A. Research into the embrittlement of prestressing steel (stress corrosion)

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Summary

Conditions of building as well as materials have undergone such rapid development in recent years that prestressed concrete constructions are much more exposed to the danger of stress corrosion than had been the case hitherto.

This motivation had lead to research by a project group of TNO in order to find an answer on the questions: "How does stress corrosion arise?" and "Is it possible to develop a forecasting test by means of process simulation?" The group's first findings are described in a series of articles from which the first gives an overall view of the state of the problem and the various investigations carried out.

1 Introduction

Prestressing steel in concrete is under high tensile stress. Fracturing of the steel will result in collapse of the structure, with all the attendant consequences thereof. For this reason it is endeavoured by means of official approval procedures (certifications) for prestressing steel and anchorage systems to ensure a high degree of reliability of this feature of prestressed concrete. Acceptance testing of the steel and the concrete in accordance with the relevant regulations aims at providing optimum certainty as to the behaviour of the prestressed concrete structure. The work of many Committees (national and international) has resulted in revised standards and codes.

Despite these precautions, instances of structural damage do occasionally occur, these being mostly due to mistakes unwittingly made. However, cases are still encountered where fracturing of prestressing steel occurred without any subsequently ascertainable cause (see, inter alia, CUR Report 49*). In particular, so-called stress corrosion is liable to bring about embrittlement of the prestressing steel, which may arise fairly suddenly or may develop progressively in course of time by which fracture of the steel becomes possible. Although this defect has hitherto been of relatively rare occurrence, the possibility cannot be ruled out that, as time goes by (ageing of prestressed concrete), this type of damage may become more frequent.

Stress corrosion of prestressing steel may occur, inter alia, when the steel under tension is so affected by environmental factors that, to put it in the simplest terms, atomic hydrogen can penetrate into the steel and disturb the structure thereof, e.g.,

* Report 49 "Cases of damage due to corrosion of prestressing steel" of the Netherlands Committee for Concrete Research, P.O. Box 61, Zoetermeer.

by the formation of small cracks and by giving rise to brittle fracture (but see also 3).

The primary requirement would therefore be to have a reliable method of investigation for predicting the possibility of stress corrosion in actual practice. Such a method is at present *not* available, however. This view is widely endorsed. Thus, it is significant in this context to cite the conclusion of the second FIP Symposium "Stress corrosion of prestressing steel", held at Arnhem in September 1973, which began as follows: "A more intensive study of the mechanism causing stress corrosion cracking in prestressing steel is considered to be very important. A test method has to be developed enabling the stress corrosion susceptibility of drawn wire to be checked".

At that Symposium the now extensively used stress corrosion test on prestressing steel under tension in a 20% ammonium rhodanide solution (sometimes specified as a thiocyanate solution) was rightly regarded as not sufficiently reliable "to compare the sensibility to stress corrosion of prestressing steels, produced in different ways, as for lack of sufficient knowledge of the scatter of results (in time to fracture) with different types of steel". It is then recommended, inter alia: "The applicability of the ammonium thiocyanate test has to be further investigated in the near future, without abandoning research on other test methods".

To illustrate the importance of research on the stress corrosion resistance of prestressing steel it is relevant to note that prestressing bars newly marketed (26–32 mm diameter, grade St 110/135), recently had to be withdrawn from production because of the many instances of brittle fracture that occurred in practice and for which no conclusive explanation has been found. These fractures mostly occurred at periods ranging from a few days to a few weeks after the bars had been tensioned to around 60% of the guaranteed tensile strength, in some cases even to only about 30%. Despite the care bestowed on the manufacture and processing of the steel and the fact that this steel is claimed to possess lower notch sensitivity than other grades marketed (80/105), it nevertheless turns out to be more sensitive to corrosion than other prestressing steels.

The need to be able to control stress corrosion becomes even more strikingly obvious when we consider the following developments in practical application:

- the increasing use of smaller diameters of drawn prestressing wire;
- the use of higher-grade prestressing wire, i.e., possessing higher tensile strength;
- the increasing use of partially prestressed concrete, i.e., explicitly accepting a certain amount of cracking of the concrete, with the attendant risk of steel corrosion;
- the increasing use of prestressed concrete with ungrouted tendons;
- the increasing use of prestressing bars of larger diameters;
- the increasingly aggressive conditions of exposure of many prestressed concrete structures: offshore structures are an example, while environmental pollution is also significant in this context.

Not only did the checking and testing methods formerly used fail to provide any reliable prediction of the stress corrosion hazard, but in addition the progress of technical development is being held up because the consequences thereof with regard to stress corrosion cannot be predicted with the aid of the currently available methods.

Already some years ago the present author called attention to this serious situation and therefore, partly at his initiative, a project group "Stress corrosion in prestressing steel" was set up within the context of the TNO organization; the group comprises members of the staffs of the following TNO divisions: CL, IBBC and MI,* co-operating under the author's co-ordinating direction. The fact that so far upwards of half a million guilders has been devoted to this field of research is an indication of how much importance is attached to it by TNO.

It therefore appears important to bring the first results of this research, presented here in a number of articles, to the attention of those interested.

It is hoped that this will lead to further concentration of activities, for which purpose it will certainly be of importance to base oneself on the considerable amount of knowledge and experience already possessed by TNO in this field of investigation. Joint continuation of research on the subject is indeed to be considered useful, important and highly desirable.

2 Statement of the problem

There are three general types of prestressed concrete, which are represented schematically in Fig. A1. Various interactions are thus possible, as indicated in Table A1. This table gives rise to two questions:

a. How is stress corrosion susceptibility of prestressing steel affected by variations in the condition of the steel itself?

b. What is the effect of the environment on possible stress corrosion of prestressing steel and what conditions have to be fulfilled in order that the existing susceptibility will not result in brittle fractures?

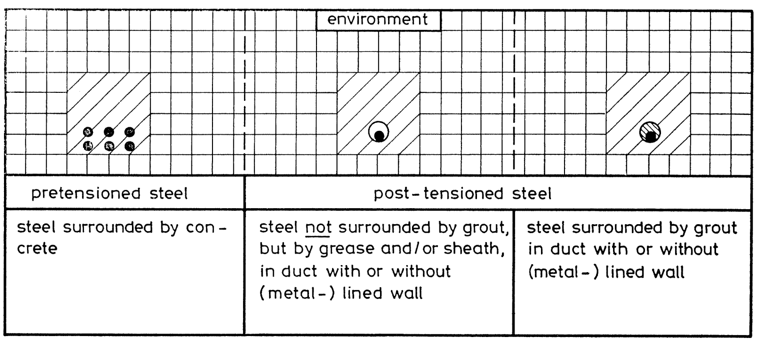

Fig. A1. Various forms of prestressed concrete (schematic).

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* TNO = Netherlands Organization for Applied Scientific Research
IBBC = Institute for Building Materials and Building Structures
MI = Metal Research Institute
CL = Central Laboratory

Table A1. Interaction between prestressing steel, concrete and environment

prestressing steel	environment *in* the concrete	environment *outside* the concrete
composition of steel	type of cement	light/dark
method of manufacture: heat treatment surface treatment stretching treatment, etc.	cement content water/cement ratio method of compaction micro-cracking	air (temp., relat.humidity, pollution) water (ground, surface, sea, condensation, sewer water)
notches, rust, salts on steel	presence of foreign ions (Cl^-)	bacteria (especially in soil and in sewers)
state of prestress	curing changes due to: adsorption and diffusion chemical reaction (e.g. carbonation, sulphate attack, etc.)	moss, algae, fungi (especially in air)
determines important properties such as:		
strength of steel	strength of concrete, quality of concrete, porosity (pore system), acidity (pH), etc.	
susceptibility to hydrogen embrittlement		
failure mechanism, etc.		

To find answers to these questions it is necessary to have a reliable method of investigation of stress corrosion phenomena affecting prestressing steel; for this in turn it is necessary to know the mechanism of stress corrosion. At the present time neither of these requirements is fulfilled.

3 From stating the problem to investigating it

The so-called Pourbaix diagram is very useful in ascertaining whether corrosion is liable to occur in a certain environment. For the metal-water system it gives the lines of equilibrium between the various stable phases in relation to the electrode potential and the pH. This diagram for iron is given in Fig. A2.

In the environment formed by concrete – which, as a first approximation, may be conceived as a saturated calcium hydroxide solution with $pH = 12.6$ – iron is, depending on the electrode potential, in a state of immunity or passivation. In the event of immunity, no corrosion can occur. In the passivated state the iron is covered by a thin pore-free layer of iron oxide which has a highly inhibitory effect on the dissolving of iron. In actual practice the potential is so high that the iron (steel) is in this state of passivation.

It may occur, however, that *locally* – in micro-cracks and small pits on the surface,

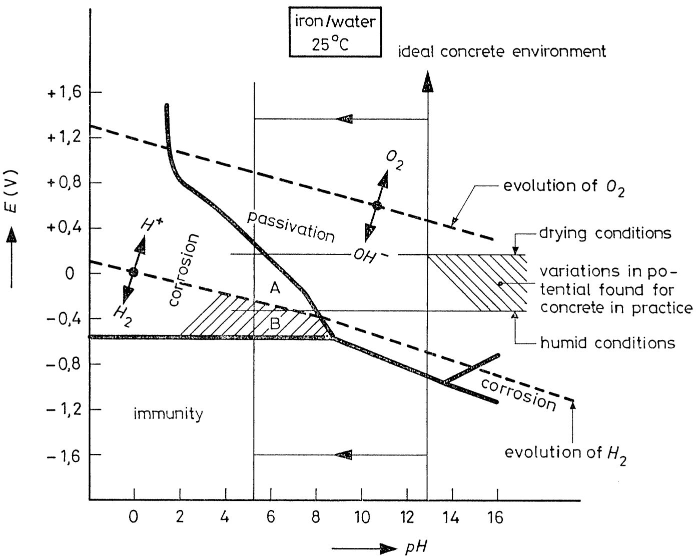

Fig. A2. E-pH diagram for iron, according to Pourbaix.

for example – the iron undergoes a change of condition, which now corresponds to the areas A and B in Fig. 2. For this to happen a local lowering of the pH and of the potential is necessary. In a subsequent article it will be shown that this may indeed occur. When it is in a condition corresponding to A and B, iron will locally pass rapidly into solution. This may result in extension of the cracks (active path anodic dissolution). Besides, evolution of hydrogen occurs in condition B. This may give rise to hydrogen embrittlement, which most experts on the subject even consider to be essential to the occurrence of stress corrosion.

Measurements of pH on a micro-scale could therefore constitute a good experimental technique in investigating the mechanism of stress corrosion. The manufacture of micro-electrodes was accordingly put in hand, but unfortunately ran into insurmountable difficulties.

It is of course necessary to obtain further information on the electrochemical corrosion process by means of determining the so-called current-voltage curves as a function of variations in the electrolyte solution. In this way it is also possible to ascertain the effect of "contaminants" such as Cl^-, $S^=$, NO_3^-, HCO_3^-, etc., as well as of variations in the prestressing steel (types of steel, surface condition, prestress, etc.).

Some important research results concerning the processes that occur in concrete when Cl^- ions penetrate into it and when $CaCl_2$ is present from the outset (introduced at the mixer) have already been collected, relating to the use of portland cement as well as portland blastfurnace cement.

Further information on these processes is given in this publication. Their significance is that contact of Cl^- ions (in sufficiently high concentration) with prestressing steel may cause the passivating layer on the steel to be disturbed, thus initiating the development of pitting and subsequent stress corrosion, as described above.

The existing methods of investigation for stress corrosion comprise so-called endurance tests. A wire, strand or bar of prestressing steel under tensile stress (usually 80% of the tensile strength) is placed in a corrosive environment and the length of time it takes for the test specimen to fracture is observed. In recent years a 20% ammonium rhodanide solution (NH_4NCS) has been most widely used (with or without artificial cathodic polarization of the prestressing steel). With this test it is possible to compare various types of prestressing steel with one another and also to investigate the effect of variations in the steel (types, surface condition, tensile strength, etc.).

To what extent this test correlates with the exposure of prestressing steel in actual practice is not known, however. So it is still necessary to proceed with caution in applying the information obtained by means of this test.

Endurance tests performed in other solutions, approximating more closely to the "concrete environment", are therefore to be desired.

The experience gained from such tests is certainly important enough to merit further mention in a subsequent article.

Detection of the degree of embrittlement in the endurance tests envisaged here may be followed up with the to-and-fro bend test well known in prestressed concrete engineering circles.

Numerous factors associated with the endurance test have been found to affect the results of these investigations. Phenomenological examination of the planes of fracture is carried out by optical and electron microscopy. These aspects will also be further considered, and possible relationships with other metal properties (composition, structure, etc.) will be pointed out.

In view of the fact that the stress corrosion phenomenon is linked with the formation of micro-cracks which are believed to spread during the embrittlement of the steel, it was attempted to keep track of this process with the aid of acoustic emission intensity measurements. Unfortunately, it was found that these cracks are acoustically detectable only just before the instant of fracturing, so that this approach does not provide a suitable method of investigation.

In view of the random location of the area(s) on the prestressing steel where corrosive attack will occur, it is obviously desirable to seek ways and means of pin-pointing such areas in advance. Since micro-cracks and small notches are believed to be a partial condition for the embrittlement process, the steel could be provided with artificial notches in order to accelerate the long-term endurance testing procedure. It is being investigated to what extent this method can be applied to prestressing steel. Progress of this research is difficult, however; various attempts to form a reproducible notch in small-diameter prestressing wire have hitherto been unsuccessful.

It can furthermore be reported that the subject of stress corrosion of prestressing steel is being studied also by other organizations in this country and abroad. Here in the Netherlands such research is more particularly being carried out by a producer of prestressing steel (Hoogovens), whose results, which are based on tests that are of course oriented towards the manufacturing process, have not been published, however. On the other hand, information derived from the research conducted by RILEM-FIP-CEB* is available. In the Netherlands, participants in these investigations were, to begin with, Hoogovens, IBBC-TNO and MI-TNO, thereafter MI-TNO and later also Hoogovens again.

In the course of these international comparative investigations it was endeavoured to develop the endurance test in rhodanide solution into a standard testing procedure. In view of the results obtained by MI-TNO, this laboratory was asked to prepare the standardization of that test. The results of these activities will be reported.

Finally, it should be mentioned that the TNO project group "Stress corrosion in prestressing steel" has, jointly with the Otto Graf Institute at Stuttgart (Prof. Dr.-Ing. G. Rehm), where a good deal of research on the subject has also been carried out, called the attention of the FIP to the need for continued research.

4 Summary

Research into the phenomenon of stress corrosion of prestressing steel is still in its infancy, and yet adequate knowledge of this phenomenon is essential in view of the following facts and developments encountered in actual practice:

a. It is still uncertain whether the occurrence of structural damage due to stress corrosion will not become more frequent as time goes by.
b. The use of larger-diameter prestressing bars and smaller-diameter drawn prestressing wires is increasing.
c. The quality (tensile strength) of prestressing steel is being further improved, with a corresponding increase in the magnitude of the prestress applied.
d. The use of prestressed concrete with ungrouted post-tensioned tendons and of partially prestressed concrete is also on the increase.
e. The conditions of exposure of many prestressed concrete structures are becoming more aggressive: offshore structures and environmental pollution may be mentioned in this context.

For these reasons it is necessary to carry out further research. A start with this has been made by the TNO project group "Stress corrosion in prestressing steel" (CL-TNO, IBBC-TNO and MI-TNO), the results of which will be reported in the following articles contained in this publication.

The aim of this research is to obtain insight into the conditions under which stress corrosion may occur and, as a result of these investigations, to develop a stress

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* RILEM = Réunion Internationale des Laboratoires d'Essais et de Recherches sur les Matériaux et les Constructions
FIP = Fédération Internationale de la Précontrainte
CEB = Comité Européen du Béton

corrosion test for prestressing steel which will possess predictive value for practical use and to draw up recommendations for avoiding stress corrosion in practice.

The case already mentioned above, where newly marketed prestressing bars had to be withdrawn from production, also clearly brings out the need for further research.