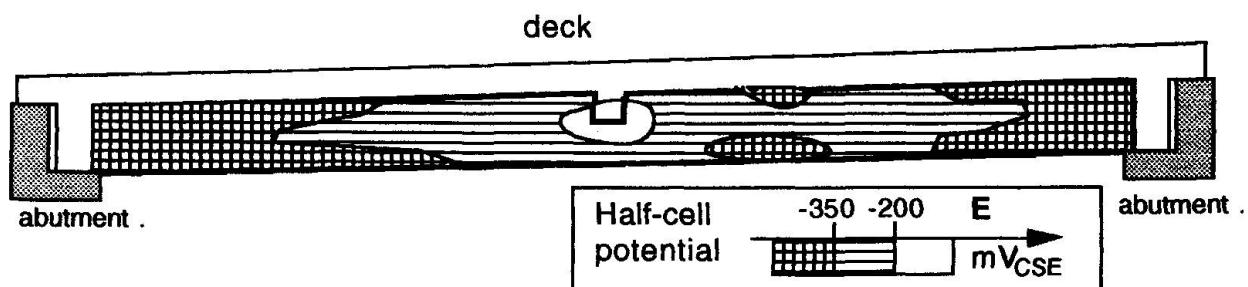


Fig. 1 : Example of potential map of a bridge member, about 7 m long and 0.5 m high.

## 2.2 : Carbonation depth

As far as rebar corrosion is concerned, the most common aggressive reagent is, in France, carbon dioxide. It means that carbonation deteriorates French concrete structures, more often than chlorides do. This gaseous atmospherical compound can decrease the pH of the concrete cover (carbonation process) and induce rebar corrosion. So, it is of importance to know how deep carbon dioxide has penetrated into the concrete cover around a rebar.

Carbonation depth is determined by using color indicator (phenol phtaleine). This measurement can be almost non destructive if the fresh surface on which the indicator is applied, is obtained with a rotating saw. However, such a slot must be correctly made, by a skilled personnel. The value of the carbonation depth  $X_c$  is to be compared with the concrete cover thickness. It means that if the whole concrete cover is carbonated and if the relative humidity around the structure is not too low, rebars are likely corroding.

Another type of result can be obtained by measuring carbonation depth  $X_c$  at various ages  $t$ . Such measurements give the effective diffusion coefficient  $D'$  of carbon dioxide into concrete, according to the formula :

$$X_c = \sqrt{D' t} \quad (1)$$

Diffusivity  $D'$  can be used for predicting the extension of damaged concrete area, as stated later.

## 2.3 : Chloride profile

Chloride ions in concrete cover can depassivate rebars, when their content reaches a critical value which depends on the pH of this cover. However, only chloride ions dissolved in the hardened cement pore water can be involved in corrosion processes.

So, soluble chloride content is determined at various depths in concrete. Results are plotted in a curve (chloride profile) giving the chloride content against the concrete depth (Fig. 2). If some assumptions are met, chloride profiles can be interpreted in terms of a diffusion process. One of these assumption is that the concrete humidity shall be almost constant. But some theoretical studies [2] [3] [4] have also shown that chloride penetration into concrete can be assumed to be a diffusion process only if the concrete cover is not deteriorated during the chloride penetration.

Under these assumptions, a diffusion coefficient of chloride ion in concrete can be determined by using the chloride profile which gives chloride content  $[Cl^-] = C$  versus cover depth  $x$ , at an age  $t$ . This gives the effective diffusion coefficient  $D$  according to :

$$C(x, t) = C_0 \left\{ 1 - \operatorname{erf} \left( \frac{x}{2\sqrt{Dt}} \right) \right\} \quad (2)$$

where  $\operatorname{erf}$  is "error function" and  $C_0$  is a parameter which is sometimes called "specific" chloride content. It is equal to the highest chloride content in the concrete cover, i.e. near its surface.

Many experimentations have shown that, in practice, chloride penetration into concrete placed in a regular atmosphere, can be described as a diffusion process [5] [6].

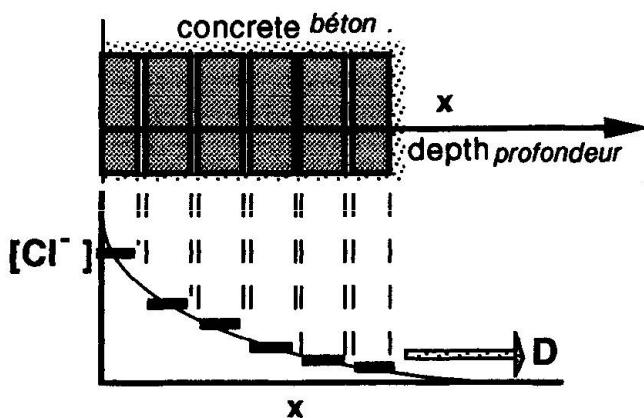


Fig. 2 :

Chloride profile which can be used for determining the chloride diffusion coefficient  $D$ .

Chloride content at depth  $x$  is in fact measured by using a concrete slice whose center is at depth  $x$ .

These slices are parts of cores drilled from the concrete cover. They are about 4mm thick



#### 2.4 : Air permeability

The chemical deteriorations of concrete are mainly due to aggressive reagents coming from the environment. These reagents are fluids (liquid, gas) and it is of importance to determine the permeability of the concrete cover to such fluids.

Fig. 3 gives the principle of an equipment used for determining the concrete surface permeability to air [7]. For this test, a tight vessel is placed on the concrete surface. The air in this vessel is evacuated by using a vacuum pump. Then, the valve of the pump is shut and air enters back in the vessel. Its pressure  $P$  is measured in function of time  $t$ . The curve  $P(t)$  obtained obeys the law

$$P = P_0 \left[ 1 - e^{-\frac{t+t_0}{T}} \right] \quad (3)$$

where  $t_0$  and  $P_0$  are experimental constant and parameter  $T$  characterizes the concrete permeability.

It means that parameter  $T$  makes it possible to locate areas where concrete is of high permeability (microcracks, etc). So, this parameter is related to the risk of rebar corrosion.

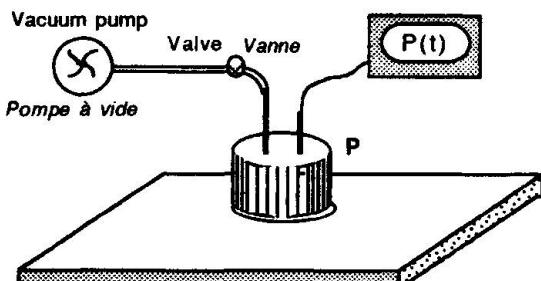
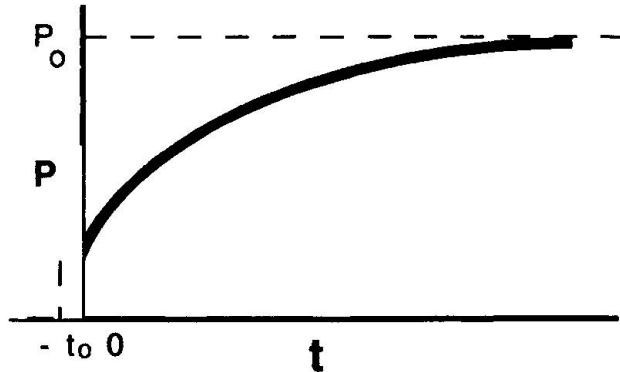


Fig. 3 :  
Principle of the equipment for measuring the air permeability of a concrete surface.



### 3. FORECASTING THE CONDITION OF REINFORCED CONCRETE STRUCTURE

As far as the future deterioration of a reinforced concrete structure is concerned, the following procedures make it possible to predict when a studied part of the structure must be repaired due to the rebar corrosion. It is to be noticed that visual examinations are needed to assess the validity of some test results.

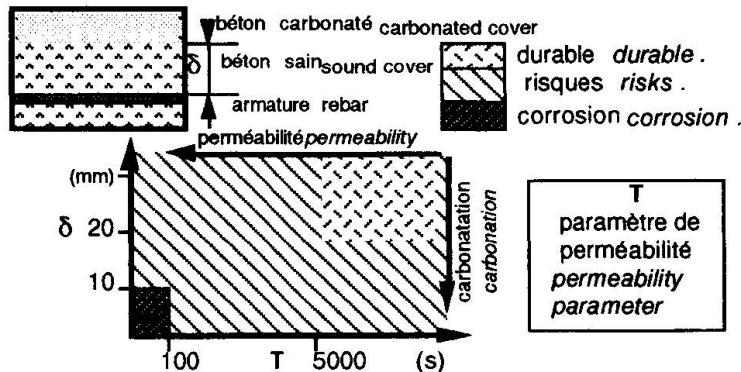
Any prediction procedure is based on test results, namely carbonation depth, chloride profile and possibly air permeability.

As mentioned here above, results of carbonation depth and air permeability measurements can predict if rebar, in the investigated area, will likely corrode [8]. Fig. 4 shows that, when the carbonation depth is thin and the air permeability low, rebar corrosion will not occur in short term. On the contrary, if the concrete cover is carbonated and if it is permeable to fluids, rebar are likely corroding.

Fig. 4 :

Procedure for predicting the corrosion of rebar by using results of carbonation depth and air permeability measurements.

Here it is assumed that no chloride is involved in the corrosion process.



This simple prediction method is no more valid, when the rebar corrosion is likely due to chlorides. So, another procedure is applied in this latter case.

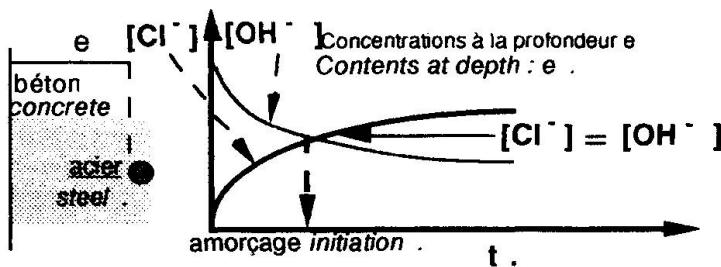
A rebar can be depassivated (corroded) when the chloride content at its level, reaches a critical value, which is equal to  $[Cl^-]_{lcr} = [OH^-]$  [9]. Another empirical rule states that  $[Cl^-]_{lcr} = 0.6 [OH^-]$ . In fact, due to the difficulties for determining the concrete pH, these two rules are equivalent.

This rule is indeed applicable both for carbon dioxide and for chloride induced corrosion. The reason is that, when concrete is carbonated (pH of about 9), the critical chloride content is very low and it is approximately equal to the chloride content in common, drinking water.

So, for predicting the corrosion of a rebar at a given location, it is necessary to know the diffusion coefficients of carbon dioxide ( $D'$ ) and of chloride ( $D$ ), as well as the "specific" chloride content  $C_0$ . If these parameters are known, relations (1) and (2) give the future carbonation depth and chloride content at an age  $t$ . Then, prediction curves can be drawn. Fig. 5 gives examples of such curves : it indicates when rebar corrosion can start in the investigated part of the structure. In this example, the chloride and  $OH^-$  contents, at a given depth  $e$ , are calculated versus (future) time  $t$ , by using diffusion laws and measured diffusion coefficients. The crossing of these two curves gives the date of the corrosion initiation.

Fig. 5 :

Prediction of the chloride and  $OH^-$  contents which make it possible to determine when rebar will corrode in a given part of a structure



It is to be noted that

- such a prediction is valid only if the concrete cover is not damaged by any other process (delamination, etc),
- sometimes the chloride diffusion coefficient decreases in function of time (because of the concrete change), then the prediction based on a constant diffusion coefficient is conservative.



#### 4. CONCLUSION

The methodology developed, in Laboratoires des Ponts et Chaussées, for assessing the opportunity of a repair is now operational. It applies to structures which are under periodic survey. It means that the damaged areas in these structures are not wide spread : the rebar corrosion is often of low rate. It is not always necessary to measure this corrosion rate, because the aim of the prediction is to determine in which part of the structure and when a given part of the structure needs to be repaired.

The following concluding remarks can be drawn about this prediction methodology.

Many damages in reinforced concrete bridges are due to rebar corrosion. So, it is of importance to determine the condition of rebar in every part of these structures. This can be achieved by drawing potential maps which show out where rebars are corroding.

If rebars are not yet corroding in some parts of the structure, it is now possible to predict the start of their corrosion. This is achieved by measuring carbonation depth and chloride profiles. So, this methodology is applicable when rebar corrosion is due to concrete carbonation and to chloride ingress, as well.

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