

# Durability Aspects of Chloride-Affected Cracked Concrete Structures Reinforced with 1.4003 Rebars

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**Abstract.** The protection of reinforced concrete components exposed to chlorides is often ensured by coating systems, which are usually associated with high maintenance costs over the service life. A possible alternative is the use of high-alloy, stainless steel reinforcement. Through smart selection in areas subject to particularly high stresses and the possibility of using mixed reinforcement with black steel, this type of reinforcement can also be used for economical construction. In many areas, it is sufficient to use significantly cheaper chromium steel rebars instead of very expensive, highly corrosion-resistant austenitic chromium-nickel steels. An industrial research project was carried out at Munich University of Applied Sciences in which the resistance of a chromium steel reinforcement with material number 1.4003 in chloride-exposed separation cracks of RC-specimens was investigated. The results obtained formed the basis for the development of design variants for underground parking garages. Structural tests on a large number of existing structures show how a long service life can be achieved with such reinforcement even under high chloride loads.

## 1 Introduction<sup>2</sup>

There are many strategies to ensure the durability of RC-components exposed to chloride. In most cases, a coating requiring high maintenance over the service life is applied on the exposed concrete surface in order to exclude chloride penetration into the concrete. If the coating systems are not properly maintained and cracking remains undetected, even one winter period with chloride ingress within the crack [2] can be sufficient to initiate rebar corrosion. The limit value of 0.5 wt.-% Cl/c, from which according to [3] an expert planner should evaluate the corrosion risk and which is considered to be the lower limit value for corrosion to occur, relates mainly to uncracked concrete and unalloyed reinforcing steel.

One way of eliminating the risk of corrosion as far as possible is to use corrosion resistant reinforcement (commonly: stainless steel or GFRP reinforcement). While GFRP reinforcement is more cost-intensive than unalloyed reinforcing steel and bending is no longer possible on the construction site, the use of the common high-alloy, austenitic stainless steels 1.4571 and 1.4401 (formerly V4A) is even more expensive (about a factor of 10 compared to unalloyed reinforcing steel) and only economical in a few cases.

Another design strategy is the use of the significantly less expensive, high-alloy, ferritic chromium steel 1.4003. The corrosion resistance of such a reinforcing steel available on the market in chloride-containing crack areas in reinforced concrete components is currently the subject of research at the Institute for Materials and Construction Research at the Munich University of Applied Sciences.

## 2 Unalloyed and alloyed reinforcing steels

Steels with material numbers 1.0438 (B500A, normal ductile) or 1.0439 (B500B, high ductile) are commonly used as unalloyed reinforcing steels [4].

The term stainless steel refers to a steel of special purity, with respect to the undesirable iron companions such as phosphorus and sulphur. The term stainless steel does not yet imply corrosion-resistant steel. In order for steels to become corrosion-resistant under normal environmental conditions, a high chromium content (10.5% and more [5], but in practice usually only from 12%) is required. Such steels with a high chromium content form a protective passive layer of chromium oxides on the steel surface. Depending on the type and content of alloying

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<sup>2</sup> preliminary tests and interim results for this research project have already been presented in [1]

elements, as well as the production process, stainless steels can have different microstructures (ferrite, austenite, martensite, a mixture of austenite and ferrite (duplex steel) or a mixture of ferrite and martensite (dual-phase steel)), which are based on a different spatial lattice arrangement of the atoms [6]. This also influences, among other things, the tendency to corrosion, hardness and strength.

Austenite-forming alloying elements include nickel, carbon, nitrogen and manganese. Chromium and molybdenum are two representatives of the ferrite-stabilizing alloying elements.

The stainless steel investigated in these tests is assigned to material number 1.4003, material abbreviation X2CrNi12 according to [7]. Material number 1.4003 describes a corrosion-resistant, high-alloy, ferritic chromium steel with 10.5 to 12.5% chromium content and nickel addition. The carbon content is 0.02%. The designation X stands for the average alloy content of an element of at least 5% [7]. Compared to the more common stainless steel reinforcements made of chromium-nickel steels, such as 1.4401 (X5CrNiMo17-12-2, formerly V4A), molybdenum is not used as an alloying element in 1.4003. The chromium content is reduced. Nickel is added only up to 1%, which means that the steel can be produced at significantly lower cost than the common austenites.

In the specific case of the stainless steel investigated here ("Top12"©), it is a ferritic steel with a chromium content of at least 12%. The manufacturer's compositional data are given in **Table 1**. An X-ray fluorescence analysis of the tested rebars at the Munich University of Applied Sciences confirmed this with a chromium content of approx. 12.5%.

**Table 1: Composition Top12-500 according to [8]**

|   | C     | Si  | Mn  | P             | S             | Cr           | Ni  | N    |
|---|-------|-----|-----|---------------|---------------|--------------|-----|------|
|   | %     |     |     |               |               |              |     |      |
| Ø | 0.015 | 0.7 | 0.5 | max.<br>0.025 | max.<br>0.005 | min.<br>12.0 | 0.5 | 0.02 |

A material mix in the reinforced concrete component consisting of stainless steel reinforcement and unalloyed reinforcing steel (mixed reinforcement) does not lead to any incompatibility due to contact corrosion. As long as the unalloyed reinforcing steel is sufficiently passivated by the alkalinity of the concrete, the free corrosion potentials of stainless steel and unalloyed steel are almost identical, so that no anodic and cathodic zones can form [9].

In high-alloyed, highly corrosion-resistant steel materials, the inertness is based on the formation of a very stable passive layer of chromium oxides, which is stable under a wide range of pH values and actions. Compared with unalloyed reinforcing steel, corrosion initiation takes place only under significantly severe boundary conditions, which - as with conventional reinforcing steel

in alkaline environments - are associated with dissolution of the passive layer. However, as soon as the passive layer of the high-alloyed steel is damaged, more localized depassivation usually occurs than with normal reinforcing steel. The corrosion rate of high-alloy stainless steels is smaller than that of unalloyed steel, but the depth of removal is roughly comparable [10]. In addition, with smaller pitting scars, there is poorer aeration of the electrolyte in the scar, which causes additional acidification that further increases the loss of material.

### 3 Previous studies on 1.4003

There are numerous studies in the literature on the corrosion behaviour of reinforcing steels with the material number 1.4003 in chloride-containing concrete. However, some of the 1.4003 reinforcing steel specimens examined in these studies were still supplied in the usual rolled skin form. Since this leads to poorer chloride resistance, new investigations were carried out at various institutes on the currently common delivery form without rolled skin (pickled). In earlier investigations, [6], [10], [11], [12], a critical corrosion-inducing chloride content above 2.6 wt.-%/c. with very different test methods had been determined. In [13], summarized in [14], a critical corrosion-inducing chloride content of 2.7 wt.-%/c. at 10% corrosion probability was determined at the Federal Institute for Materials Research and Testing.

Various test programs were summarized in [15]. The comparison of the different test methods showed a critical corrosion-inducing chloride content of the 1.4003 reinforcement of 2.3 wt.-%/c. in non-cracked concrete.

### 4 Test series on corrosion behaviour in chloride-loaded cracks

#### 4.1 specific question

As shown, there are numerous investigations on 1.4003 in non-cracked concrete, but only few tests on the corrosion behaviour of this steel in chloride-loaded cracks. This corrosion behaviour is of high practical relevance, since the initiation phase of e.g. uncracked and uncoated underground parking garage floor slabs with conventional reinforcement can be extended to more than 50 years by the specific selection of certain cements or concretes. However, the occurrence of a crack into which chlorides can penetrate leads to a high probability of corrosion of the reinforcement in the crack area.

The method of applying a crack-bridging coating to the floor slab, which is frequently used today, is very maintenance-intensive. Also, high water pressures from the outside can cause blisters and detachment.

In this respect, the use of a reinforcing steel 1.4003 with proven adequate corrosion resistance in chloride-exposed cracks would enable an economical and robust

construction method for underground parking garage floor slabs, for example.

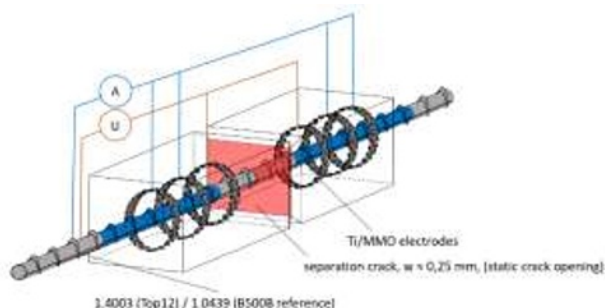
The aim of the presented research project was to determine the resistance of 1.4003 reinforcing steel in chloride-exposed, non-carbonated separation crack area. All samples of the 1.4003 were tested pickled (without rolling skin), which corresponds to the current delivery form of the "Top12" to the construction site.

From preliminary investigations at the Munich University of Applied Sciences, a procedure for the investigation had already been developed [1].

## 4.2 Experimental Setup

Reinforced concrete beams with separating crack were produced for the tests. Reinforced concrete specimens with 1.4003 as well as with unalloyed reinforcing steel 1.0439 (B500B), which serves as a reference, are examined. The different specimens are regularly exposed to chloride solutions of different concentrations in order to determine a chloride content in the crack flank leading to a first stable corrosion initiation, which is measured with an adequate electrochemical test set-up.

For each reinforced concrete beam, one reinforcing bar was centrally embedded in concrete. The beams were weakened with a predetermined breaking point via inserted triangular strips, through which the crack was later generated, see **Fig. 1**.



**Fig. 1.** Sketch of the investigated samples

Except for the area nearby the separation crack, the rebar was coated with a PU seal in order to exclude any falsification of the measurement results due to carbonation of the edge zone and to obtain a defined anode surface.

Rings made of a titanium mixed oxide strip were used as reference and counter electrodes. The distance to the reinforcement was ensured by plastic spacers, see **Fig. 2**.



**Fig. 2.** 1.4003 with Ti/MMO electrodes

The joints of the measuring cables were also provided with a PU seal to prevent contact corrosion.

For the concrete design, a CEM I 42.5 N cement with a w/c ratio = 0.45 and an A/B 8 grading curve was used.

After curing of the concrete, a separation crack was created in the testing machine via double bending in a three-point bending test and held open using stainless steel plates. ( $w = 0.25$  mm), cf. **Fig. 3**.

After a sufficient hardening period of 28 days, a tap water loading and zero measurement was started first, followed by applying chloride-containing water.



**Fig. 3.** Sample with separation crack

## 4.3 Execution of the investigation

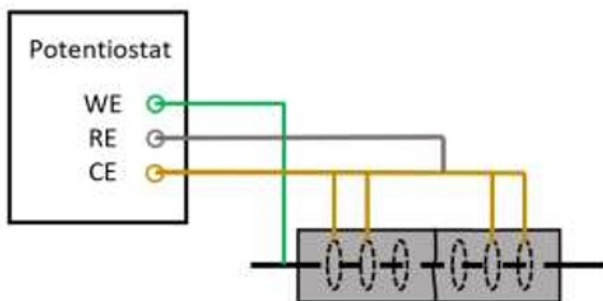
The external application of chloride-containing water was carried out using a NaCl solution in various concentrations. This solution was introduced into the crack area, which was laterally dammed and only open on one side. Chlorides from the solution can partially diffuse into the concrete, but to a large extent a "piggyback transport" of the chlorides is possible through capillary suction processes into the specimen, which is repeatedly stored dry in the meantime.

In regular cycles, the beams in the crack area were exposed to a chloride-containing solution, the concentration of which was determined on the basis of the preliminary tests from [1]. This was followed by a drying phase lasting several days. The free corrosion potentials, corrosion currents as element currents, polarization

resistances and electrolyte resistances of the samples were recorded weekly.

Part of the actual corrosion current cannot be correctly detected by the corrosion current measurement because the anode and cathode cannot be completely separated spatially. Currents consumed for the cathode reaction on the anode are therefore not separately identifiable [16]. In the following, the term element current is used as the current between the supposed anode and the cathode. Approximately, this is equated with the corrosion current. After each element current measurement, the absolute AC resistance (impedance) at 1 kHz measurement frequency was determined. This value is used for comparison with the element currents. This allows conclusions to be drawn as to whether an increase in current is merely due to reduced electrolyte resistance or to a change in the anodic corrosion activity.

For the correct recording of the very small element current, a potentiostat was used, which was connected as a Zero-Resistance-Amperemeter (ZRA). A two-electrode arrangement is used for this measurement setup, with no separate reference electrode for potential measurement. The counter electrode is used simultaneously as a reference, see Fig. 4. At the beginning of the measurement, the rest potential of the working electrode (1.4003 or B500B) against the counter electrode (titanium mixed oxide strip) is determined. The potential difference between the working and counter electrodes is then regulated to zero and maintained. The current required for this is recorded over time. The longer the measurement takes, the more the course of the "short-circuit current" converges with the element current that would actually flow in the event of a permanent short-circuit of the working and counter electrodes.

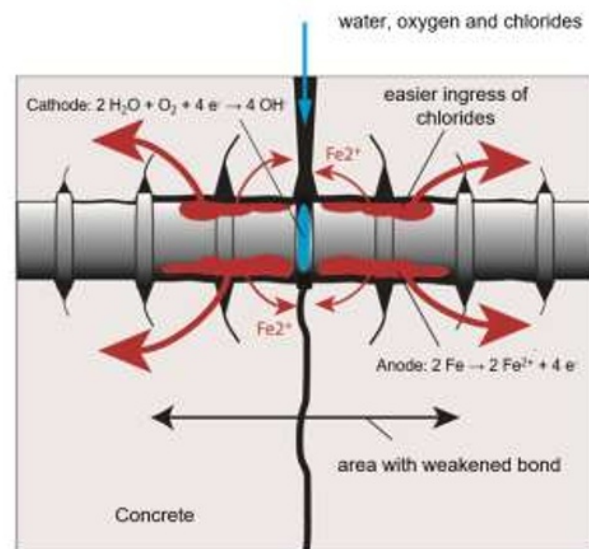


**Fig. 4.** Measurement setup (ZRA)

A problem in the experimental evaluation of the element currents arises in the determination of the anode area in the crack region, which would be required for the determination of the element current density and thus for the quantitative determination of the cross-section loss.

In this case, the element current does not correspond exactly to the corrosion current, since the working electrode (considered as the anode for the measurement) also forms cathodic regions through which part of the corrosion current is consumed as an electrolyte reaction.

There is now an imponderability here with regard to the corrosion activity of the steel in the edge zone of the crack flanks. It is not expedient to use the steel surface in the crack, which can therefore be mathematically derived, as the anode surface. The contributing anode area depends on too many influencing factors. Overall, a correct determination of the anode surface area in the case of pitting corrosion, as investigated in the present case, is hardly possible from an experimental point of view due to the formation of scars and the associated increasing of the scar. The problems become clear from the illustration in **Fig. 5**.



**Fig. 5.** Model of corrosion in the crack area according to [10], [17]

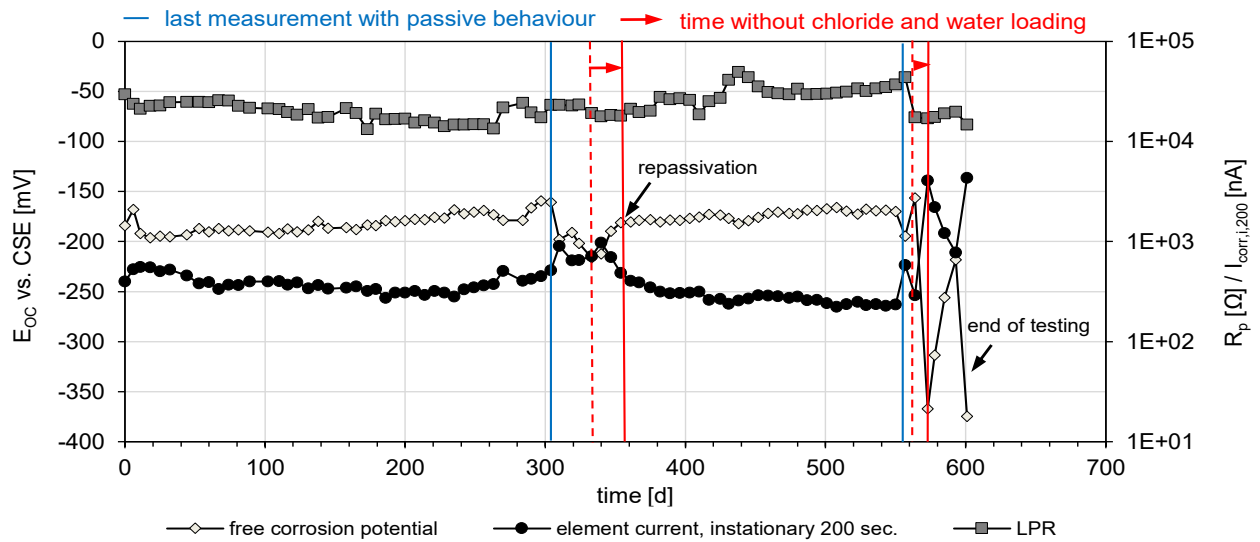
#### 4.4 Evaluation of test results

The first stable corrosion initiation without repassivation processes was chosen as the termination criterion for the tests. This is indicated by a decrease in the free corrosion potentials and a significant increase in the element currents, which do not return to their original values after two weeks of non-impact. At this point, visible corrosion was also first visible on the separated steel samples.

The exemplary course of a sample with and without corrosion initiation can be taken from **Fig. 6**.

At the end of the test, the chloride contents actually present in the concrete at the crack area are determined photometrically in the crack flanks.

Afterwards, the specimens were split and the pitting corrosion was photographically documented. The representation of a removed steel (B500B) with corrosion from the test series can be taken from **Fig. 7**. The representation of a 1.4003 specimen with corrosion is shown in **Fig. 8**. Here, the eccentrically offset scar to the separation crack area as shown in **Fig. 5** is clearly visible.



**Fig. 6.** Curves of a sample with corrosion initiation [17]



**Fig. 7.** removed black steel with corrosion in front of cracked concrete specimen



**Fig. 8.** 1.4003 Reinforcing steel in splitt concrete specimen with corrosion scar eccentric to separation crack

For each grade of reinforcing steel to be tested, 18 specimens were tested. All 18 specimens were manufactured identically to each other and were used for the usual determination of scatter in the tests.

From the determined chloride contents during corrosion initiation, a distribution function was created according to the corrosion initiation probability, see **Fig. 9**.

Using a linear distribution function and a corrosion initiation probability of 5 %, the characteristic chloride content of the 1.4003 steels is 1.7 wt.-%/c. This value is below the smallest single value for the determined samples and therefore on the safe side for the tests. With a probability of 50 % for a corrosion initiation, the tests result in a chloride content of approx. 4.1 wt.-%/c. Comparing the B500B refractory steels, the value at 50 % probability of corrosion initiation is 0.6 wt.-%/c.

Results on pickled 1.4003 reinforcing steels in uncracked concrete are presented in [15]. The mean critical corrosion-inducing chloride content was found to be  $C_{crit} = 2.3$  wt.-%/c. A comparison shows a significantly lower  $C_{crit} = 1.3$  wt.-%/c for unalloyed reinforcing steel. The significantly better performance of the unalloyed reinforcing steel in non-cracked concrete is primarily due to the continuous coating by the alkaline environment of the concrete compared to the crack area.

All test results refer to pickled reinforcement made of 1.4003.

## 5 Possible applications of 1.4003 for parking structures

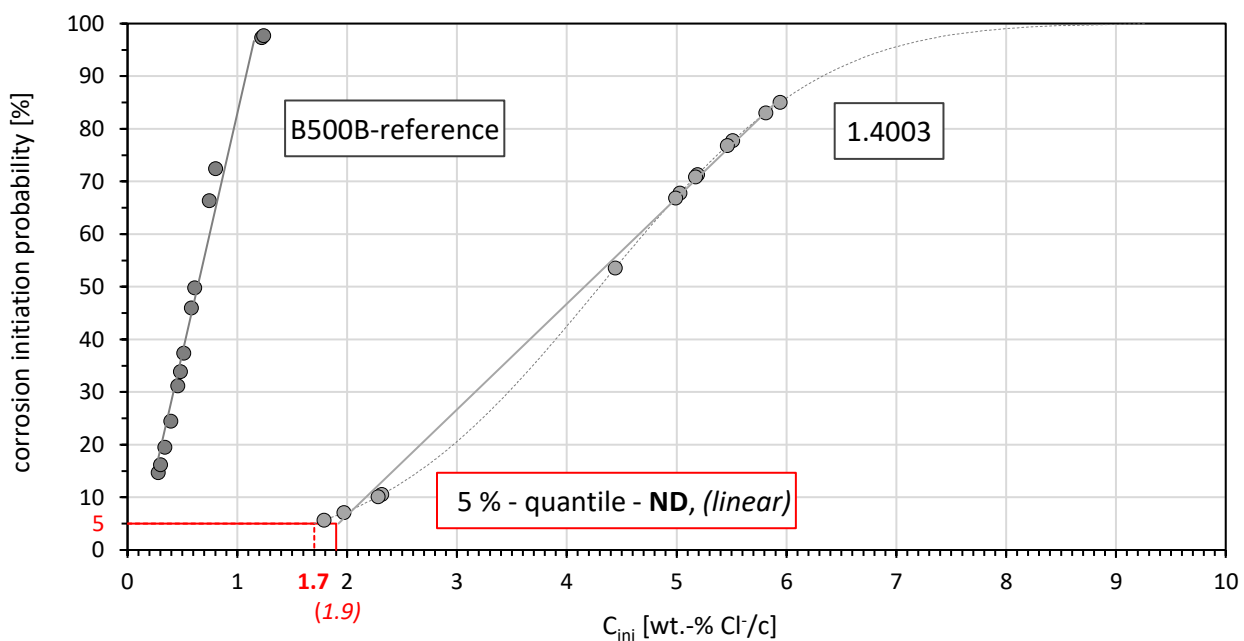
The higher chloride resistance of 1.4003 reinforcing steel compared to unalloyed reinforcement is the decisive property for use in underground garages. However, a distinction must be made depending on the component as to whether it makes sense to use it or not. The component catalogues [19] and [20], which have been specially compiled for this application, can provide some pointers. They discuss the possible applications for 1.4003 reinforcement in components under pavements [19], as well as horizontal components subject to direct traffic in accordance with EGS C (design principle C with planned cracks) [20].

Using [19] as an example, the uncoated reinforced concrete components below or just above the pavement were examined for their chloride content at 13 paved existing underground garages between 8 and 47 years of age. From the 172 investigation sites, cumulative

2.3 wt.-%/c was exceeded by less than 10% of the test locations.

In most cases, the use of mixed reinforcement, as already suggested in [21] for very high-alloy reinforcement, is recommended from an economic point of view. The high-alloy reinforcement steel is used in neuralgic points (e.g. column and wall bases in the chloride exposure area) while the unalloyed reinforcement steel is used in the remaining areas.

Various applications are reasonable for 1.4003. For example, its use in rising components in the base area and on foundation tops and distorting beams without further sealing is target-oriented. Here, for example, a permanent construction can be achieved with a separate protection of the construction joint between column/wall and foundation by means of a fillet, see **Fig. 10**. The advantage compared to a waterproofing according to DIN 18533 [22] is the omission of the waterproofing work at an unfavorable time of the construction phase. An exemplary



**Fig. 9.** summed corrosion initiation probabilities (values of stable corrosion initiation on the samples) with linear regression function and (dashed) normal distribution from [18]

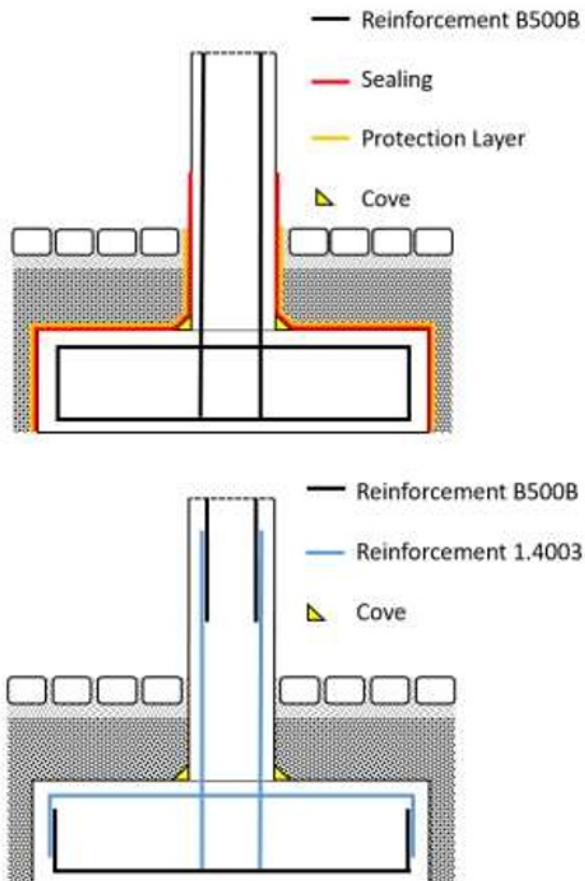
frequencies of the chloride contents were formed as a function of the sampling location of the bore dust at an average depth of 20 mm. A distinction was made between the areas above the pavement, the construction joint and the top of the foundation. While a chloride content of 0.5 wt.-%/c. was exceeded at 65% of the locations above the pavement, the results were significantly lower at 41% (construction joint) and 28% (top of foundation). With a critical corrosion-inducing chloride content of 1.7 wt.-%/c for the cracked area, only 6% of all measured values in the construction joint were above this level. In the non-cracked area of the upper edge of the pavement, about 3% were above a value of 2.6 wt.-%/c. A value of

cost comparison [23] showed that for a column with a top-reinforced foundation, the manufacturing costs were almost the same as for a design with OS5b.

There are also advantages compared to conventional reinforcement for applications in the area of horizontal structural components in design principle C (planned cracks). For example, the use of 1.4003 in combination with controlled crack inducers makes it possible to wait for one or more winter periods until a final crack width opening has occurred. The cracks then formed can be reworked with a crack bandage. The advantage of this is

that the crack bandage is far less likely to tear than if it is reworked very early.

Reinforcing steel made of material number 1.4003 proves more resistant to chloride exposure than conventional reinforcement. Even if this steel does not have such a wide-ranging resistance as, for example, 1.4571, its use is still conceivable for a large number of applications.



**Abb. 1: Comparison of column design under pavement with waterproofing (top) and 1.4003 reinforcement (bottom), principle sketch based on [23]**

At present, the use of 1.4003 as reinforcement in most areas is still considered to be a non-generally recognized rule of technology, which is why a comprehensive explanation of the advantages and disadvantages, as well as technical risks, is necessary for the building owner.

As in the case of very high-alloy reinforcement, the application in individual cases will have to be subjected to an economic assessment in comparison with currently common and code-compliant construction methods. However, if mixed reinforcement is used and the high-alloy chromium steel is applied in well-designed areas, it is possible in some cases to achieve a similarly economical construction method as with sealing or coating systems in production, which offers additional advantages with regard to the construction process and follow-up costs.

## 6 Conclusion

Reinforcing steel made of material number 1.4003 proves more resistant to chloride exposure than conventional reinforcement. Investigations on the corrosion resistance of those rebars in cracks containing chloride shows, that the corrosion inducing chloride content  $C_{crit}$  is approx. three times higher than  $C_{crit}$  of unalloyed reinforcing steel. Even if the 1.4003 steel does not have such a wide-ranging resistance as, for example, 1.4571, its use is still conceivable for a large number of applications.

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