SPECIAL CORROSION PROBLEMS IN POST-TENSIONED STRUCTURES

BESONDERE KORROSIONSPROBLEME BEI SPANNBETON MIT NACHTRÄGLICHEM VERBUND

DES PROBLEMES PARTICULIERS DE LA CORROSION DANS LES ELEMENTS DE CONSTRUCTION PRECONTRAINTS AVEC ADHERENCE ULTERIEURE.

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SUMMARY

Water in ungrouted ducts, resulting from bleeding of fresh concrete, fulfils the best prerequisites for pitting and hydrogen induced stress corrosion. The report present typical failures and discusses the circumstances of bleeding and fractures of prestressing steel.

ZUSAMMENFASSUNG

Durch Bluten entstehendes Absatzwasser im unverpreßten Hüllrohren ist eine wesentliche Voraussetzung für Lochkorrosion und wasserstoff-induzierte Spannungsrißkorrosion. Der Bericht beschreibt typische Schäden und diskutiert die Voraussetzung für das Bluten und Spannstahlbrüche

RESUME

L'eau dans la gaines en tôle d'acier pas encore injectéés, qui vient du ressuage du béton frais, présents les meilleurs conditions pour la piqûre et la et la corrosion dans les fissures, provoquée par la tension et l'induction de l'hydrogéne. Le communiqué présent des défaillances typiques et discute les circonstances qui mènent au ressuage et à la rupture de l'acier précontraint.

Key-words: Stress-corrosion, prestressed concrete, damages, bleedings.

1 INTRODUCTION

In post-tensioned members of prestressed concrete structures high-strength steel wires, strands or bars are arranged in ducts. After casting and hardening of concrete prestressing steels are tensioned and the concrete becomes under compression. After that tension members are grouted with cement mortar in order to protect the steel against corrosion. In case prestressing steels fracture, concrete in the tension zone or the whole structure may break down, if the forces cannot be carried by the reinforcement.

Fractures of prestressing steels (fig. 1) as a rule can be refered to hydrogen induced stress corrosion cracking (HI-SCC) /1/. It should be pointed out that depending on steel qualitiy (sensitivity to hydrogen), processing and environment (that means construction materials, field conditions an corrosion exposure) this type of cracking may take place. Failures may be happened before grouting of tension members (during erection of the construction) or during the later use.

During the past ten years in Germany some serious damages in post-tensioned components have been occured, which were mainly due to onsite conditions and favoured of a sensitiveness of the used prestressing steel. In the following report these cases will be discussed and we'll get out with conclusions.

Fig. 1
Fracture of a wire
because of HI-SCC

2 THE BASIS OF HI-SCC

The following conditions are necessary to favour HI-SCC /2,3/:

- a sensitive material or state,
- sufficient tension load (also internal stresses in the steel),
- at least a slight corrosion attack.

During the corrosion process hydrogen atoms have to be set free and absorbed by the steel. In sensitive steels the hydrogen under the effect of mechanical stresses can create precracks in critical structural areas such as grain boundaries. The cracks may be grown to fractures. In sensitive steel structures already minimal contents of hydrogen could bring irreversible damages.

Special corrosion conditions have to exist, to activitate the formation of adsorbable hydrogen atoms. To understand the correlations between procedure on site and development of damage the chemical reactions of corrosion should be considered:

anodic iron dissolution

1 $Fe \rightarrow Fe^{2+} + 2e^-$

cathodic reactions

2 $1/2\ O_2 + H_2O + 2e^- \rightarrow 2OH^-$

if pH < 7 besides or instead of reaction 2

3 $H^+ + e^- \rightarrow H_{ad}$ (hydrogen discharge)

rivalry reaction with regard to 3

4 $2H_{ad} \rightarrow H_2$ (recombination)
(is prevented in the presence of promotors)

5 $2H_{ad} + 1/2\ O_2 \rightarrow H_2O$
(if oxygen is present or air access)

Harmful hydrogen could arise only, if the cathodic reaction of corrosion is discharging hydrogen (reaction 3) and the adsorbable atomic hydrogen is not changed into the molecular state or to water (reaction 4 and 5).

Therefore, at the surface of corroding steels the adsorbable amount of hydrogen atoms rises
- with increasing H^+-concentration or decreasing pH-value (reaction 3 is accelerated),
- in the presence of promotors (reaction 4 is hindered),
- with reduced oxygen content (reaction 5 is hindered).

Besides hydrogen evolution is only possible in the active state of corrosion or after depassivation (reaction 1 is possible).

Regarding the practical point of view considerable hydrogen damages are only possible in acid mediums or in the presence of promotors such as sulphides S^-, thiocyanates SCN^- and compounds of arsenic or selenium.

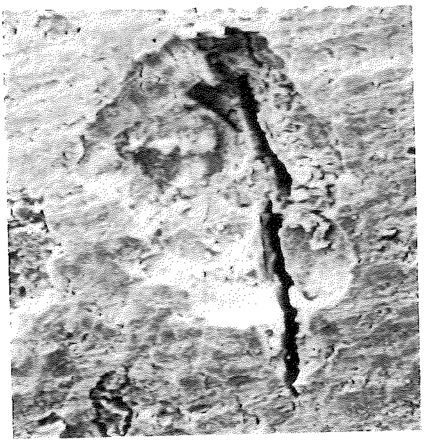
In concrete structures the attacking medium is mostly alkaline and acid solutions are limited to exceptions. Eg. atmospheric waters have pH-values lower than 7 (table 1).

Table 1: pH-values and corrosion-promoting substances in prestressed concrete

	atmospheric attack (rain, condensed water)	tap water	water resulting from bleeding +)	concrete (soluble contents, relative to cement)
pH-value	3 - 6	7 - 8	< 10 - 13	9 (carbonized) - 13,8
sulphate	20 - 1000 mg/l (town)	till 100 mg/l	2000 - 6000 mg/l	till 0,5 mass % (from ~ 5 % damaging)
chloride	3 - 16 mg/l (inland) till 60 mg/l (seacoast)	till 30 mg/l	100 - 500 mg/l	till 0,5 mass % (from ~ 0,2 % damaging)

+) 60 - 90 mg Ca^{+}/l, 180 - 370 mg Na^{+}/l, 3600 - 7300 mg K^{+}/l

In natural environments which means practical conditions as well, the pitting induced stress corrosion cracking will be existed (fig. 2). In the corrosion pits the pH-value falls



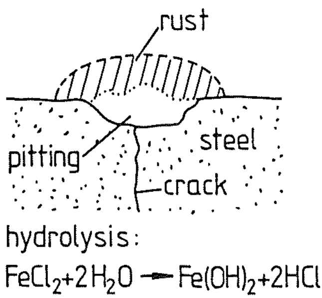


Fig. 2 Pitting induced stress corrosion cracking

down because of hydrolysis of the Fe^{2+}-ions. The decreasing of pH-value may be considerable and also the ability to avalute hydrogen, if Fe^{2+}-ions with the assistance of oxygen are oxidyzed to Fe^{3+}-ions and hydrolyzed completely.

Pittings or spots of local corrosion are being inducator to aeration cells because of condensed water drops on the steel surfaces and crevice corrosion. Further, we know concentration elements in a salt rich electrolyte with the active anodes and passive cathodic areas.

The failure reasons during the building use periode could be mostly lead back to a loss of passivity (carbonation of concrete, corrosion of duct and carbonation of mortar) or another depassivation (chloride attack). The main reason of problems during the erection of a building is water in the ducts, which resulting from the watery phase of fresh concrete. These partly carbonized waters, with relatively high contents of sulphates and chlorides (table 1), fulfil the best prerequisites for a local-cell formation and pitting corrosion.

3 TYPICAL FAILURES

3.1 Fractures due to salt-rich concrete water (bleeding) /2/

Some cases of steel fractures in the yet ungrouted ducts of post-tensioned structures could be attributed to the presence of aggressive water. While concreting a deposition of an alcalic watery phase, the so-called bleeding occurs for a limited period, in which especially high contents of sulphates and increased quantities of chlorides can be accumulate. The sulphates result from the cement (gypsum) and may be enriched during the short-term watery phase before being chemically bounded. The chloride content in the water cannot be clearly related to a certain constituent of concrete. But a leaching effect of the construction materials (cement, aggregates, water) in the fresh concrete must be considered.

High concentrations of sulphate and chloride in the liquid phase of concrete are limited to the period of fresh or green concrete. In fig. 3 the composition of the pore water in cement stone within the hydration time is shown (from fresh to hardened concrete). At first there is a high concentration of sulphates and alkalies (sodium and above all potassium) (compare table 1). Because of intended contamination also chloride content is higher. The values of sulphate, chloride an calcium during hydration decrease to a minor value and alkali and hydroxyl increase. The pH value is varying from ~ pH 13 to ~ 13,4 after some years.

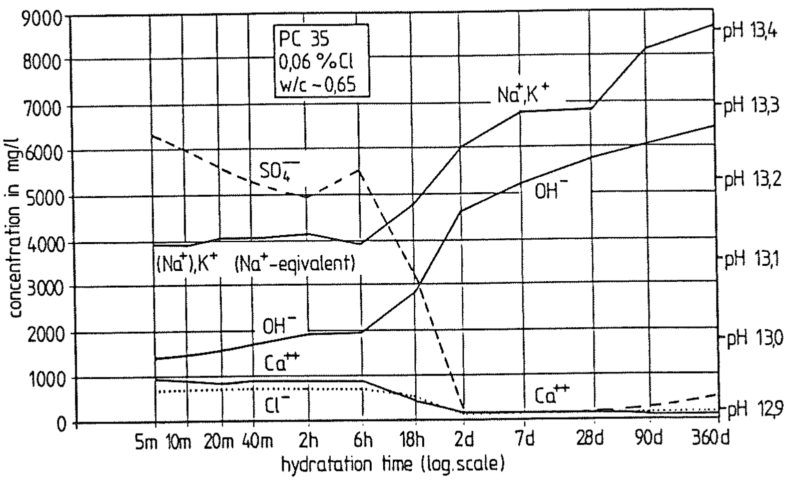


Fig. 3 Composition of the watery phase of cement stone during hydration (Gunkel)

The watery phase of fresh concrete penetrates into the ducts and accumulates at the deepest points. The anchorages, couplings and defects in the ducts, may be considered as the most points of week in the prestressing system and sometimes some litres of water with mineral constituents penetrate in the mentioned point of week in the prestressing system.

Already in the not prestressed condition the steel suffering are local limited, but intense corrosion takes place in the ungrouted status (fig. 4). From early age untill few months following the prestressing, fractures in steel take place starting from corrosion pits with a depth up to 1 mm (fig. 5). Normally fractures which are concentrated metres away from the anchorages. The tendons break at the deepest position, where the aggressive water accumulated.

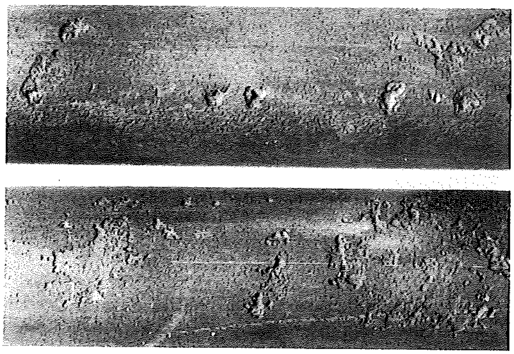


Fig. 4
Corrosion of prestressing steel in water resulting from bleeding

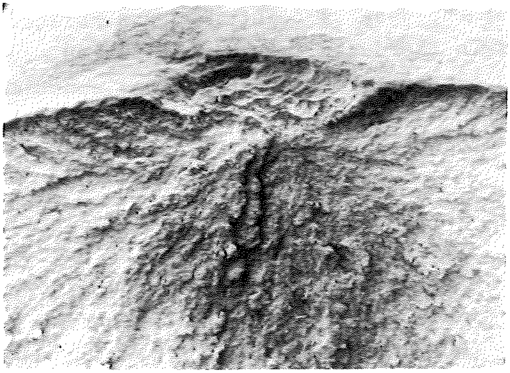


Fig. 5
Pitting induced stress corrosion fracture in water resulting from bleeding

Because of the strong influence of concrete bleeding on corrosion formation and crack initiation, corrosion experts recommend to wash or evacuate out the aggressive water.

Further, from a practical point of view attention should be paid to know, which concrete technology could favour the undesirable bleeding:
Bleeding is a separation of fresh concrete or mortar, where the solid content sink down and the displaced water rises. Water may be also accumelated beyond aggregates, reinforcing steel and ducts of prestressing systems. It has also very small particles of cement and gypsum ($CaSO_4$) in solution. By increasing the water-cement-ratio increases bleeding as well. Further, the type of cement is important: With falling fineness of grind the tendency to bleeding becomes stronger. Fine grain additives with a large specific surface such as puzzolane and especially silica fume (specific surface ~ 20 m^2/g) adsorbe water and deminish bleeding, also special stabilzers (e. g. polyethylene oxide and cellulose mixtures) are able to bind water. Bleeding also is time - dependent: The longer the solidification the greater ist bleeding. This is

due to the adding of retarder which can increase the quality of water in ducts. The addition of a liquefier or a plastiziser may reduce bleeding, if at the same time the water-cement-ratio is low. Water separation may be increased without reduction of water liquefiers. Table 2 summrizes all aspects of bleeding.

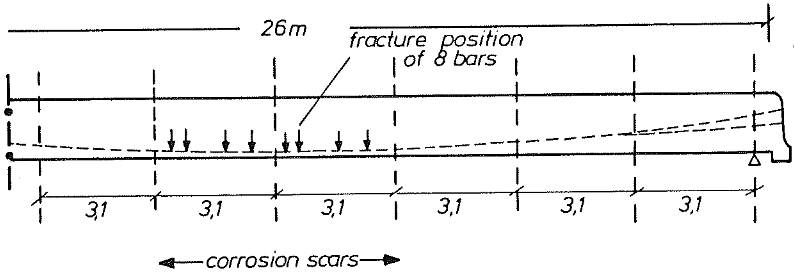
bleeding	
increase	reduction
high W/C - ratio	low W/C - ratio
fine grain deficiency	fine grain additives (e.g. silica fume)
	stabilizer (polyethylene oxide, cellulose mixtures)
retarder	accelerater
slow solidification	quick solidification
liquefier	liquefier (if W/C is reduced)
	vibration

Table 2
Influences on concrete bleeding

3.2 Fractures due to salt- and promotor - rich concrete water /4,5/

A further damage, similar to those described in chapter 3.1, could be attributed to salt rich waters in ducts, but also related to the use of a concrete liquefier with thiocyanate as active agent, which is not admitted for prestressed concrete.

While erecting a one-field slab deck bridge of prestressed concrete, some fractures were stated during the structural phase. There were totally 8 fractures in steel bars in longitudinal direction in the deepest points 2 till 8 days after prestressing (fig. 6). Per duct it could be taken off from 1/4 to 1 litre of liquid.



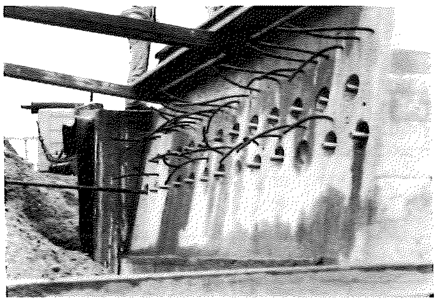


Fig. 6
Position of fractures and corrosion attack along the bars

The fractures started from the deepest corrosion pittings. Quantitative analyses of water appeared high contents of sulphates and potassium and the presence of chloride and thiocynate (till 0,5 g/l). The pH-values were between 10 and 13. Table 3 shows the analyses of waters in 5 ducts, those of used construction materials and the soluble components of hardened concrete. Thiocyanate was only stated in the concrete liquefier. It is enriched in the bleeding water. In watery phase of hardened concrete only traces were detectable. Compared to the water of fresh concrete the watery extracts of consolidated concrete coantain much lower portions of sulphates chlorides and thiocyanates.

Some stress corrosion tests were done for clearing up the damage and the effect of neutral salts (SO_4^{2-}, Cl^-) and promo-

Table 3: Composition of duct-water, components and concrete

WATER IN THE DUCTS

1900 - 5200 (MW 3920) mg sulphate/l
133 - 177 (MW 164) mg chloride/l
126 - 499 (MW 323) mg thiocyanate/l
62 - 90 (MW 78) mg calcium/l
180 - 370 (MW 290) mg sodium/l
3600 - 7300 (MW 5390) mg potassium/l
pH-value: ~ 10 - 13

COMPONENTS AND CONCRETE

aggregates-soluble	< 0,02 %	0,0002 %	not detectable
cement -soluble	< 0,1 %	2,06 %	not detectable
liquefier	0,03 %	0,07 %	4,0 %
retarder	0,01 %	0,03 %	not detectable
water	39 mg/l	93 mg/l	not detectable
concrete -soluble	0,02 %	0,01 %	0,006 %
	chloride	sulphate	thiocyanate

tor (SCN^-). Specimens of a sensitive prestressing steel wire under tension were testet up to 30 weeks embeded in moistened sand. The sand embedment was impregnated with different solutions; their compositions corresponded to that of the bleeding water in ducts in cases of failures. These tests using impregnated sand considered the fact that steel in ungrouted ducts have contact with mineral constituents. The specimens were taken out after a certain storage time and investigated upon cracks and fractures. Fig. 7 shows the results summrized: By adding the solution 4 and 5 containing thiocynates, the formation of cracks is much more initiated than by adding solution 1 to 3 with only salts, which favour pittings. A solution with salts and promotor (solution 5) showed the highest aggressivity.

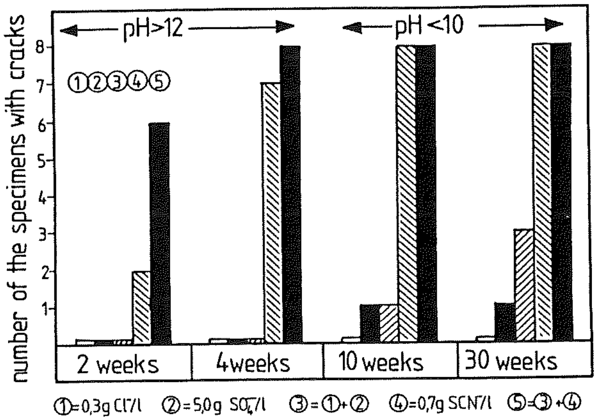


Fig. 7
Cracking behaviour of stressed prestressing wires in sand + solution (saturation 80 %)

3.3 Failure after 28 years because of pre-demaging

In a laboratory a ceiling collapse has been took place due to fractures of the two tension members following 28 years of erection (fig. 8), where alle wires of the bundles were broken in one section. There were older fractures resulting from an early phase and new ones (fig. 1). The older surfaces of fractures showed deposits wiht rust and/or mortar. The ducts were grouted very well and fractures have been occured within an alkaline and chlorid free, but wet injektion (fig. 9). Corrosion has been took place in the lower past of the ducts and calcareous separations along a former water line within the duct was of significance (fig. 10). From the analysis (high sulphate and potassium contents) is could be concluded, that bleeding water has been within the ducts. The wires showed a miner corrosion attack and besides fractures numerous cracks (fig. 11).

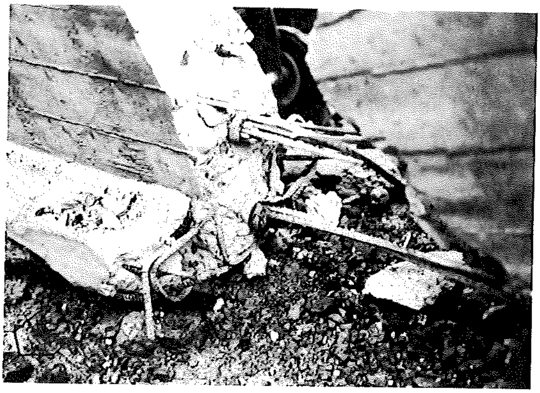


Fig. 8
Broken tension members of the beam

In SCC-tests in thiocyanate solution it was found out, that in saturated $Ca(OH)_2$-solution with small amounts of sulphates and chlorides wires with cracks but not an uncracked steel may fractures. That means precracks resulting from bleeding water in the ungrouted duct later can grow in the ungrouted state if the prestressing steel is sufficiently sensitive.

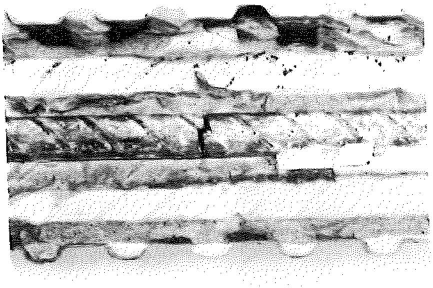


Fig. 9
Steel fracture in a well grou-
ted duct

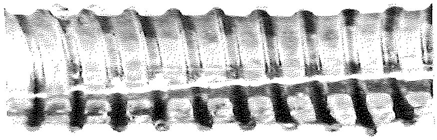


Fig. 10
Calcareous salts along
the former water line
within the duct

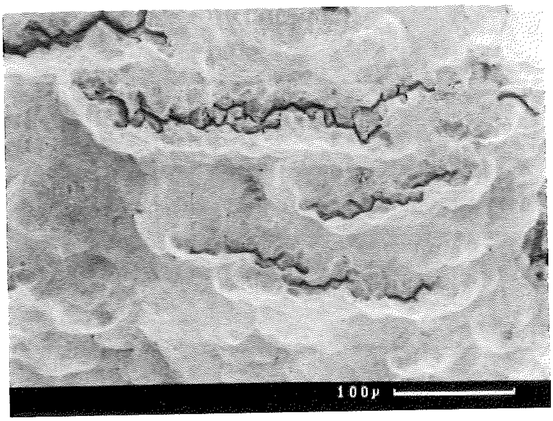


Fig. 11
Microcracks on the
corroded surface of
wires

4 CONCLUSIONS

Under the effect of water in ungrouted ducts, which resulting from bleeding of fresh concrete, strong corrosion and stress corrosion of the prestressing steel may be occured. Therefore the watery phase of concrete has to be evacuated. Flushing and drying of ducts ist recommended. Further, sufficiently heavy ducts-systems should be used and bleeding of concrete should be controlled to improve the corrosion behaviour in ungrouted ducts.

REFERENCES

[1] U. Nürnberger: Analyse und Auswertung von Schadensfällen an Spannstählen. Heft 308 Forschung, Straßenbau und Verkehrstechnik, 1980, 1/195

[2] Autorenkollektiv: Spannungsrißkorrosion in Spannbetonbauwerken, Verlag Stahleisen mbH, Düsseldorf 1983

[3] U. Nürnberger: Wasserstoffinduzierte Spannungsrißkorrosion bei Spannstählen. Maschinenmarkt 95 (1989), 30/34, 68/72, 128/134

[4] G. Rehm, U. Nürnberger, R. Frey: Zur Korrosion und Spannungsrißkorrosion von Spannstählen bei Bauwerken mit nachträglichem Verbund. Bauingenieur 56 (1981), 275/281

[5] G. Rehm, U. Nürnberger: Neue Methoden zur Beurteilung des Spannungsrißkorrosionsverhaltens von Spannstählen. Betonwerk + Fertigteiltechnik (1982), 287/294