CORROSION OF STAINLESS STEEL REINFORCEMENT IN CRACKED CONCRETE

KORROSION VON NICHTROSTENDEM BETONSTAHL IN GERISSENEM BETON

LA CORROSION DE L´ACIER D’ARMATURE INOXIDABLE DANS LE BETON FISSURE

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SUMMARY

The corrosion risk of stainless steel is more pronounced in chloride containing carbonated concrete than in salt enriched alkaline concrete. Therefore doubts had been existed that stainless steel is sufficiently sure in cracked concrete of parking decks and walls by the road side contaminated with de-icing salts. Cracks can carbonate quickly and are open for chloride penetration. Electrochemical corrosion potential measurements and corrosion tests on cracked beams, reinforced with welded stainless steel bars, could not confirm this assumption. Stainless steel reinforcement, licensed in Germany, is also suit for the very unfavourable case of highly chloride contaminated cracked concrete.

ZUSAMMENFASSUNG

Das Korrosionsrisiko von nichtrostendem Stahl ist in chloridhaltigem karbonatisiertem Beton ausgeprägter als in salzangereichertem alkalischem Beton. Deshalb bestanden Zweifel darüber, daß der nichtrostende Stahl im gerissenen Beton von Parkdecks und Stützmauern entlang von Straßen ausreichend sicher ist, wenn der Beton tausalzhaltig ist. Risse können verhältnismäßig rasch karbonatisieren und Chloride können leicht eindringen. Elektrochemische Messungen des Korrosionspotentials und Korrosionsuntersuchungen an gerissenen Stahlbetonbalken, die mit nichtrostenden Stählen bewehrt waren, konnten die genannte Vermutung jedoch nicht bestätigen.

Die in Deutschland zugelassenen nichtrostenden Betonstähle sind auch für den sehr ungünstigen Korrosionsfall des mit Chloriden verseuchten gerissenen Betons geeignet.

RESUME

Le risque de corrosion de l’acier inoxidable dans le béton carbonatisé qui contiens des chlorides est plus grave que dans le béton alcalin enrichi du sel. Pour cette raison on avait des doutes, si l’acier inoxidable dans le béton fissuré des garages en élévationet des murs de soutènement á coté des routes serait assez sûre, lorsque le béton contiens du sel antigel. Les fissures peuvent carbonatiser relativement vite et les chlorides peuvent pénétrer facilement. Des recherches électro-chimiques sur le potentiel de corrosion et sur la corrosion dans des poutres en béton armé avec de l’acier inoxidable ne pouvaient pas verifier cette hypothese. Les aciers d’armature inoxidables qui sont acceptés en Allemagne sont utiles aussi pour le cas très défavorable d’un béton fissuré et contaminé de chlorides.

KEYWORDS: corrosion, concrete crack, reinforcement, stainless steel, chloride, carbonation

1. INTRODUCTION

In reinforced concrete structures the concrete guarantees chemical and physical corrosion protection of the unalloyed reinforcement. Thus, the alkaline electrolyte of the pores passivates the steel and the concrete - as a more or less dense (fine porous) material - keeps corrosion-promoting substances away from the reinforcement. That is, if a sufficient depth of concrete cover is provided. In general, steel in concrete is adequately protected against corrosion.

However, despite these protective mechanisms, corrosion of reinforcement can occur. This can result either from the carbonation of the concrete or from the effect of chloride ions if oxygen and moisture are also available. Chloride ions may penetrate into hardened concrete of structures exposed to marine environments or to de-icing salts.

If corrosion problems persist additional corrosion protection methods such as galvanising, epoxy coatings, inhibitors or cathodic protection must be used. Nevertheless, there are limits to the application of these [Nürnberger, 1995] and more comprehensive solutions need to be developed.

Alternatively a corrosion resistant stainless steel reinforcement can be used. Nevertheless, it is not envisaged that stainless steel will replace any really significant part of the massive tonnage of the present carbon steel reinforcement output. The use of higher quality steel, such as austenitic stainless steels, will increase the reliability of multi-storey car park decks and outer stairs which are likely to be contaminated with de-icing salts, concrete elements in thermal baths, piers at the sea-coat and plants for the desalination of sea water. Stainless steel is also suitable for the reinforcement in lightweight pre-cast elements.

Test results [Nürnberger et al., 1995; Nürnberger et al., 1993; Nürnberger, 1996(1); Nürnberger, 1996(2)] concerning the corrosion behaviour of stainless steel in concrete have shown that the corrosion risk is more pronounced in chloride containing carbonated concrete than in salt enriched alkaline concrete. Therefore engineers in Germany had doubts about the fact that stainless steel is sufficiently sure in cracked concrete contaminated with chlorides. Concrete cracks carbonate very quickly and they also favour chloride penetration [Nürnberger, 1995]. As a consequence the reinforcement may be embedded in a depassivated chloride containing environment.

There exist concrete constructions such as parking decks and walls by the road side, where cracking of the concrete and chloride contamination may occur. Therefore the investigations on stainless steel reinforcement in uncracked concrete [Nürnberger et al., 1995] had been continued to characterise the corrosion behaviour in cracks of the concrete.

2. CORROSION RESISTANCE OF STAINLESS STEEL REINFORCEMENT

In the elder research programme [Nürnberger et al., 1995; Nürnberger et al, 1993] the corrosion behaviour of traditional stainless steel types in the unwelded and a welded state was clarified.

The research programmes comprised

- electrochemical tests
- and fielding testing

In the former laboratory tests for several steel types with graded alloying elements the pitting potential with respect to

- the chloride content,
- the state of concrete (alkaline or carbonated),
- the workmanship (unwelded and welded)

was determined. The exposure tests on reinforced concrete beams concentrated on the behaviour of the material

- 1.4003 a ferritic steel X 2 Cr Ni 2,
- 1.4571 a austenitic steel X 6 Cr Ni Mo Ti 17-12-2
- 1.4462 a ferritic-austenitic steel X Cr Ni Mo N 22-5-3.

The pitting potential characterises the risk of localised corrosion in the form of pitting. Experimentally the value of the pitting potential can be determined by polarising a mortar electrode in the positive direction by application of an external current until pitting occurs. The more positive the pitting potential the lower the corrosion risk. The pitting potential may vary depending on

- the corrosive environment,
- the type and level of alloying additions of the steel,
- and surface parameters such as roughness, oxyde layers, crevices and welds.

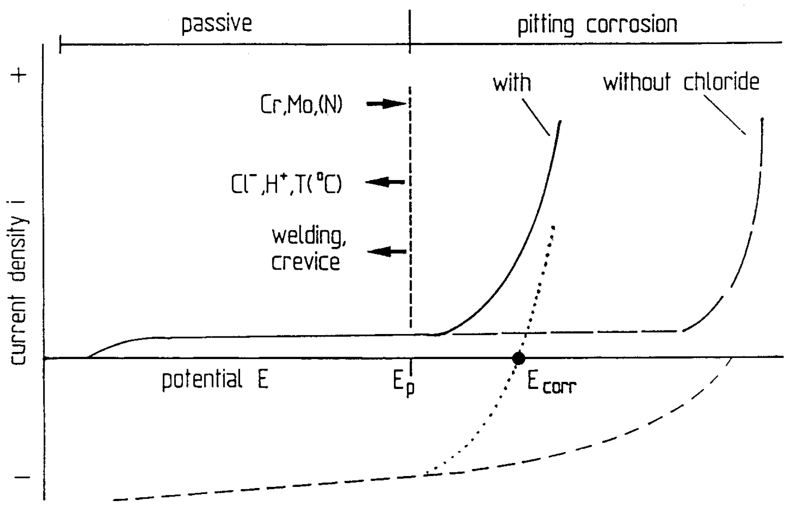

Fig. 1. *Parameters of current density versus potential curve of stainless steel in neutral to alkaline mediums*

Fig. 1 schematically shows the relationships. The pitting potential becomes more negative with increasing chloride concentration and temperature and falling pH-value. The figure explains an anodic curve of steel in an electrolyte without and with chlorides. Alloying elements such as chromium and molybdenum increase the pitting potential, respectively the corrosion resistance. Welded steels show a worse behaviour than unwelded steels.

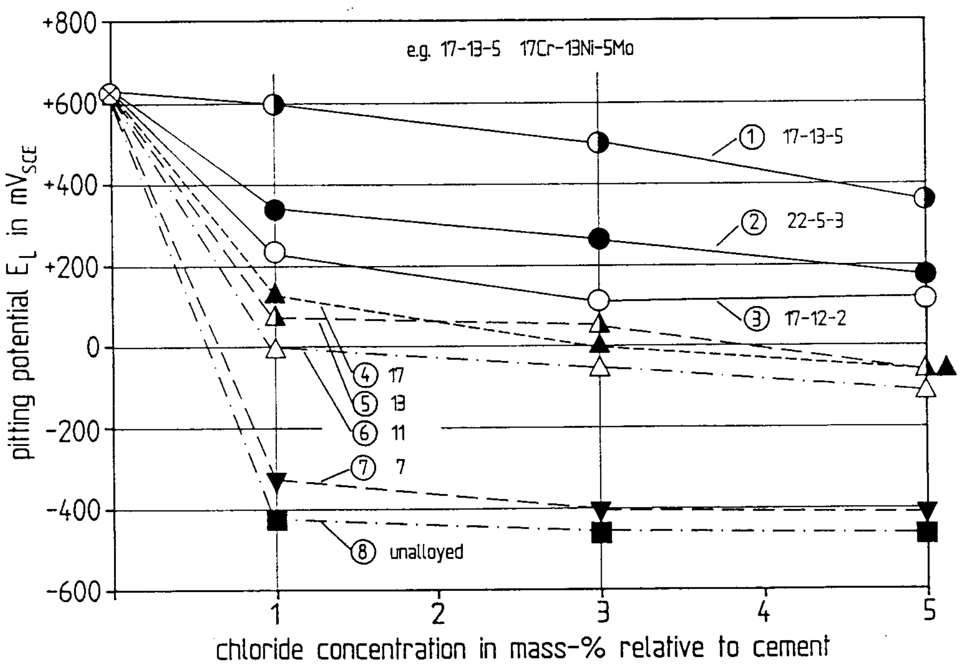

Fig. 2. *Pitting potential of plain welded steel specimens in PC-mortar (potentiostatic test)*

Fig. 2 demonstrates results of potentiostatic electrochemical tests with mortar electrodes and steel specimens with plain surface. It shows the pitting potential of stainless steels and one unalloyed steel in the welded state in alkaline concrete with respect to chloride content. The numbers beside the pitting potential versus chloride concentration curves refer to the content of chromium, nickel and molybdenum. Based on these and further test results the following important conclusions can be drawn:

- The pitting potential decreases with decreasing content of alloying elements.
- Three main groups can be identified
  - the austenitic and ferritic-austenitic steels 1 to 3 with the highest resistance,
  - the ferritic types: material 4 to 6 with chromium contents higher than 10 % in a middle range,
  - the ferritic types: material 7 and 8 with chromium lower than 10 % and a low resistance comparable to unalloyed steels.
- As expected the pitting corrosion potential decreased with increasing chloride content of the concrete.

In carbonated concrete with chlorides, this conditions may be typical for lightweight concrete or cracked concrete contaminated with de-icing salts, the pitting potential was always shifted to the negative values compared to alkaline concrete with chlorides (Fig. 3).

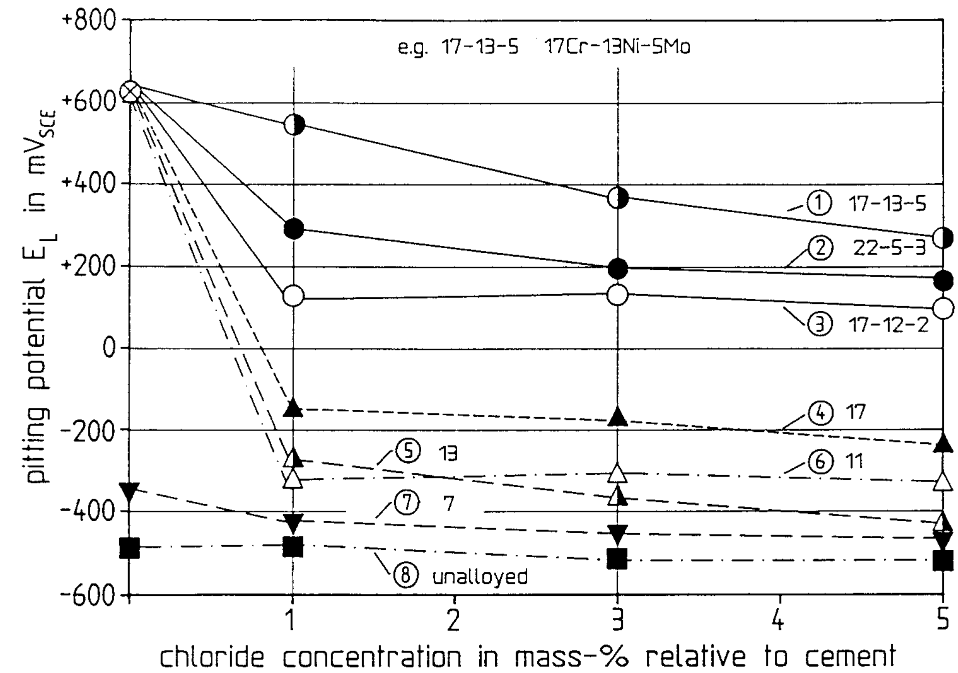

Fig. 3. *Pitting potential of plain welded steel specimens in carbonated PC-mortar (potentiostatic test)*

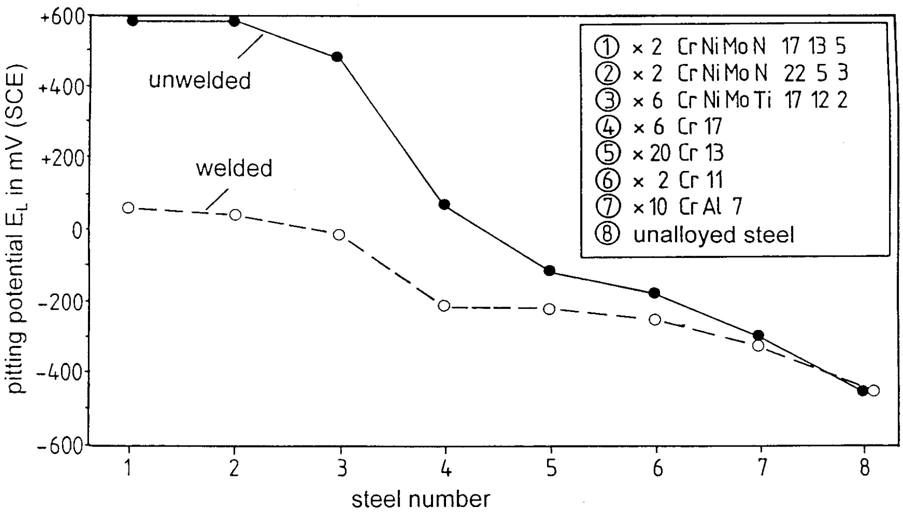

Fig. 4. *Pitting potential of steel specimens with plain surface in saturated $Ca(OH)_2$-solution with 5 M.-% chloride (potentiokinetic tests)*

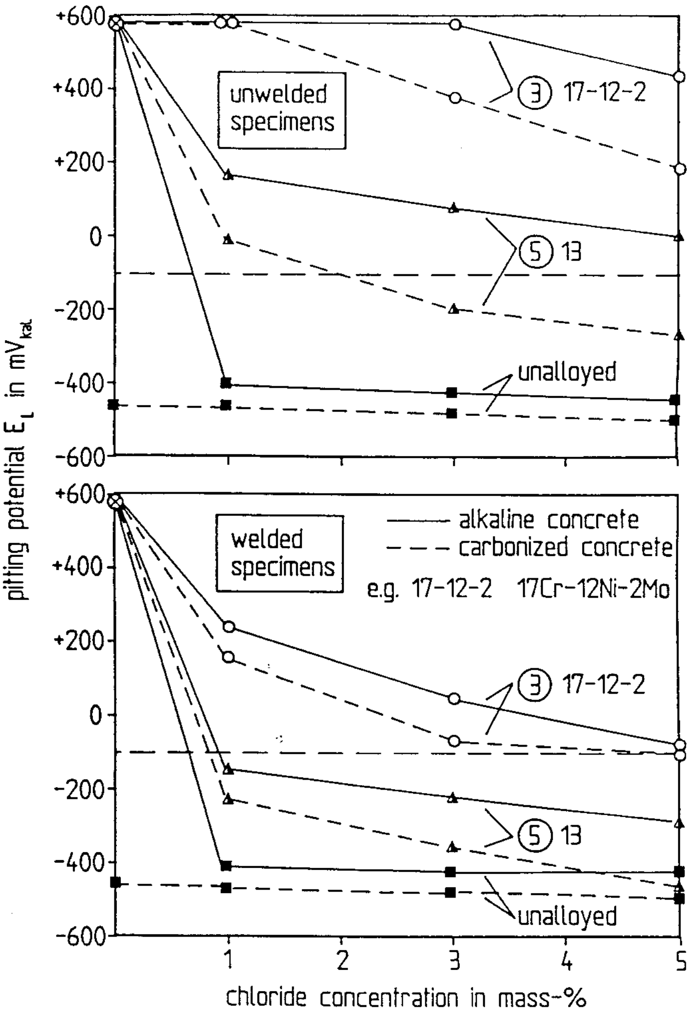

Fig. 5: *Pitting potential of deformed steel specimens in mortar (potentiostatic test)*

Fig. 4 gives you a short impression of the very different behaviour of unwelded and welded steels. The pitting potential of the welded specimens becomes more negative, but the difference between unwelded and welded steels decreases with decreasing chromium and molybdenum. In the case of welds scale and temper colours reduce passivity and can aggravate pitting if nor removed.

Fig. 5 shows the results of ribbed

- austenitic steel 1.4571 with 17 % chromium, 12 % nickel and 2 % molybdenum,
- a ferritic steel 1.4003 with 13 % chromium
- and the unalloyed steel.

The steel specimens were unwelded (above) or welded (below) and tested in alkaline concrete (continuous curves) and carbonated concrete (interrupted curves). In addition to those results from welded pieces with plain surface the following conclusions can be drawn:

- Ribbed reinforcing bars show a more unfavourable behaviour than plain bars.
- Unwelded ribbed stainless steel bars (above) in concrete with chlorides show a more positive pitting potential than welded bars (below).
- For unalloyed material no difference between welded and unwelded bars was observed.

The 2.5 year field exposure on reinforced concrete beams took into account

- the steel grade,
- the concrete quality (normal-weight and light-weight concrete) and the concrete cover,
- the state of concrete (alkaline and carbonated),
- the chloride content,
- the test pieces were welded and unwelded.

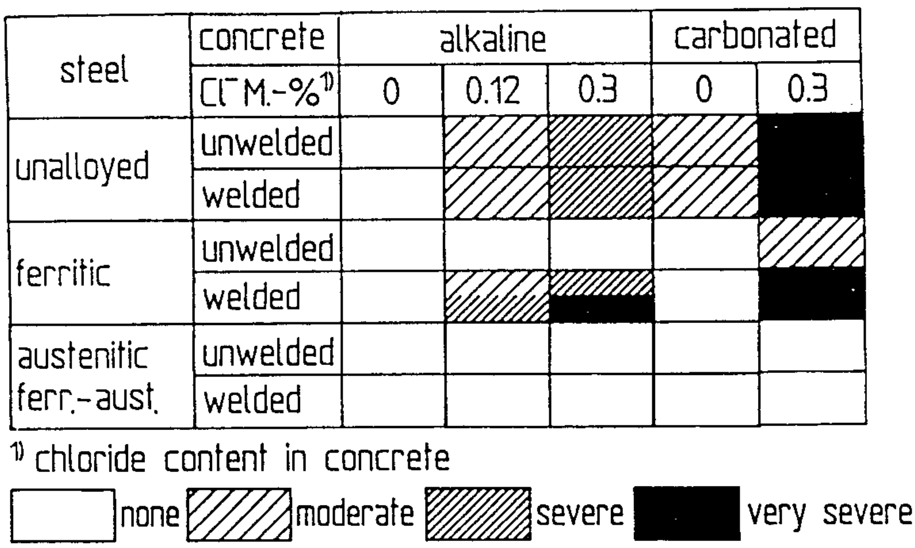

Fig. 6. *Corrosion behaviour of steel in concrete*
ferritic 1.4003   austenitic 1.4571   ferr.-aust. 1.4462

Fig. 6 shows a very simple but clear representation of the test results by means of corrosion degrees basing on pitting depth and loss of weight. Areas without and with welds are separated. As expected, unalloyed steel corrodes in carbonated and/or chloride concrete. The strongest attack occurred in carbonated plus chloride-contaminated concrete. No corrosion appeared with the austenitic and ferritic-austenitic steel in the unwelded or welded states.

The unwelded ferritic chromium steel showed a distinctly better behaviour than unalloyed steel. Only in chloride-contaminated carbonated concrete a reduced pitting corrosion occurs. For the welded steel within the weld line chlorides produced locally distinct pitting corrosion. The depth of pitting increased with increasing chloride content and was more pronounced in chloride-containing carbonated concrete. In carbonated chloride-free concrete no corrosion occurred.

As a consequence of the performed investigations austenitic steel 1.4571 and ferritic-austenitic steel 1.4462 proved to give excellent performance under conditions, where chlorides can enter concrete constructions. A ferritic grade 1.4003 will suffice in less aggressive environments. It will hinder spalling of concrete cover and corrosion in carbonated concrete.

3. INVESTIGATIONS IN CRACKED CONCRETE

In the new research programme it should be tested, whether the problem of strong chloride corrosion of the (unalloyed) reinforcement in cracked concrete constructions can be solved by use of stainless steel. If such a reinforcement in welded condition is sufficiently safe, such a preventive measure should be recommended, even if the concrete may be cracked over the whole section and contaminated with de-icing salt. Therefore cracked concrete beams reinforced with welded unalloyed and stainless bars had been stored under conditions of parking decks and walls by the road side exposed to chloride containing water.

Reinforced concrete beams had been manufactured and the following parameters had been varied:

- steel quality — unalloyed, ferritic-austenitic, austenitic } welded, unwelded

Concerning the welded bar a weld seam was crossing the cracked area.

- concrete — normal weight concrete (B 35)
- crack width — 0.05 - 1.0 mm
- concrete crack — uncarbonated, artificial carbonated
- concrete cover — 2.5 and 5.0 cm
- storage conditions of the reinforced beams
  - outdoor conditions (Fig. 7)
  - indoor conditions

The reinforced construction elements were sprayed with chloride solutions and dried out analogous to the conditions of a wall by the road side and of parking houses.

Fig. 7. *Storage of cracked concrete specimens under outdoor conditions*

During storage of 2.5 years the corrosion potential of the steel was measured continuously, to detect the start of corrosion inside concrete cracks. Some beams were opened to reveal the state of the bars.

The following Fig. 8 - 10 show exemplary the test results of potential measurement for the indoor storage of three welded steels:

- unalloyed steel,
- ferritic-austenitic steel X 2 Cr Ni Mo N 22-5-3 (1.4462),
- austenitic steel X 6 Cr Ni Mo Ti 17-12-2 (1.4571)

The concrete cracks were carbonated artificially.

In the case of unalloyed steel there exists an essential drop of corrosion potential, when the chloride reached the reinforcement in the concrete crack and the steel became active after 1 to 3 months. There is no clear influence of welding and concrete cover. These results point to a strong corrosion of the whole unalloyed reinforcement.

Concerning the corrosion resistant reinforcement the steel remained passive over the whole testing time. This indicates a corrosion resistance under these very aggressive environment.

After breaking up some beams after 2.5 years strong corrosion was found in the carbonated and not carbonated concrete cracks if the crack width exceeded 0.1 mm in the case of unalloyed steel. The corrosion type was more or less uniform and wide pitting in the carbonated chloride containing concrete. In the alkaline chloride containing concrete crack the corrosion type was strong wide pitting. The corrosion degree depended of the parameters of the concrete (concrete cover) and the crack (crack width), but the influence of these parameters was not clearly. No serious corrosion was to detect on the high alloyed steels up to a crack width of 1 mm. The alloyed steel only showed some very small and shallow corrosion pits along the border of the welding material. That was independent of other parameters of the concrete and the cracks.

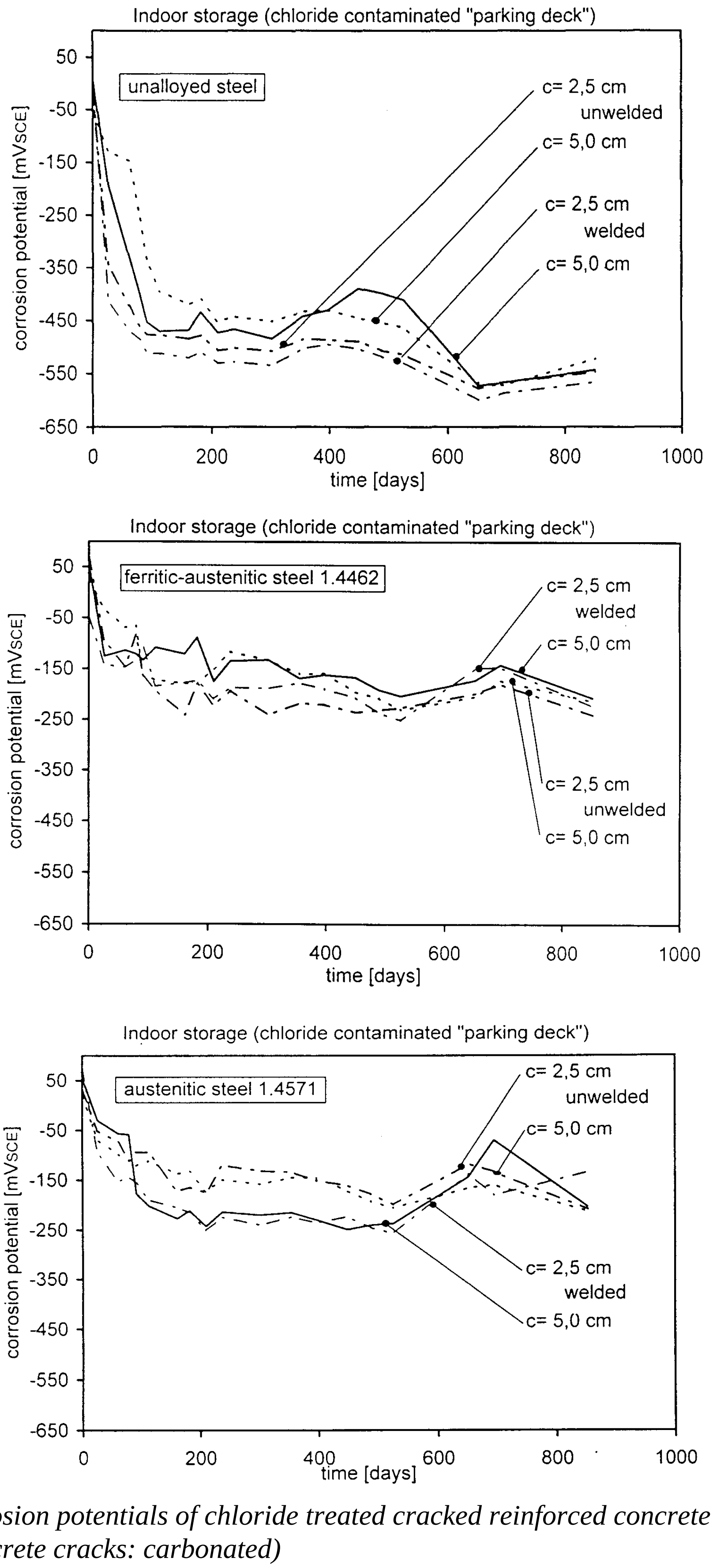

Fig.8-10. C*orrosion potentials of chloride treated cracked reinforced concrete beams (concrete cracks: carbonated)*

The chloride profiles of the uncracked concrete and along the concrete cracks confirmed (Fig. 11) that extreme contents of chlorides had reached the steels with a concrete cover of 2.5 and 5.0 cm.

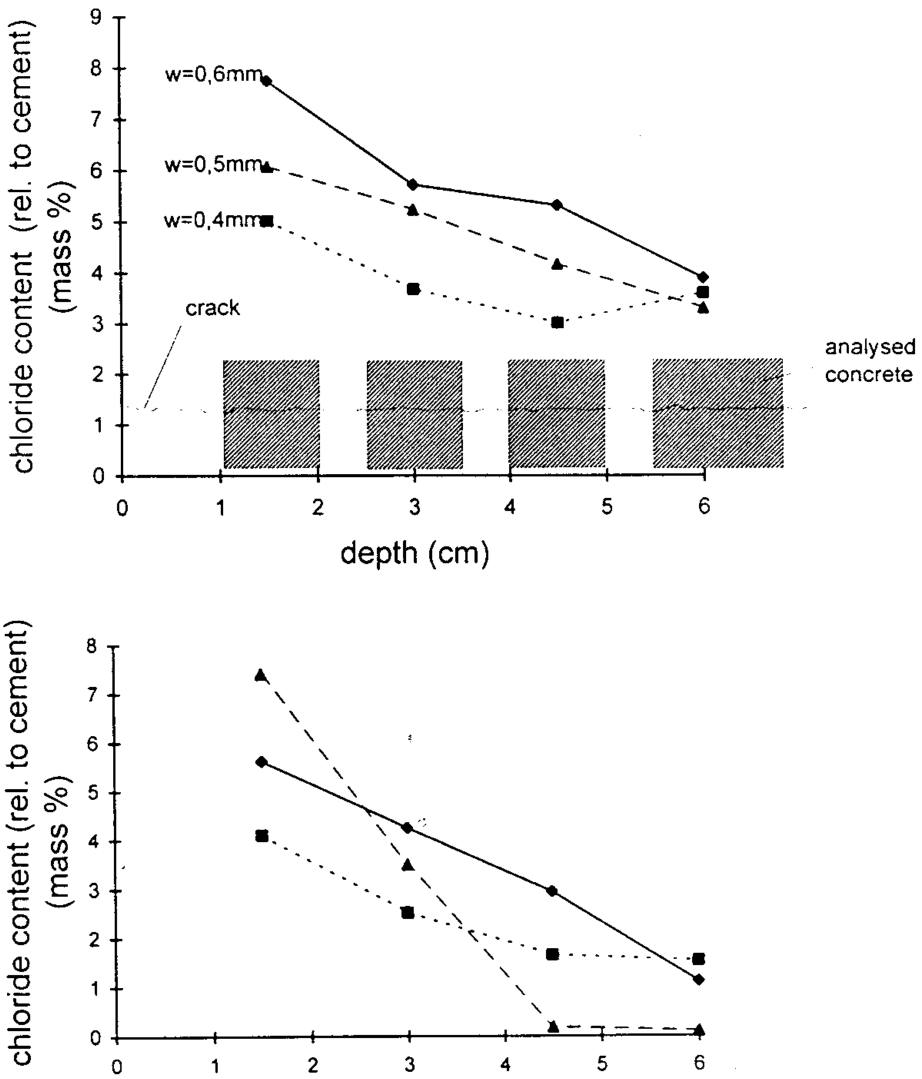

Fig. 11. *Chloride profile in cracked (above) and uncracked (below) concrete*

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