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Attack of lime-dissolving carbonic acid in in situ tests on the load capacity of grouted anchors in sands

Attaque d'acide carbonique dissolvant la chaux dans des essais in situ sur la capacité de charge de tirants d'ancrage dans les sables

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ABSTRACT: Occasionally problems arise with chemical attack on geotechnical elements such as micro piles and grouted anchors. The most common difficulty is currently attributed to the occurrence of carbonic acid in groundwater. Excess carbonic acid in water leads to a lime-dissolving environment which attacks the grout body of geotechnical elements. Primarily, calcium oxide - quicklime - chemically converts, being the main component of cement. This influences the concrete-soil interface and negative changes occur in the pull-out resistance. Such losses could already be proven in laboratory tests, although no impacts are known with installed grouted anchors and micro piles.

RÉSUMÉ: Parfois, des problèmes surviennent lors d'attaques chimiques sur des éléments géotechniques tels que les micropieux et les tirants d'ancrage. Pour l'instant le plus grand besoin est attribué à la présence d'acide carbonique dans les eaux souterraines. L'excès d'acide carbonique dans l'eau amène à un environnement de dissolution de la chaux attaquant le corps de coulis des éléments géotechniques. L'oxyde de calcium est le composant chimique principal du ciment. Cela a un impact sur l'interface béton-sol, ainsi des changements négatifs se produisent dans la résistance à l'arrachement. Des pertes ont déjà pu être prouvées lors d'essais en laboratoire. Cependant, aucun impact n'est connu par rapport aux tirants d'ancrage et aux micropieux installés.

Keywords: grouted anchors; micro piles; chemical attack; lime-dissolving carbonic acid

1 INTRODUCTION

Difficulties arise with ongoing projects and construction measures of the German Federal Waterways and Shipping Administration (WSV) by interpreting the effects of chemical attack on mortar or concrete of geotechnical elements, like grouted anchors and micro piles, with regard to realistic valuation of pull-out resistance in determining appropriate requirements for building materials and construction methods. In addition to lime-dissolving carbonic acid, sulphate, ammonium and magnesium also constitute to the types of chemical attack by groundwater. The pull-out resistance of anchors under attack of lime-dissolving carbonic acid has been investigated only by few laboratory tests so far (Manns 1997, Hof 2004, Triantafyllidis and Schreiner 2007). These studies show significant differences in reduction of the load capacity between 20% and 80% (Figure 1), which are partly due to varying experimental boundary conditions. No failures due to this chemical attack have been observed on structures to this day.

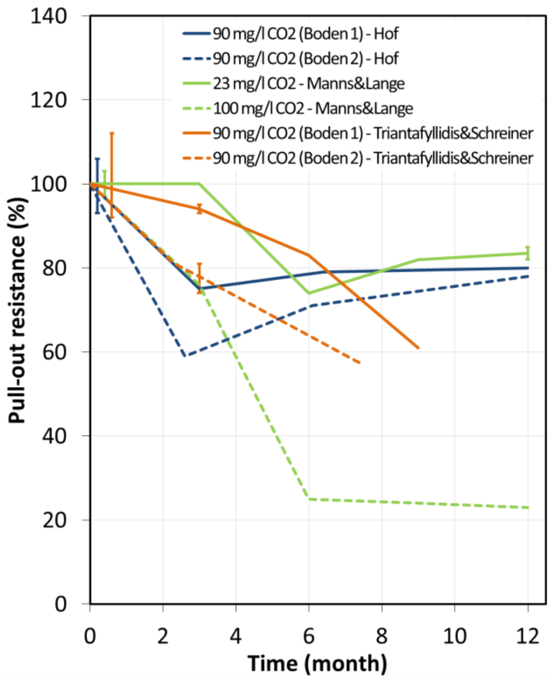

Figure 1. Changing in the maximum load capacity in laboratory tests

In addition to newly conceived laboratory tests, grouted anchors have been manufactured at construction sites of the WSV for research and planning purposes namely in the area of excess carbonic acid in groundwater. Results of selected realised grouted anchor tests of three locations are discussed.

2 CHEMICAL ATTACK DUE TO LIME-DISSOLVING CARBONIC ACID

In the course of the preliminary planning of construction measures, in particular in the area of the grouted anchors and micro piles, groundwater samples were taken to determine the chemical constituents of the water. Based on the concentration ranges according to DIN EN 206 (2017) or DIN 4030 (2008), high values of lime-dissolving carbonic acid were determined at various locations. The standards define criteria for the classification of the aggressiveness of water on concrete. The concentrations of concrete-damaging substances detected are assigned to an exposure class - weak, medium and highly aggressive - which represents the basis for the planning and construction of concrete structures. Exceedances of the threshold values result in an increased need for investigation in relation to the effects on the load capacity, as the lime-dissolving carbonic acid corrodes the concrete surface (Grün 1936, Mall 1951, Ballim and Alexander 1990) and thus causes a reduction in the interlocking of the concrete-soil interface (Manns 1997, Hof 2004).

Various factors, such as cation exchange, solution, precipitation as well as redox reactions, influence groundwater quality. In addition, anthropogenic and geogenic impacts can have considerable effects on the formation of CO_2. The identification of the respective characteristic influences of the formation of lime-dissolving carbonic acid on affected construction measures still has to be carried out.

The groundwater flow has to be taken into account, which is decisive for the replenishment of the attacking medium. Already Grube (1987) has shown with his experiments that with almost stagnant water and a permeability coefficient $k_f < 1x10^{-4}$ m/s no erosion of the concrete surface takes place. In the investigations carried out by Hof (2004), no relevant losses in pull-out resistance were found within the test period with a permeability of less than $k_f < 2x10^{-7}$ m/s.

3 IN SITU TESTING

3.1 Overview

Some construction sites in Germany affected by lime-dissolving carbonic acid are located on the Dortmund-Ems Canal (DEK), which runs between the port of Dortmund in North Rhine-Westphalia and the Ems River in Gleesen in Lower Saxony (Figure 2).

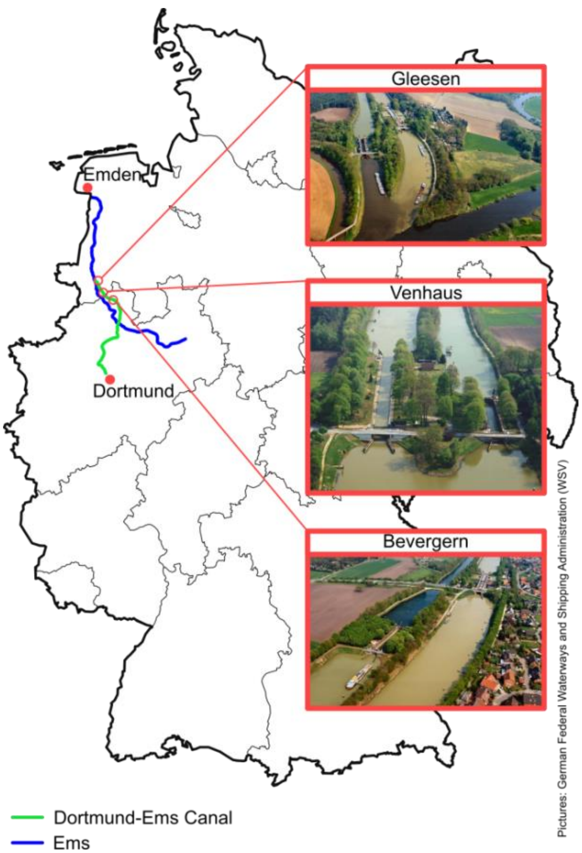

Figure 2. Map of Germany with three locations under attack by lime-dissolving carbonic acid on the Dortmund-Ems Canal

Investigations on grouted anchors and micro piles were carried out at three sites. To perform suitability tests, test fields were set up in the area of high chemical exposure. In Venhaus in 2011 and 2016, in Bevergern in 2011 and 2018 and in Gleesen in 2011 and 2016 as well as in 2017 and 2018, an initial and a second test were performed on grouted anchors and micro piles. During loading, unloading and each load step, the displacement was recorded in addition to the loads in order to determine the elastic and plastic strains, the apparent tendon free length and the creep rate. The load was applied stepwise with respective unloading to the datum load of 50 kN up to the maximum test load or up to exceeding the creep rate α > 2 mm. In the following chapters, boundary conditions and results of anchor tests are described in more detail.

3.2 Venhaus

3.2.1 Geotechnical investigation

According to the investigations on the outcrops, the following soil layers are present in the area of the lock from the top of the terrain downwards: Filling, medium sand (V1) and marly claystone (V2). Relevant soil parameters are listed in Table 3. The values of the stiffness modulus E_s correspond to the determination from the first loading.

In 2011, the groundwater samples in the direct surrounding of the grout bodies were unobtrusive with a value of 1 mg/l lime-dissolving carbonic acid. In the second investigation in 2016, water analysis by the laboratory detected up to 43 mg/l of lime-dissolving carbonic acid in groundwater, which results in a classification of moderately aggressive according to DIN EN 206 (2017) or DIN 4030 (2008).

Table 3. Soil characteristics of specific layers in Venhaus

	$\boldsymbol{\varphi'_k}$ (°)	$\mathbf{c'_k}$ (kN/m²)	$\mathbf{E_s}$ (MN/m²)	$\mathbf{k_f}$ (m/s)
V1	35,0	0	40	$1x10^{-4}$ … $1x10^{-3}$ *
V2	25,0	20	200	$1x10^{-9}$ … $5x10^{-6}$ **

* Empirical approach by Hazen
** Hydraulic pressure tests

3.2.2 Anchor installation

A total of six single-rod grouted anchors with a grout body length of 3 m (VEN401-403) or 5 m (VEN404-406) were installed and tested. The position of the grout bodies is completely in the marly claystone, as shown in Figure 3. The steel bar used has a diameter of 75 mm and was put in a drill hole of 160 mm diameter. A pressure of 4 to 6 bar was applied during manufacturing. The grout body was limited by water flush and the resulting free space above was filled with a bentonite suspension. Measurements were made only during the anchor tests. After the initial test, the reinforced concrete slabs, which served as abutments, were removed and the anchor heads were shortened below the ground level. These were excavated after five years for the investigation in 2016 and a new abutment was constructed. The initially tendon free length of about 18.65 m was reduced to around 16.60 m.

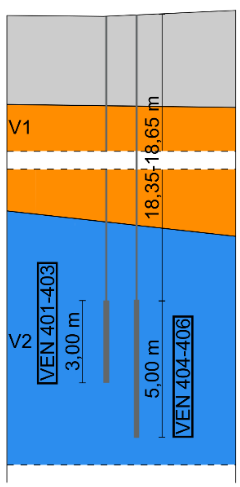

Figure 3. Part of the cross-section of the soil profile including the single-rod grouted anchors in Venhaus

3.2.3 Results

The proof load determined in advance for the first investigation was 2812 kN. In the second test, the proof load was reduced to around 2665 kN due to the possible weakening of the steel by corrosion.

The pull-out resistance of the respective short grouted anchors with values between 1950 and 2665 kN is almost identical in both investigations. With values from 44.8 (VEN401) to 58.8 mm (VEN402) in 2011 to 44.5 (VEN401) to 66.1 mm (VEN402) in 2016, there is a steady to increasing elastic deformation despite the shortening. With 15.3 (VEN402) to 29.9 mm (VEN403) in 2011, the plastic deformation of the grouting anchor is, as expected, above the values from 2018, which are between 8.6 (VEN402) and 24.6 mm (VEN401). In the second investigation, the apparent tendon free length of short anchors increased from 19.5 to 20.4 m despite the shortening of the tendon by up to three meters to 20.7 to 23.4 m.

In the case of the long anchors (VEN404-406), the maximum pull-out resistances with values between 2512 and 2812 kN are almost similar in both tests. The measured elastic deformations at the anchor head in both investigations are between 52.1 to 58.1 mm. The recorded plastic deformations in 2016 of 4.6 (VEN405) to 10.3 mm (VEN406) result in a 75% reduction. The values of the apparent tendon free length of the long anchors are almost the same at 19.0 to 20.2 m compared with 18.3 to 20.8 m in 2016 despite the shortening.

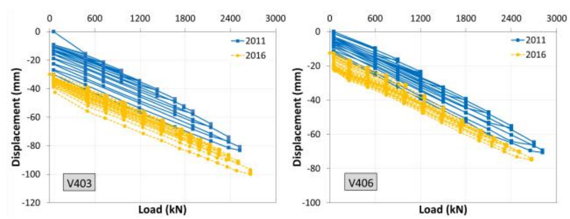

Figure 4. Load-displacement curve anchor V403 (short anchor) and V406 (long anchor)

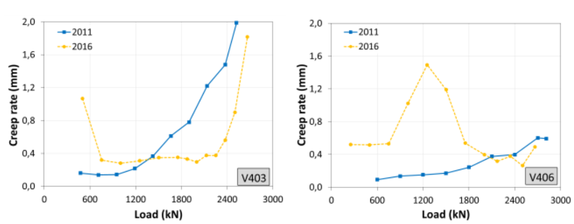

Figure 5. Development of creep rate of anchor V403 (short anchor) and V406 (long anchor)

3.3 Bevergern

3.3.1 Geotechnical investigation

The strand anchors are located between the existing and the newly planned lock. In this area the subsoil structure can be described from top to bottom as follows: Filling, fine to medium sand (B1), silty sands / sandy silts (B2) and till (B3). Table 2 shows relevant soil parameters of the soil layers in the area of the grout bodies.

In 2011, the lime-dissolving carbonic acid in the surroundings of the anchors was just over 20 mg/l. Further measurements in 2016 showed an increase to around 40 mg/l. Before the second suitability test in 2018, similar values of the lime-dissolving carbonic acid were obtained as in the previous one. Based on the values, a classification according to DIN EN 206 (2017) or DIN 4030 (2008) as moderately aggressive is made.

Table 2. Soil characteristics of specific layers in Bevergern

	φ'_k (°)	c'_k (kN/m²)	E_s (MN/m²)	k_f (m/s)
B1	32.5	0	22.5	2×10^{-5} … 5×10^{-4} *
B2	27.5	10	-	1×10^{-8} … 4×10^{-5} *
B3	27.5	10	13	1×10^{-9} … 5×10^{-6} **

* *Empirical approach by Hazen*
** *Empirical approach by Kaubisch*

A section of the soil profile including a schematic representation of the anchors is shown in Figure 6.

3.3.2 Anchor installation

Six strand anchors with nine strands each with a diameter of 0.6" are installed at an angle of 30°. The length of the grouted bodies, which were post-grouted, is 5 m (BEV101-103) and 9 m (BEV201-203) respectively. These are located on the one hand in the area of medium to fine sand and on the other hand in the transition from sand to till. 141 mm is the outer diameter of the borehole. The cement suspension was pressed in with 6 to 8 bar, flushed out above the grout body and free space filled with a bentonite suspension. A sheet pile wall functioned as abutment for the first test and was subsequently pulled out. The strands were shortened accordingly. A new concrete foundation with a corresponding inclination was constructed and the ends of the strand anchors were excavated for the second test. As a result, the tendon free lengths are reduced from 22.8 to 19.1 m and 12.8 to 9.1 m respectively.

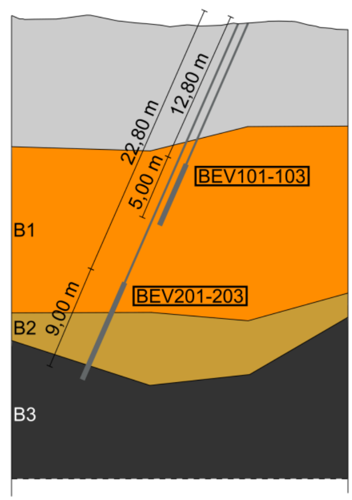

Figure 6. Part of the cross-section of the soil profile including the strand anchors in Bevergern

3.3.3 Results

In both investigations, a proof load of 1750 kN was specified in advance. The loading procedure of the validation was adapted to the first test and almost identically followed.

The maximum test loads of 610 to 1025 kN in 2011 were in a similar range as in the second test with 660 to 950 kN. From the first test in 2011 with 31.5 (BEV 103) to 49.2 mm (BEV 102), the elastic deformations have decreased correspondingly to shortening of the tendon to 25.3 (BEV103) to 39.6 mm (BEV 102) in 2018. The plastic strain of the anchors varies between

18.2 mm (BEV103) and 24.4 mm (BEV101) in 2011 and 12.2 mm (BEV103) and 15.7 mm (BEV102) in 2018, as shown in Figure 7. The development of creep rate of the first investigation is a bit higher, as demonstrated in Figure 8 for anchor BEV101. At 12.5 m, the apparent tendon free lengths in the suitability test in 2011 are larger than 9.1 (BEV101) to 10.2 m (BEV102) in 2018 due to the shortened strands, which corresponds to the new reduced tendon free length.

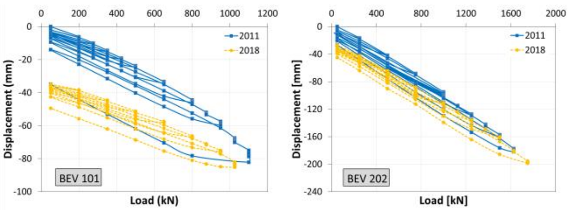

Figure 7. Load-displacement curve anchor BEV101 (short grout body) and BEV202 (long grout body)

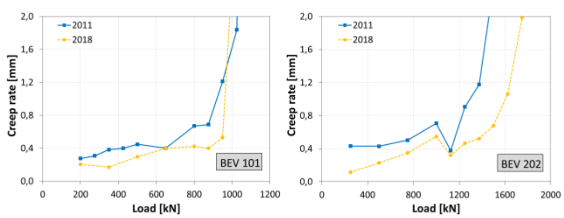

Figure 8. Development of creep rate of anchor BEV101 (short anchor) and BEV202 (long anchor)

The strand anchors with a deeper anchorage show that the pull-out capacity in the first test with 1375 to 1750 kN is up to 25% lower compared to 1550 to 1750 KN in 2018. In both tests, the elastic deformations are in a range between 151.2 and 155.3 mm. Only for anchor BEV201 the value in 2018 is 130.5 mm. In 2011, the permanent deformations are between 18.9 (BEV201) and 26.5 mm (BEV202) and thus have greater values than in 2018, where the values range from 11.6 (BEV201) to 18.4 mm (BEV202). The development of creep rates over the load stages is similar, with values in 2011 always above those of 2018 (Figure 8). The apparent tendon free lengths of the anchors BEV202-203 were up to 1.0 m above the tendon free length of 22.8 m in 2011 and up to 4.8 m above the tendon free length of 19.1 m in 2018. The third anchor BEV 201 has similar values in both tests.

3.4 Gleesen

3.4.1 Geotechnical investigation

The research anchors at the lock are located in the riverbank of the underwater. The order of the subsoil layers is from the ground level downwards: Filling, medium dense or dense sands (G1), till (G2), dense or very dense sands (G3), sands with clay and silt lens (G4) and tertiary sands. Relevant soil parameters are listed in Table 3.

The groundwater samples taken from wells next to the grouted anchors show a lime-dissolving carbonic acid content of 30 to 40 mg/l in 2011. After completion of a nearby waterfront structure, the values increased up to 58 mg/l in 2017 and 110 mg/l in 2018. The values are classified as moderately aggressive in accordance with DIN EN 206 (2017) or DIN 4030 (2008). The value of more than 100 mg/l causes a classification in a highly aggressive attack.

Table 3 Soil characteristics of specific layers in Gleesen

	φ'_k (°)	c'_k (kN/m²)	E_s (MN/m²)	k_f (m/s)
G1	35.0	0	35	$1x10^{-3}$ … $1x10^{-5}$ *
G2	32.5	5	5	$5x10^{-5}$ … $5x10^{-8}$ **
G3	37.5	0	100	$1x10^{-3}$ … $1x10^{-4}$ *
G4	32.5	0	50	$1x10^{-3}$ … $1x10^{-5}$ *

* *Empirical approach by Beyer*
** *Empirical approach by Kaubisch*

3.4.2 Anchor installation

A total of six additional grouted anchors (FA1-FA6) are installed vertically. These are single-rod anchors with a 63.5 mm bar diameter and a 185 mm drill hole diameter. The grout bodies are limited to five metres by a flush and the free steel length is filled with a bentonite suspension. As shown in Figure 9, the grout bodies are mainly located in the area of sands and partly in sands with clay and silt lens. The cement slurry was injected at a pressure of 5 bar. A load cell is attached to each anchor head for permanent measurement of the lock-off load. The abutments, which were designed as reinforced concrete slabs, remain permanently installed.

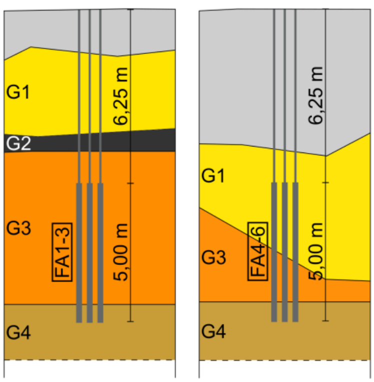

Figure 9. Part of the cross-section of the soil profile including the research anchors in Gleesen

3.4.3 Results

The research anchors were originally to be investigated with a proof load of around 1670 kN. During the first suitability test at anchor FA5, it was already established that the installed fibre optic cables could not withstand the large deformations at the fourth load level (1420 kN). Thus, the following grouted anchors were loaded with 480-660-840-1020-1200 kN. Following the tests, the anchors were fixed at a lock-off load of 840 kN. During the second anchor test in 2018, the load levels of 340-460-590-720-740-840-950 kN were determined in order to take into account previous settlements with regard to the measurements and functionality of the fibre optic cables.

The elastic strains of the first experiments lie between 12.9 (FA2) and 16.3 mm (FA2) and thus at similar load levels in a range as the measured displacements in 2018, which are between 13.6 (FA6) and 16.2 mm (FA1). At 6.1 (FA4) to 14.9 mm (FA1), the permanent deformations of the first test are significantly greater than the measured value of 0.8 (FA6) to 2.5 mm (FA1) in 2018. Exemplary representations of the load-displacement curves are shown in Figure 10. The creep rate development is similar for three of the six anchors (FA1-FA3), as can be seen for example for anchor FA1 in Figure 11.

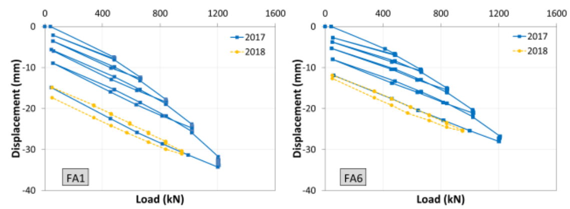

Figure 10. Load-displacement curve of anchor FA1 and FA6

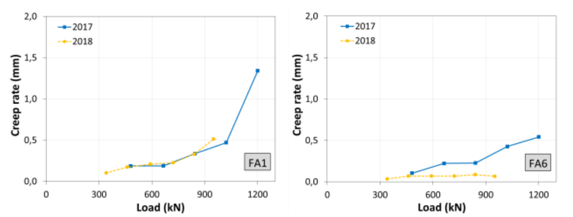

Figure 11. Development of creep rate of anchor FA1 and FA6

For the other anchors, the creep rate in 2018 is much smaller up to the maximum load level. Anchors FA1, FA2 and FA 5 have an apparent tendon free length of 10.7 to 11.0 m in 2017, which is longer than 9.4 to 9.9 m in 2018. Anchors FA4 and FA6 are similar in both investigation. Only anchor FA3 has an approximately one metre higher value of 10.0 m. However, all values are significantly above the tendon free length of 7.65 m. In addition, the heights of the concrete abutments were determined before and after the anchor tests by a surveyor. The permanent settlements resulting from the first test were around 20 mm. Up to the second test, about

8 mm further settlements were caused by the lock-off. The permanent displacement of the abutment in the second test was about 1 mm.

4 CONCLUSIONS AND OUTLOOK

The test results at the three sites all show quantitatively similar results with regard to the question of the loss of load capacity of geotechnical elements such as grouted anchors and micro piles due to the influence of lime-dissolving carbonic acid. The required pull-out resistance up to the maximum test load or exceeding the creep rate α = 2 mm are almost unchanged or slightly increasing over the investigated time of up to 7 years. These results are in contrast to the laboratory tests by Manns (1997), Hof (2004) and Triantafyllidis and Schreiner (2007), which recorded significant losses. The results of the suitability tests presented from Venhaus and the deeper anchors in Bevergern can be explained by the low permeability coefficients. Due to the slow flow rate there is practically no replenishment of lime-dissolving carbonic acid. The settlement of the abutment in Gleesen until the second investigation and the resulting compaction of the subsoil counteract a possible loss of pull-out resistance. The comparatively higher values of the apparent tendon free lengths indicate that there is no increased friction in the free steel length which would lead to higher load capacities.

In summary, the current results of the investigations on the construction sites show no significant change in the pull-out capacity due to the lime-dissolving carbonic acid.

Due to the absence of reference anchors without chemical attack, it is difficult to make a qualitative statement on the development of the load capacity under the investigated conditions. Further research will also focus on ensuring that the relationship between laboratory and in situ results can be established. Against this background, the relevant influences on site and in the laboratory must be identified and correlations established.

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