Tunnelling and Underground Space Technology 59 (2016) 16–23

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Critical embedment length and bond strength of fully encapsulated rebar rockbolts

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ARTICLE INFO

Article history:
Received 9 November 2015
Received in revised form 7 June 2016
Accepted 8 June 2016
Available online 17 June 2016

Keywords:
Rockbolt
Embedment length
Pullout test
Bond strength

ABSTRACT

A series of rock bolt pull tests were carried out in the laboratory to determine the critical embedment length of a specific type of fully cement-grouted rebar bolt. The rebar bolt is 20 mm in diameter, and it is widely used in underground excavations in Norway. Three water-cement (w/c) ratios were used in the tests. It was discovered that the critical embedment length of the rock bolts was approximately 25 cm for the water-cement ratio 0.40 (the corresponding uniaxial compressive strength (UCS) of the grout is 37 MPa), 32 cm for the ratio 0.46 (UCS 32 MPa), and 36 cm for the ratio 0.50 (UCS 28 MPa), for the specific type of cement, Rescon zinc rock bolt cement. It was found that the bond strength of the rock bolt is not a constant but is related to the embedment length. The bond strength was linearly proportional to the UCS of the grout.

1. Introduction

The rebar rock bolt that is fully encapsulated in a borehole with cement mortar or resin grout is the type of rock bolt widely used in civil and mining engineering. The wide use of this type of rock bolt is predominately owed to its high load-bearing capacity. The grouting quality and performance of the rock bolt are usually examined by pull test. In such a test, a rock bolt grouted in a borehole is either pulled out to measure the bond strength in the case of a short embedment length (Hyett et al., 1995; Benmokrane et al., 1992; Benmokrane et al., 1996; Zhao and Yang, 2011) or pulled until failure of the rock bolt shank (Stillborg, 1994; Stjern, 1995; Chen and Li, 2015). Pull tests may be conducted in the field (Franklin and Woodfield, 1971; Franklin et al., 1974; Bjurholt, 2007; Soni, 2000) or in laboratories (Ito et al., 2001; Li et al., 2014).

The performance of a fully grouted rebar rock bolt is very much affected by the bond at the rock bolt-grout interface. The bond strength directly determines the critical embedment length of the rock bolt, which refers to the longest encapsulated length at which the rock bolt is pulled out of the borehole. The rock bolt will fail in the shank if the grouted section is longer than the critical embedment length. For instance, in order to stabilise a loosened rock block with fully grouted rock bolts, the length of the rock bolt portion that is installed in the stable stratum must be longer than the critical embedment length. The quality of grouting and the load-bearing capacity of grouted rock bolts are often examined through pull tests in the field. One of the concerns with such a pull test is whether the performance of the rock bolt is negatively affected by the pull test. The authors acknowledge that the issue of the critical embedment length was studied by others in conjunction with individual engineering projects, but little information about it can be found in the literature. Therefore, a series of tests were carried out at the Laboratory of Rock Mechanics at the Norwegian University of Science and Technology to determine the critical embedment length of a specific type of 20 mm rebar rock bolt using the cement mortar Rescon zinc rock bolt cement mix in three different water-cement ratios. Both the rock bolt and the cement mix are widely used for rock support in Norwegian tunnels and underground caverns. The test results are reported in this article. In addition to the determination of the critical embedment length, the bond strength of the fully grouted rock bolts was also studied. It was found that the bond strength is not a constant but is related to the embedment length.

2. Specimens

2.1. Rock bolts

The type of rebar rock bolt tested is 20 mm in diameter, which is widely used in road tunnels in Norway (Fig. 1). It is made of steel B500NC according to the Norwegian standard NS 3576-3, which specifies the mechanical properties of the steel, the formation of the rib pattern, and the production control. For the sake of

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http://dx.doi.org/10.1016/j.tust.2016.06.007
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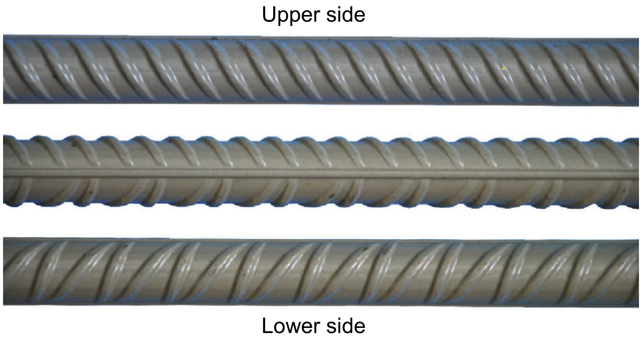

Fig. 1. The rib pattern of the rebar bolt, viewed in three orthogonal directions. Bolt diameter 20 mm, rib spacing approximately 12.5 mm.

corrosion protection, the rock bolt surface is treated by hot zinc-galvanisation with a minimum thickness of 65 μm and a coating of epoxy powder with a minimum thickness of 60 μm. The characteristic yield and ultimate tensile loads of the bolt are 157 kN and 188 kN, respectively.

2.2. Cement grout

The grouting agent used in the tests is Rescon zinc rock bolt cement mix, which is used for grouting rock bolts in road tunnels in Norway. The cement mix is made of cement (c) and silica (s). The weight ratio of the mix (cement and silica) to the cement is (c + s)/c = 1.7. The ratio of the mix (c + s) to the water (w) has the following relationship with the conventional water-cement ratio (w/c):

$$\frac{w}{c+s} = \frac{c}{c+s}\frac{w}{c} = \frac{1}{1.7}\frac{w}{c} \tag{1}$$

For instance, the ratio of w/(c + s) should be 0.235 if the water-cement ratio of the grout is intended to be 0.40. Three water-cement ratios, 0.40, 0.46, and 0.50, were used in the tests and the corresponding water-mix ratios (i.e., w/(c + s)) were 0.235, 0.270, and 0.294, respectively.

Table 1
Number of rock bolt specimens for every water-cement ratio and for every embedment length.

Embedment length (cm)	Water-cement ratio		
	0.40	0.46	0.50
10	3	3	3
15	3	–	–
20	3	3	3
25	–	3	–
30	3	3	3
40	1	–	2
Total	13	12	11

3. Testing

3.1. Test plan

The embedment length of the rock bolt was varied for every water-cement ratio in order to find the critical embedment length. In general, three rock bolt specimens were pulled for every embedment length. The number of rock bolt specimens for every embedment length and every water-cement ratio is given in Table 1.

The uniaxial compressive strength (UCS) of the grout was measured after the same curing time as the tested rock bolts. Three cubic grout specimens, 100 × 100 × 100 mm in size, were prepared when the rock bolt was grouted and then tested on a servo-controlled test machine, GCTS RTR-4000, on the same day the rock bolt was tested.

3.2. Test arrangement

Boreholes were percussively drilled with a 48 mm drill bit in a cubic concrete block with a dimension of 950 × 950 × 950 mm. The UCS of the concrete is approximately 110 MPa. The grout was mixed with one of the water-cement ratios given in Table 1. The ready-mixed grout was pumped into the hole and the rock bolt was inserted to a desired depth. The curing time was scheduled to be seven days, but some of the rock bolts were pulled out after eight days. When a rock bolt was tested, a cylindrical spacer, collaring the rock bolt, was placed on the top of the concrete block, a hydraulic cylinder (jack) was placed on the top of the spacer, and finally a rock bolt plate and a barrel-and-wedge unit were placed on the top of the setup string to fasten the rock bolt (Fig. 2). The purpose of using the barrel-and-wedge to replace the nut and thread is to avoid premature failure of the rock bolt in the thread. With such an arrangement, the rock bolt does not need to be threaded so that the rock bolt head is not weakened due to threading. Thus, the failure occurs either in the grout along

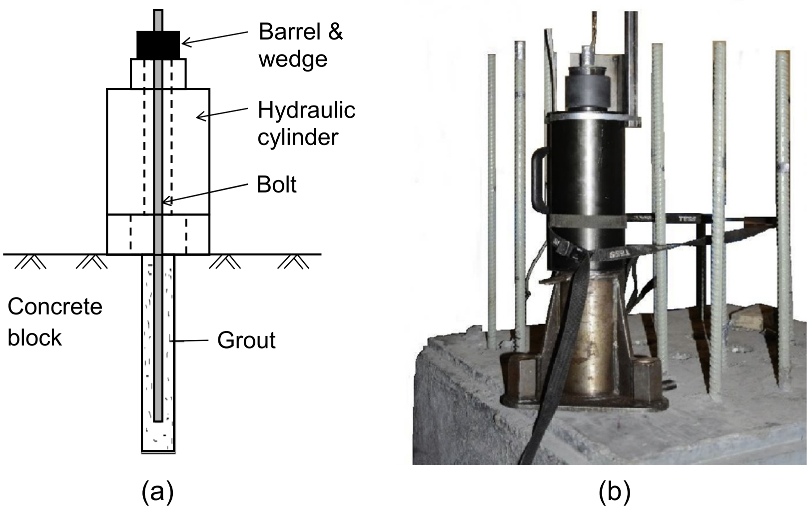

Fig. 2. Pull test arrangement. (a) A sketch and (b) the test arrangement.

the rock bolt-grout interface or in the bolt steel under the pull load. The distance from the surface of the concrete block to the barrel-and-wedge, that is, the freely stretched length of the rock bolt is 60 cm. The movement of the bolt head was measured with respect to the base of the hydraulic cylinder with an extensometer. Rock bolts with long enough embedment lengths will fail in the shank. To avoid damage to the extensometer after the violent failure of the bolt shank, when the rock bolt risks failure in the steel, the test was terminated when the load reached the tensile strength of the rock bolt but “necking” had not started.

4. Results

4.1. Pull test results

Every rock bolt specimen is labelled with three digits after the letter B. The first digit represents the parameter of water-cement ratio, the second represents the group of the embedment length, and the third represents the sequence number of the specimen in the group. The rock bolts were tested after curing for seven to nine days.

4.1.1. Water-cement ratio 0.40

The load-displacement curves of the rock bolts grouted with a water-cement ratio of 0.40 are presented in Fig. 3. The test results of rock bolts with an embedment length of 100 mm are shown in Fig. 3a. The displacement of rock bolt B213 was measured using an extensometer, but the other two rock bolts, B211 and B212, were measured manually using a calliper. The ultimate load was 57 kN for B213 but 77 and 87 kN, respectively, for B211 and B212. All three rock bolts slipped in the grout to the end.

The test results of rock bolts with an embedment length of 150 mm are shown in Fig. 3b. The ultimate load varied from 97 to 118 kN, and all three rock bolts in the group slipped along the

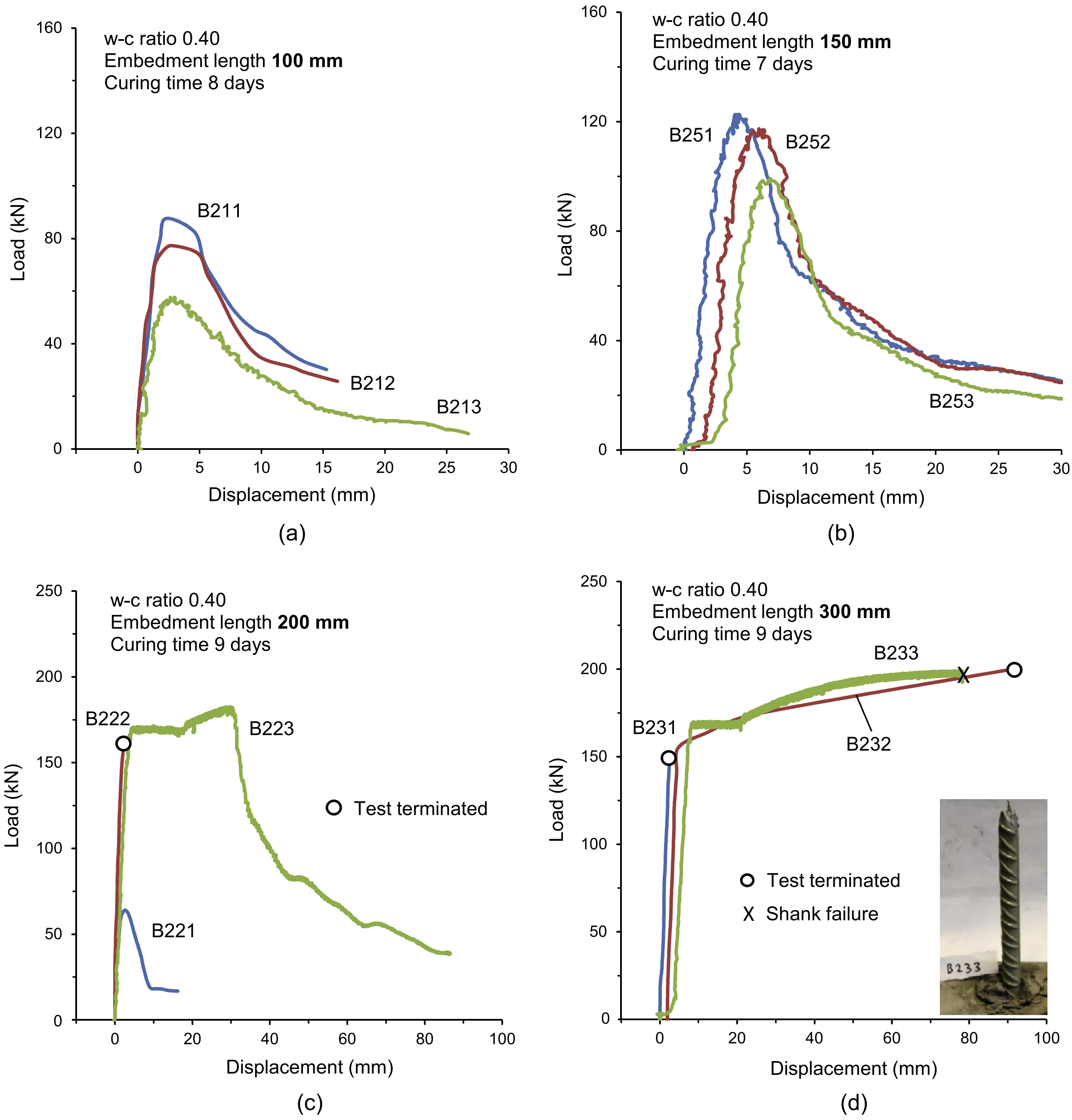

Fig. 3. Pull load–displacement curves of the bolts grouted with water-cement ratio 0.40 for embedment lengths (a) 100 mm, (b) 150 mm, (c) 200 mm, and (d) 300 mm.

bolt-grout interface. Rock bolt B253 had the lowest load at 97 kN. It was observed that the borehole was not fully cement filled to the borehole collar so that its actual embedment length was a little shorter than 15 cm. Thus, it was excluded in the calculation of the average bond strength of the rock bolts.

The test results of rock bolts with an embedment length of 200 mm are shown in Fig. 3c. The ultimate load was only 64 kN for rock bolt B221. The low ultimate load might be owing to poor grouting. The test of B222 was wrongly interrupted when the load was at a level close to the yield load. Therefore, only the test result of bolt B223 is representative in this group. Bolt B223 first yielded and elongated up to 30 mm, and then the embedded section started to slip at a load of 180 kN.

The test results of rock bolts with an embedment length of 300 mm are shown in Fig. 3d. The tests of both B231 and B232 were terminated before the rupture of the bolt shank. The test of bolt B231 was terminated just prior to yielding. Bolt B232 yielded and displaced 90 mm when the test was terminated. It was expected that it would fail in the shank if the loading continued. Bolt B233 failed in the shank after a displacement of 78 mm. The insert picture in the figure shows the necking failure of the bolt. No slippage occurred for all three rock bolts.

4.1.2. Water-cement ratio 0.46

The load-displacement curves of the rock bolts with a water-cement ratio of 0.46 are presented in Fig. 4. The test results of rock bolts with an embedment length of 100 mm are shown in Fig. 4a. All three rock bolts in the group slipped in the grout, and their ultimate loads varied from 39 to 48 kN.

The test results of rock bolts with an embedment length of 200 mm are shown in Fig. 4b. All the three rock bolts in the group slipped after the peak loads. The ultimate loads of B321 and B322

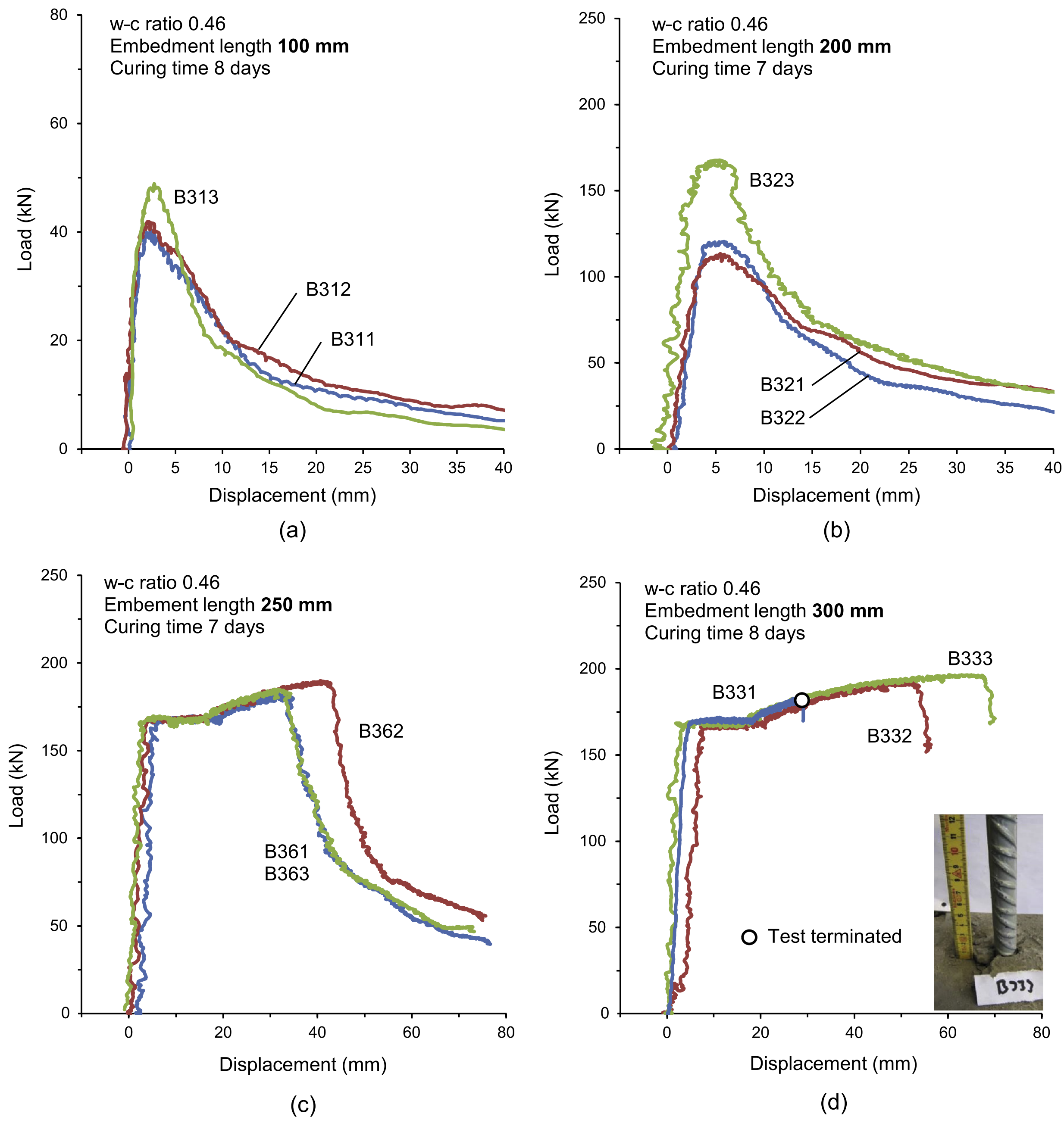

Fig. 4. Pull load–displacement curves of the bolts grouted with water-cement ratio 0.46 for embedment lengths (a) 100 mm, (b) 200 mm, (c) 250 mm, and (d) 300 mm.

were similar, 113 and 119 kN, respectively, but the ultimate load of B323 was significantly higher at 167 kN. It was found after the test that the embedment length of B323 was approximately 230–240 mm, longer than the other two rock bolts. The result of B323 is thus excluded in the calculation of the average bond strength of the bolts in the group.

The test results of rock bolts with an embedment length 25 cm are shown in Fig. 4c. All three rock bolts in the group yielded and started to slip in the grout at 180 or 190 kN.

The test results of rock bolts with an embedment length of 300 mm are shown in Fig. 4d. All three rock bolts in the group yielded, and rock bolts B332 and B333 started to slip in the grout at approximately 200 kN. The test of B331 was terminated before slippage. The embedment length of 300 mm is very close to the critical length so that no embedment lengths longer than 300 mm were tested for the water-to-cement ratio of 0.46.

4.1.3. Water-cement ratio 0.50

The load-displacement curves of the rock bolts with a water-cement ratio of 0.50 are presented in Fig. 5. The test results of rock bolts are shown in Fig. 5a for those with an embedment length of 100 mm and in Fig. 5b for those with an embedment length of 200 mm. All rock bolts in these two groups slipped in the grout at a load below the yield load of the bolt shank.

The test results of rock bolts with an embedment length of 300 mm are shown in Fig. 5c. The shanks of all three rock bolts in the group yielded first and then slipped in the grout.

The test results of rock bolts with an embedment length of 400 mm are shown in Fig. 5d. The bolts did not show any sign of slippage in the grout so that the tests were terminated when the loads reached 200 kN. Clearly, the critical embedment length of the bolts is shorter than 400 mm for this water-cement ratio.

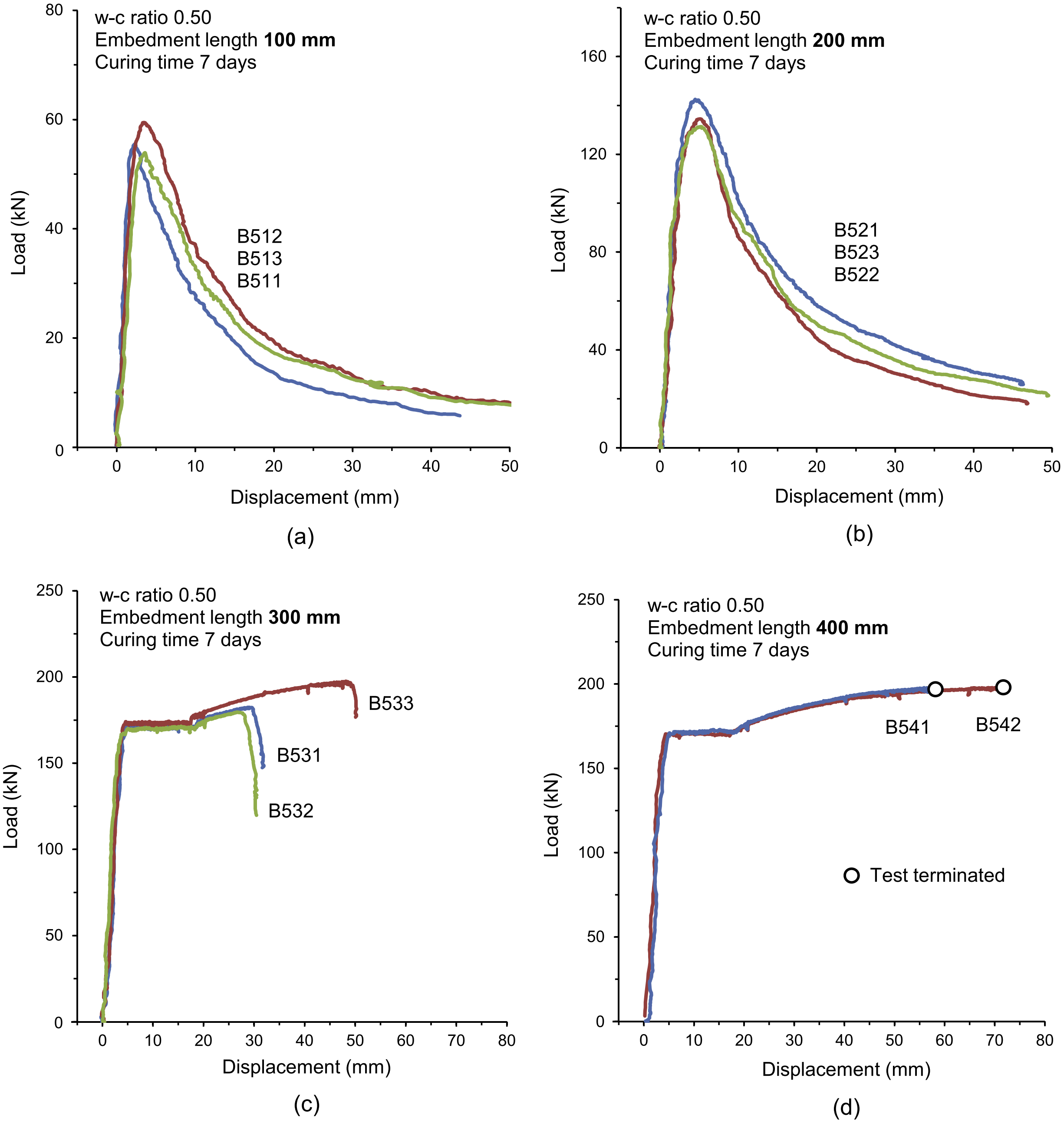

Fig. 5. Pull load–displacement curves of the bolts grouted with water-cement ratio 0.50 for embedment lengths (a) 100 mm, (b) 200 mm, (c) 300 mm, and (d) 400 mm.

Table 2
UCS values of the cubic specimens of the grouts after 7–8 days of curing (Specimen size: 100 × 100 × 100 mm).

w/c ratio	UCS (MPa)	
	Round 1	Round 2
0.40	33, 49, 43	38, 36, 37
0.46	29, 31, 29	33, 32, 32
0.50	45[a], 43[a], 43[a]	27, 28, 30

[a] Abnormal values.

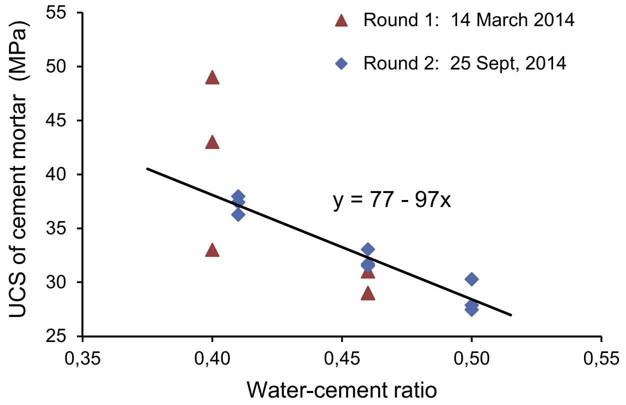

Fig. 6. UCS values of the grouts, measured with cubic specimens, for different water-cement ratios after 7-day curing.

4.2. UCS results of the grout cubes

The cubic specimens of the grout for every water-cement ratio were tested for UCS after seven-eight days of curing. Abnormal results were obtained for the water-cement ratio 0.50 in the first test round so that a second round of tests was run afterward. The UCS results of the grouts for different water-cement ratios are presented in Table 2 and in Fig. 6. Note that the abnormal UCS values for the water-cement ratio 0.50 in the first round were excluded in the figure.

5. Analysis of the test results

5.1. The critical embedment length

The ultimate pull loads of the bolt specimens are plotted against the embedment lengths for the three different water-cement ratios in Figs. 7–9. The critical embedment length of the rebar rock bolt for a given water-cement ratio is determined so that the points representing slippage fit a regression curve and the abscissa of the intersection of the regression curve with the strength line (at 200 kN) of the rock bolt shank is defined as the critical embedment length. Fig. 7 is the load-embedment length diagram of the rock bolts for the water-cement ratio 0.40. Notice that the results of rock bolts B253, B221, B222, and B231 were excluded in the plot for the reasons described in Section 4.1. The specimen with a 300 mm embedment length failed in the shank, while the others slipped under their ultimate loads, indicating bond failure at the rock bolt-grout interface. The critical embedment length of the rock bolt for the water-cement ratio 0.40 is determined to be approximately 250 mm.

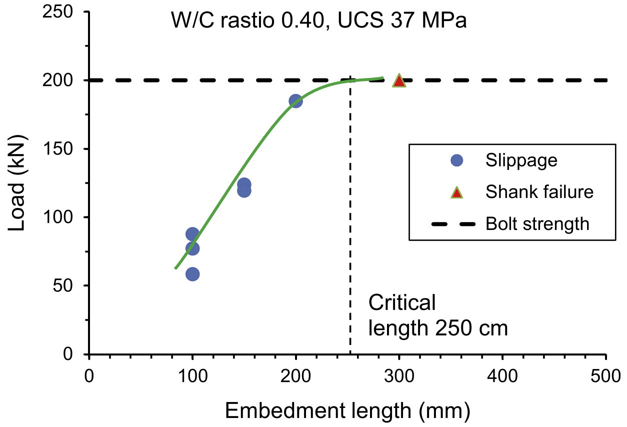

Fig. 7. Ultimate pull load versus the embedment length of the bolt for water-cement ratio 0.40.

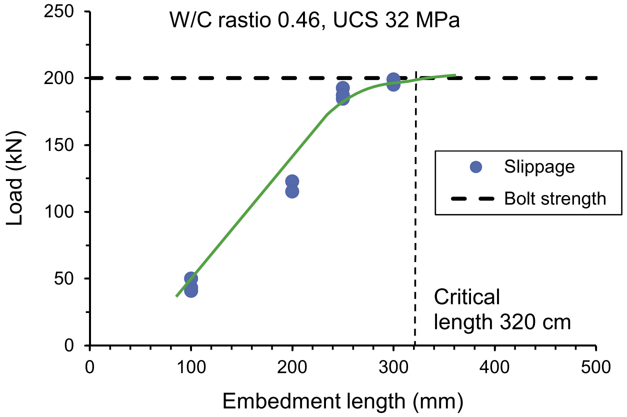

Fig. 8. Ultimate pull load versus the embedment length of the bolt for water-cement ratio 0.46.

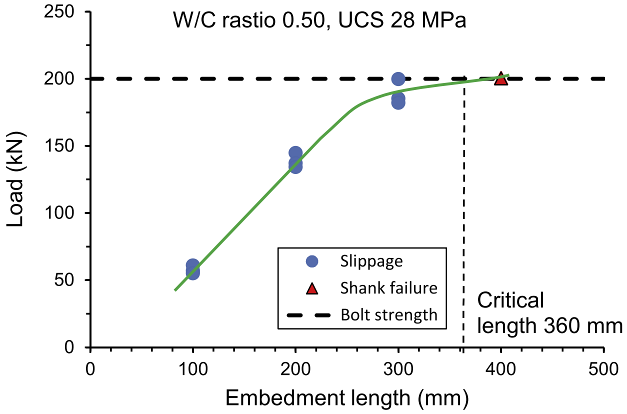

Fig. 9. Ultimate pull load versus the embedment length of the bolt for water-cement ratio 0.50.

The ultimate loads of the rock bolt specimens in the group with a water-cement ratio of 0.46 are plotted against the embedment length in Fig. 8. Notice that the result of rock bolt B323 was excluded in the plot because of its abnormality. All the rock bolts slipped in the grout, but the rock bolts with a 300 mm embedment length started to slip when the load was at a level close to the ultimate load of the bolt shank (see Fig. 4d), indicating that this length is close to the critical embedment length. The critical embedment length of the rock bolt for the water-cement ratio 0.46 is determined to be approximately 320 mm.

All the rock bolts with a water-cement ratio of 0.50, except those with an embedment length of 400 mm, slipped in the grout (Fig. 9). The two rock bolts with an embedment length of 400 mm did not slip when the tests were terminated at load levels very close to the tensile strength of the bolt to avoid damage to the measurement instrument (see Fig. 5d). Thus, these two rock bolts were treated as failures in the diagram. The critical embedment length of the rock bolt for the water-cement ratio 0.50 is determined to be approximately 360 mm.

The critical embedment length of the bolt, L_c, is linearly related to the water-cement ratio, as shown in Fig. 10, as follows:

$$L_c = 110 \times (w/c) - 19.1 \tag{2}$$

and to the UCS of the grout as follows:

$$L_c = 72.5 - 1.28 \times UCS. \tag{3}$$

The critical embedment lengths derived in this section were based on the results of the pull tests carried out under strictly controlled laboratory conditions, which guaranteed satisfactory grouting qualities. The critical embedment length in the field could be longer than the laboratory-obtained value, taking into account variations in grouting quality as well as rock mass quality. Therefore, a safety factor between two and four should be used for the critical anchoring length of rock bolts in the support design (Littlejohn, 1992).

5.2. Bond strength

Bond strength, defined as the average shear strength, of the rock bolt-grout interface, is usually used to describe the binding capacity of an encapsulated rock bolt with the grout. It is calculated as:

$$s = P_{max}/\pi d_b l_o, \tag{4}$$

where P_{max} is the ultimate pull load in the case of bolt slippage in the grout, d_b is the rock bolt diameter, and l_o is the embedment length of the rock bolt. It makes more sense to plot the bond strength against the UCS of grout than the cement-water ratio because the strength of the grout is not only dependent on the cement-water ratio but also on the cement type. The average bond strengths of the rock bolts for three different grouts of UCS 32, 37, and 47 MPa are calculated according to Eq. (4) and are plotted in Fig. 11. The data for the grout of UCS 47 MPa are taken from another series of pull tests, which are plotted in the figure for the sake of comparison. The last point for UCS 32 MPa grout, marked by a circle in the figure, is the value for the rock bolts the shanks of which significantly yielded at a strain of approximately 10%. Except that point, the bond strength tends to increase with the embedment length of the rock bolt for all three types of grouts. Note that the grouting cement mortar failed in the collar of the borehole, forming a crater (see the photos in Figs. 3d and 4d). Thus, the average bond strength should be slightly higher than that presented in Fig. 11 if the effective embedment length is used for the calculation.

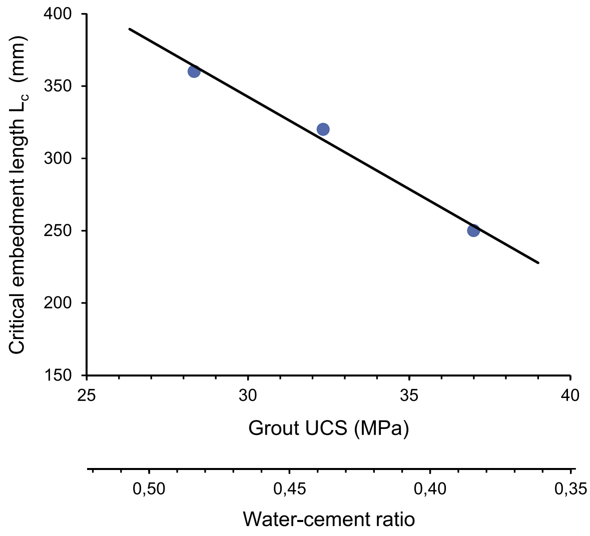

Fig. 10. Critical embedment length versus the UCS of grout and the water-cement ratio.

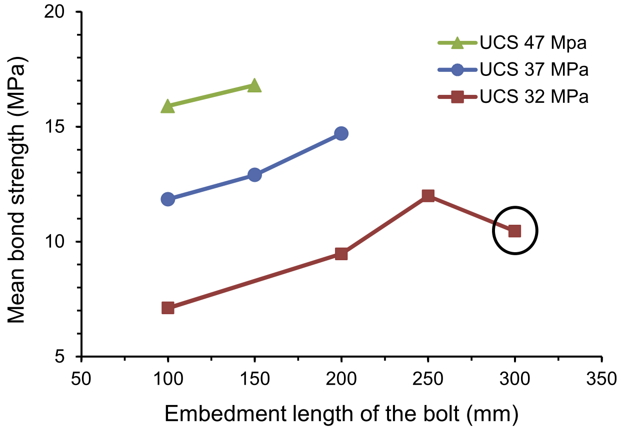

Fig. 11. The average bond strength versus the embedment length of the bolt. The circled point represents the specimen the shank of which was significantly yielded (approximately 10% strain).

It is noticed that Kilic et al. (2002) experimentally investigated the influence of the embedment length on bond strength. In their laboratory tests, the rebar bolts were 12 mm in diameter, installed in 22 mm holes with Portland cement mortar of UCS 35.5 MPa (with a water-cement ratio of 0.4). The embedment length varied from 15 to 32 cm. The bond strengths of the bolts varied in a very small interval from 7.58 to 7.98 MPa. In other words, their tests showed that the bond strength is independent of the embedment length. Further experimental tests need to be carried out to clarify whether the bond strength is dependent on the embedment length or not.

6. Conclusions

A series of pull tests were conducted to determine the critical embedment length of a specific type of 20 mm rebar bolt that is widely used for rock support in tunnels and underground caverns in Norway. It was found that the critical embedment length is linearly proportional to the water-cement ratio and the UCS of the grout. The critical embedment length is approximately 25 cm for the grout of UCS 37 MPa (water-cement ratio of 0.40), 32 cm for the grout of UCS 32 MPa (water-cement ratio of 0.46) and 36 cm for the grout of UCS 28 MPa (water-cement ratio of 0.50), for the Rescon zinc rock bolt cement used in the tests.

The bond strength is linearly proportional to the UCS of the grout. The bond strength of the rock bolt, that is, the average shear stress at the bolt-grout interface when the bolt starts to slip along the interface, does not seem to be a constant but increases with the embedment length as long as the yield strain of the bolt shank is not significantly large, for instance <10%. More experimental tests need to be carried out in the future to clarify whether the bond strength is dependent on the embedment length or not.

Acknowledgements

The authors would like to thank Mr Gunnar Vistnes and Mr Torkjell Breivik for their valuable assistance in the laboratory. The support by the Norwegian Road Authority–Statens vegvesen is gratefully acknowledged.

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