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Cement & Concrete Composites 27 (2005) 103–109

Cement & Concrete Composites

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Bond of cement grouted reinforcing bars under constant radial pressure

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Received 28 October 2003; accepted 15 December 2003

Abstract

A ribbed rebar or rock bolt, grouted with Portland cement is the most common type of reinforcement in geomechanical projects such as tunnels, rock slopes and foundations. Due to the frictional nature of the bond slip the normal stress acting on the rebar is the most important parameter controlling the bond capacity of the reinforcement. The more the confining stress, the higher would be the mobilized load bearing capacity of the system. To quantify this effect, series of laboratory tests were designed to study the effect of confining pressure on the bond capacity. A modified triaxial Hoek cell (usually used for testing the strength of rock samples under radial confining pressure) was used to facilitate application of a "constant radial confining pressure" to the grouted sample while pulling the bolt axially through the cement annulus. During test, axial load and displacement of the bolt as well as the radial dilation of the grout was recorded and stored in computer using a data acquisition system. The results show a non-linear relation between the increase of bond capacity and confining pressure. The radial dilation is quantified also as a function of confining pressure. A peak-residual behaviour is also a characteristic of these results which shows the importance of limiting the deformation of rock blocks to avoid entering into the post peak range of the reinforcement with low values of bond.

Keywords: Bond capacity; Shear strength; Pull-out strength; Deformed bar; Dilation; Portland cement; Rock bolt

1. Introduction

The idea of using steel bar as a means of reinforcement goes back to 1877 where Hyatt [2] referred to the possibility of using iron combined with Portland cement to overcome the weakness of the concrete under tensile flexure. This initiated plenty of experimental studies starting as early as 1900 which revealed that in most of the cases, the failure is not due to the excessive tension in the bar, it rather is related to slip. Therefore bond was recognized as a critical parameter in reinforced concrete design.

The widely use of a bar as a means of reinforcement in geotechnical and tunnelling projects was however delayed until later. Due to the successful use of bolts in many projects since 1940, fundamental studies on bolting action were performed both in the mining and construction fields in parallel, the most important of which is research by Gilkey et al. [1], Rabcewicz [16] and Panek [11–15], and also Littlejohn and Bruce [4].

2. Definition of bond

Bond may be defined simply as the gripping effect of an annulus (usually concrete or cement) on an embedded length of a steel bar (smooth or deformed) to resist forces tending to slide the bar longitudinally. There are contradictory ideas about whether bond is a property of the annulus or of the bar. However, there is no doubt that the properties of both (for the annulus, compressive strength and confinement and for the bar, smoothness and the shape of indentations) play important roles in developing high or low values of bond capacity. The conclusion here is that bond consists of three components: adhesion, friction, and lug resistance (or interlocking effect of the cement ribs). Each might have different roles in different conditions but the dominant effect is due to the frictional effect especially after the onset of slip. Since the slip between rebar and grout

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doi:10.1016/j.cemconcomp.2003.12.002

annulus is mainly a frictional failure, the confining (normal) stress has an important role in this load utilization. In mining situations, where the geometry of the underground excavations changes continuously, the stresses vary all the time. This can be either positive (stress increase) or negative (stress decrease) which will affect the bond capacity of the rock bolts accordingly. The impact of stress change on cable bolt performance was studied earlier by MacSporran [5].

For reinforcement with roughness on its surface when installed in a rock mass, any axial slip will generate some radial dilation depending on the roughness geometry. This lateral movement is restricted by the rock mass stiffness which surrounds the rebar. If the rock mass has a high stiffness (hard rock with no joints), the dilation will generate lateral confining pressure which results in high bond capacity of the reinforcement. On the other hand, soft rock masses specially when jointed have low radial stiffness and would not generate high confining pressures in response to the dilation. This mechanism emphasizes the importance of dilation and confining pressure when studying bond capacity of a grouted deformed bar.

The aim of this research is to describe the laboratory test program used to study this frictional–dilational effect. In the test setup, the bolt is pulled through a cement grout while a constant lateral oil pressure is applied to the sides of the sample. This is made possible by manufacturing a modified Hoek cell (usually used for triaxial testing of rock samples) to accommodate the grouted bolt sample. A similar setup was used earlier by Hyett et al. [3] but for testing cable bolts.

Reymond et al. [17], investigated the effect of a compressive stress applied to two opposite faces of a pull-out specimen in which a deformed bar was embedded in a concrete block. They pointed out that "bond strength was found to increase with normal pressure in proportion to the square root of the normal pressure when other factors are constant". Robins and Stanish [18] pulled 8 and 12 mm diameter bars from 100 mm lightweight concrete cubes laterally loaded on two opposite sides. The pull-out load increased more than 100% for lateral pressure of about 10 MPa. They noticed that additional application of lateral pressure, up to 28 MPa did not increase the axial load. Navaratnarajah and Speare [10] also reported an increase in bond capacity with increasing lateral pressure up to a limiting value on concrete samples.

The most relevant tests to the present study are tests on cement grout annulus (and not a concrete mix) under constant radial pressure which were performed by Malvar on rebars [6] and FRP samples [7]. A split pipe with a confining ring was used to apply the confinement, and opening of the ring was translated into lateral dilation assuming a uniform cylindrical expansion. The setup which is presented in the current paper facilitates the direct measurement of grout's lateral displacement (dilation) at four individual points around the sample which is quite different from the previous research works.

3. Sample preparation and testing procedure

To investigate the effect of confining pressure on bond capacity of bolts, two different types of rock bolt which are common in tunnelling practice with different diameters were considered for the research. These are 20 mm Dywidag continuous thread (CT) bar and also 22 and 28 mm ribbed rock bolts (referred to as P22 and P28 hereafter) as shown in Fig. 1. The objective was to determine the bond capacity of these bolts to axial pull while radial confining pressure was held constant.

To achieve the proper conditions for the tests, a pressure vessel was designed and manufactured (Fig. 2) similar to the one used for modified cable bolts by Moosavi [8] with the following specifications:

1. The cell was designed to withstand high internal pressure (up to 50 MPa).
2. The relatively rigid bladders (which are usually used in triaxial tests of rock samples) were replaced by a

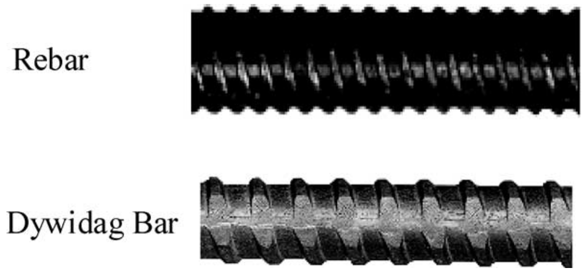

Fig. 1. Deformed and Dywidag bars used for the tests.

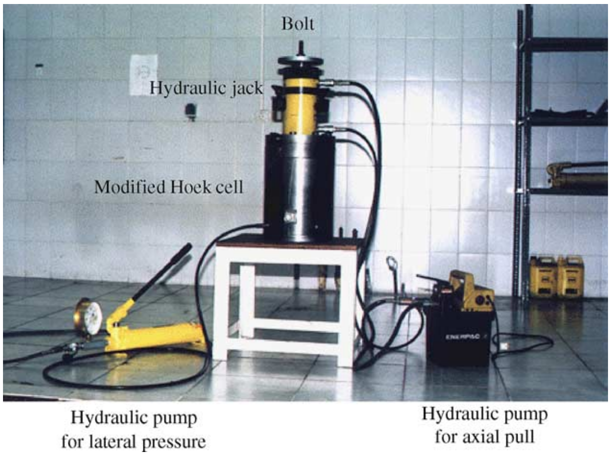

Fig. 2. Modified Hoek cell and setup for the constant radial pressure tests.

more compliant one which facilitated removal of the dilated sample and reuse of the bladder. This compliant bladder also prevented oil penetration into the grout.

3. Behind the bladder, four cantilever strain gauged arms were mounted on a collar to measure the dilation of the deformed bolt at the mid height of the sample (Fig. 3). At this level, four arms were mounted in two perpendicular sets with two opposite arms in each set.
4. The cell was designed to accommodate a sample with a diameter of 61 mm (2.5'') which is the same size of the boreholes usually used for placing the bolts in the ground.

The casting length of the sample was 300 mm, including two steel rings at the two ends. These smooth metal surfaces were meant to push against O-rings designed in the cell body to ensure sealing. The rings were placed at the proper locations inside the mould at the time of pouring the grout. Since the confining pressure was not transferable to the bar at the location of the rings, the corresponding bolt length should be excluded. PVC tubes were used to debond the bolt beneath the steel rings so the effective embedment length was 150 mm (and 100 mm in some of the tests). Sufficient extra length of bar was left free at the top of the sample to provide space for gripping the bar for pull as well as providing space for monitoring the bolt slip at the upper end.

For the tests, samples according to Table 1 were used. After the samples were taken out of the mould and prepared, they were placed into the cell. A 600 kN hollow ram hydraulic jack was put on the extra length of the bolt and was held tight using a plate and nut. The jack was then attached to a hydraulic pump. The confining pressure was then increased to the desired level and maintained constant using a side pump and valve. To measure the bolt displacement during pull an LVDT was mounted at the top and the centre of the bolt. In all stages of sample preparation, the bolt was held central with respect to the mould so no tilt was observed during pullout. With this setup true displacement of the bolt without errors due to probable slack in the system was recorded. All seven channels of data (including four readings from arms, one reading from each of load cell, confining pressure sensor and LVDT) were recorded by a data acquisition system and stored in the computer. The bolts were usually pulled to at least 25 mm so that the residual capacity of the system (post peak response) could be determined. Fig. 4 shows some of the tested

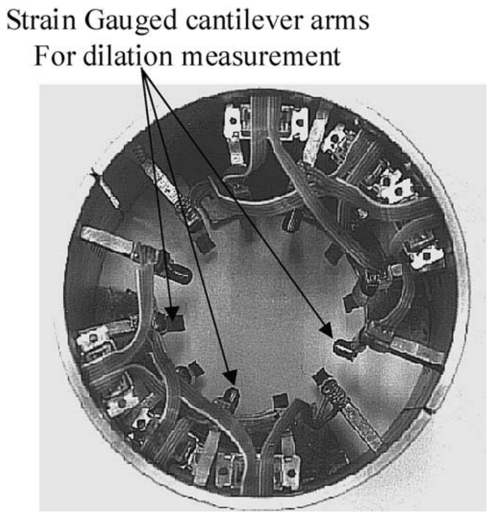

Fig. 3. Cantilever arms for dilation measurements.

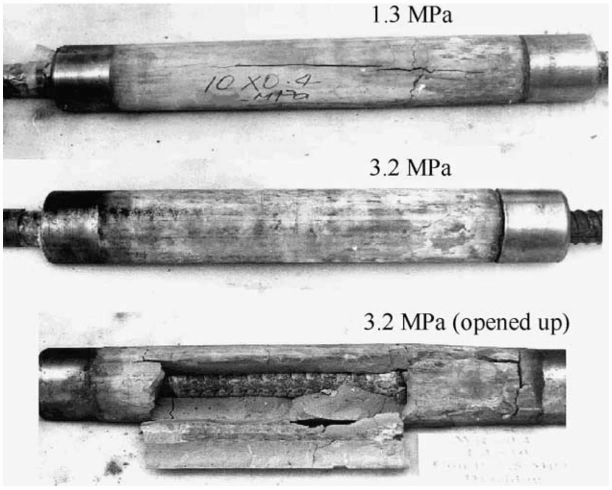

Fig. 4. Some of the tested samples.

Table 1
Number of samples tested under constant radial pressure

	Bolt type	Confining pressure (MPa)							
		1	1.5	2	3.2	3.5	5	6.4	7.5
UCS = 42 MPa	P22	3	3	4	–	3	1	–	2
	P28	–	3	2	3	–	1	–	–
	Dywidag	1	1	1	1	–	2	1	1
UCS = 30 MPa	P22	2	3	3	–	–	1	–	1
	Dywidag	1	–	1	–	–	1	–	1

samples. As it can be seen, cracks are fully developed for lower confining pressures. In this case the failure mechanism and slip is more dilational. At higher confining pressures, cracks can not fully open therefore lower dilations are generated and grout lugs are completely sheared during pullout of the bolt so the bond failure mechanism is more of a frictional type than dilational.

4. Results of the tests

As indicated in Table 1, in many cases there are more than one single test results available. In these cases, the average of these results is presented. It is also notable that each dilation graph is average of dilations recorded from four individual arms. Fig. 5 shows a sample of such averaging.

Some of the general specifications in all the tested samples are 150 mm embedment length (EL) and 2.5" diameter. The test results are presented in both load and bond capacities format to enable the user to compare bond in bolts with different diameters. The type 1 Portland cement used for the grout was a 0.4w:c mix. It is important to consider the different Portland cement qualities produced by different factories. By experience, the same type of cement produced by different factories when mixed with exactly the same amount of water may result in different strength. To avoid any misunderstanding between the strength of different cement grouts used for the tests and to enable sharing of experiences between tests performed in different research projects it is recommended to talk about the uniaxial compressive strength (UCS) of the grout samples used for the pullout tests rather than only mentioning the w:c ratio of the grout mix. In this paper two series of tests with UCS of the grout equal to 30 and 42 MPa are performed according to Table 1.

The results of the constant pressure tests on P28 and Dywidag bars (for UCS = 42 MPa) and P22 and Dywidag bars (for UCS = 30 MPa) are shown in Figs. 6–9 respectively. From the obtained results the following points can be observed:

- In load plots, there is always a peak at early stages of pull followed by a residual behaviour at higher axial displacements regardless of the level of confining pressure. After the onset of axial pull, the axial load in the bolt increases linearly to a point where divergence from elastic behaviour begins. As the confining pressure increases, this peak point in most of the cases tends to shift to the right (higher axial displacements) both in the load and dilation graphs. At this load level, radial cracks are believed to have fully

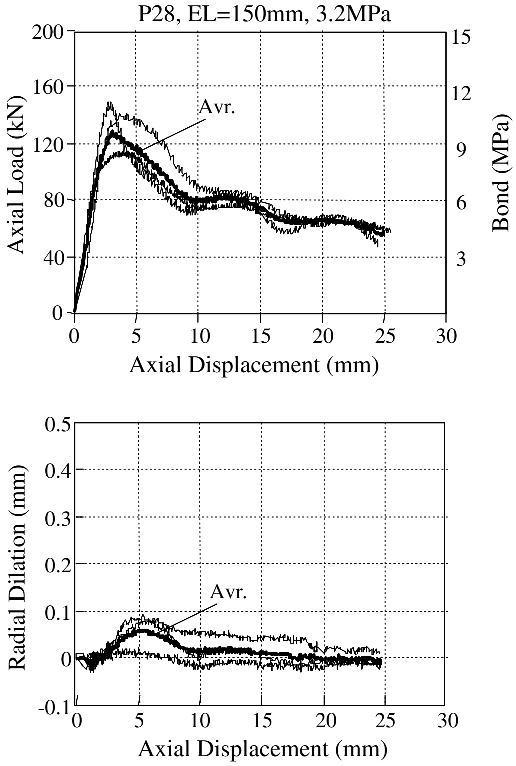

Fig. 5. Averaging three test results for P28 bolt at 3.2 MPa confining pressure.

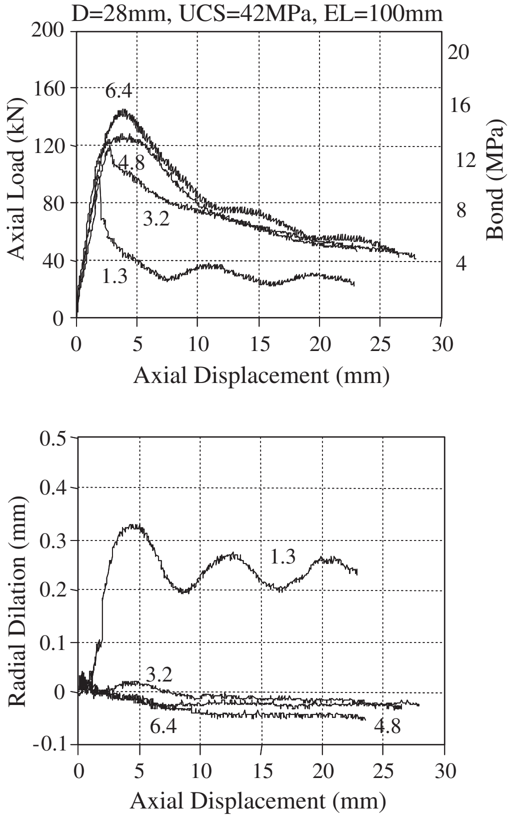

Fig. 6. Results of pull test for P28 bolts with UCS = 42 MPa for the grout.

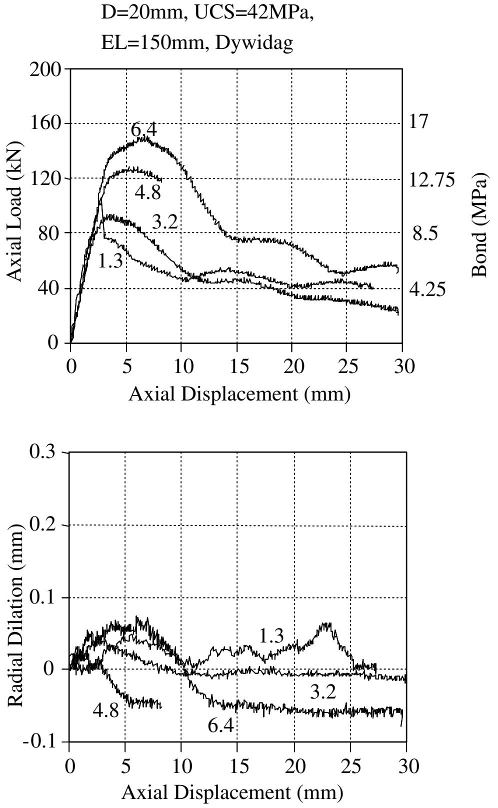

Fig. 7. Results of pull test for 20 mm Dywidag bar with UCS = 42 MPa for the grout.

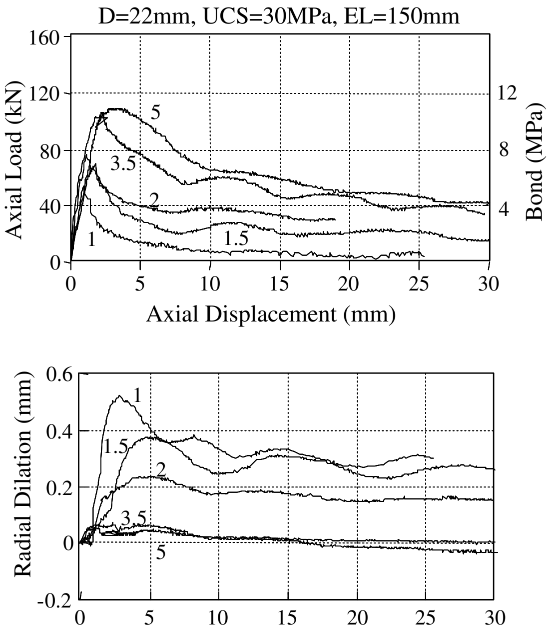

Fig. 8. Results of pull test for P22 bolts with UCS = 30 MPa for the grout.

developed in the sample and, as a result, bond strength begins to decrease.

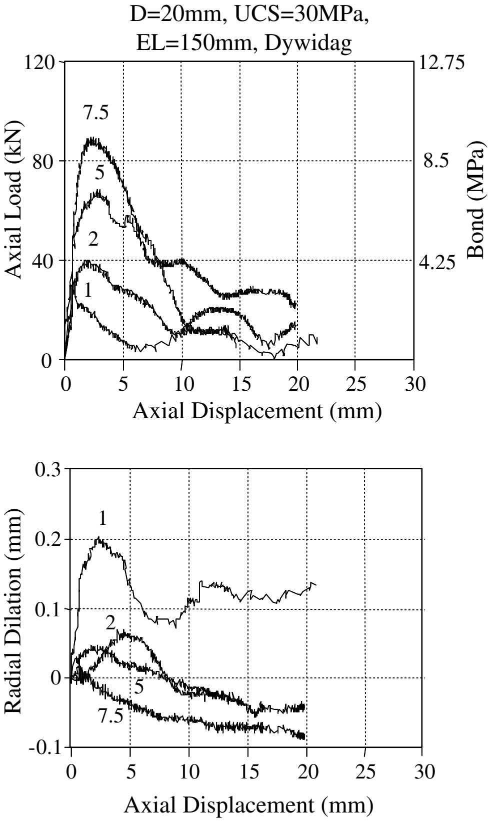

Fig. 9. Results of pull test for 20 mm Dywidag bar with UCS = 30 MPa for the grout.

- The results of pullout test for P22 and Dywidag bars grouted with a lower quality annulus shows the same trend for load and dilation but with lower values. This emphasizes the importance of grout quality control in installation phase to obtain better reinforcement performance.
- As expected, the mobilized load in the bolt increases with increasing confining pressure while radial dilation decreases, although the pressure dependency is not linear, particularly at higher pressures. This trend is shown in Fig. 10 for different bolt types and grout strengths.
- When the bolt is pulled, the ribs pass under the arms. The arms record an outward movement as each rib passes by. The spacing between the peaks in the dilation graphs is in very good agreement with the spacing of the ribs in both deformed bars (8 mm) and Dywidag bars (10 mm). The lateral movement of the arms goes from dilation to contraction after the bolt passed quite enough distance through the cement grout in the post peak region. Since the bond capacity decreases in post peak, one should avoid situations with large rock movements which can result in low bond capacity and hence insufficient load bearing capacity of the bolt.
- Much lower lateral dilation results are obtained in these tests compared to those recorded using

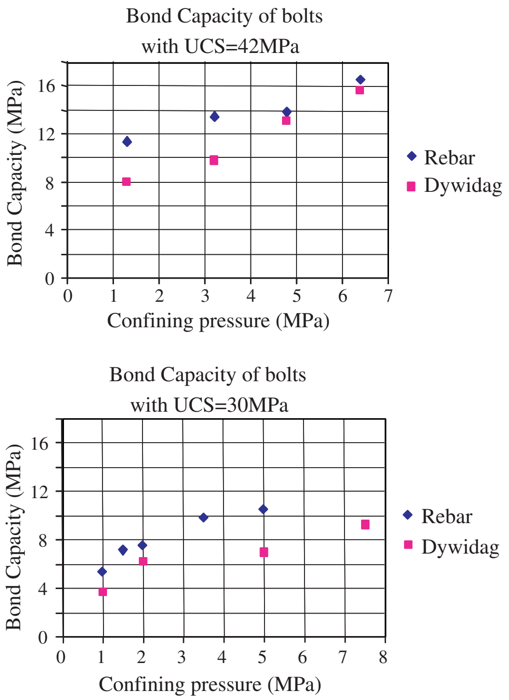

Fig. 10. Pressure dependency of the bond capacity.

modified cable bolts (such as Garford Bulb) tested earlier [9] shown in Fig. 11. Therefore the use of deformed bars might not be as effective as modified cables in soft and low quality rock masses which require large radial deformations to generate enough confining pressure for the reinforcement.

- From the same figures, it can be concluded that bond capacity is generally lower for Dywidag bars compared to the same diameter rebar. This is believed to be associated with the two flat sides with no ribs on this type of bolt as shown in Fig. 1. On these surfaces, slip occurs at steel-grout interface which is a low friction surface compared to the rest of the bolt which slips at grout–grout interface with higher friction angle. For the same reason, the total generated dilation in these bolts is usually lower compared to that of deformed rebars.

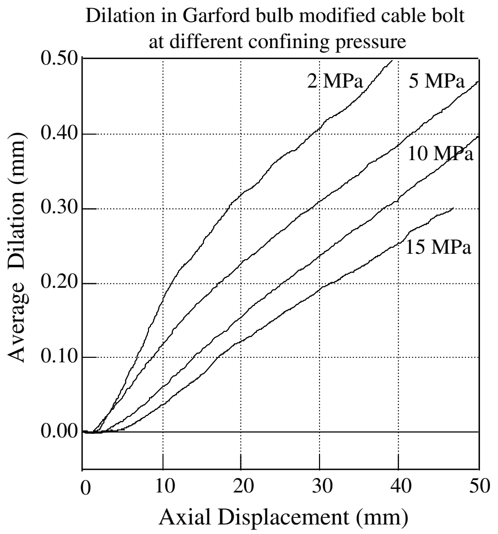

Fig. 11. Dilation of grouted modified geometry Garford bulb cable bolt after [9].

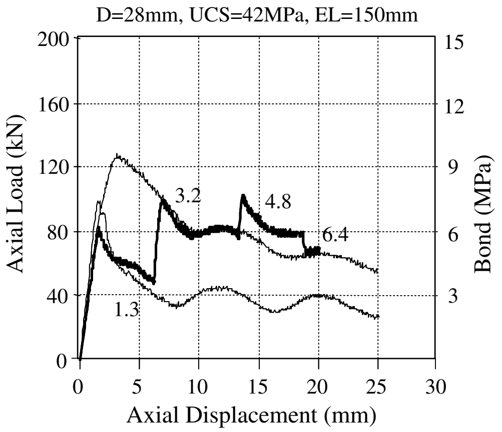

Fig. 12. Variable pressure test for path-dependency control.

- A test with variable lateral pressure was also performed to study the path-dependency of bond capacity to pressure change. Test started at 1.3 MPa confining pressure and bolt was pulled till 7 mm and stopped. Then the pressure was increased to 3.2 MPa and pulling continued for another 6 mm. This sequence was repeated for 4.8 and 6.4 MPa confining pressures as shown in Fig. 12. The load-displacement curves for 1.3 and 3.2 performed individually are also included in the figure for comparison. As it is clear, the bond capacity for each level of confining pressure lies on one another as long as we are in the residual part of the graph. Therefore no matter how we get to a level of confining pressure, the bond capacity would be the same. This is an important observation which can simplify some aspects of modelling fully grouted bolts in numerical analysis methods (such as finite element method).

5. Conclusions

A special test setup was designed to study the bond capacity of three types of bolts under "constant radial stress" boundary conditions. In these tests, measurement of generated dilation was made possible which is a key parameter controlling the bond capacity. Higher bond results and lower generated dilations were measured in each test with increasing confining pressure. The pressure dependency of the bond capacity and radial dilation is quantified. Lower quality grouts will generate fewer amounts of dilation as well as lower bond capacities which emphasize the importance of quality control while grouting. Based on the test performed at variable radial pressure condition, no path dependency was observed for bond capacity which can simplify the simulation of such reinforcements in numerical programs.

Acknowledgements

Financial support of this research program is provided by Tehran University, which is acknowledged. Cooperation of the rock mechanics laboratory in performing the tests in the Mining Engineering Department is also very much appreciated.

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