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Shear strength of Portland cement grout

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Abstract

The direct shear test program described in this paper determined the shear strength parameters of Portland cement grout with 0.4 and 0.5 w:c ratios. The test set-up facilitated applying different levels of normal pressure on the shear plane which led to the determination of pressure dependency of the shear strength parameters. Dilation and contraction of the samples during shear was carefully measured using a servo controlled MTS system. The peak-residual form of the shear graphs is similar to results of often obtained in pull-out tests with deformed bars and steel cables embedded in Portland cement grout. Comprehensive understanding of shear strength of cement grout can result in more effective design of fully grouted reinforcements such as grouted bolts, cables and tendons.

Keywords: Bond strength; Shear strength; Pull-out strength; Mechanical properties; Cement; Deformed bar; Steel cable; Dilation

1. Introduction

The stability of underground excavations during and after construction is the main concern of geomechanical design engineers since any instability problem may cause damage as well as additional cost. Rock masses contain natural discontinuities which may cause stability problems, therefore most underground openings need to be stabilised to maintain their integrity during their service life. As stated by Hoek and Brown [1], "The principal objective in the design of underground excavation support is to help the rock mass to support itself". The best way to achieve this is through the use of reinforcement to help maintain the load-carrying capability of rock masses near excavation boundaries. Fully grouted reinforcements (such as rebars and steel cables) are popular types of reinforcement in rock engineering projects, and Portland cement grout is the most widely used agent to bond this to the surrounding rock mass. Therefore a more detailed understanding of the shear strength properties of cement grout seems to be the key parameter for the optimal design of reinforcing systems.

Early works by Moosavi [2,3] on the bond failure mechanism of grouted rebar and cable bolt revealed that "cement shearing" is the key parameter controlling the behaviour of such reinforcements during axial pull-out through the annulus. A series of tests on deformed bars and modified geometry cable bolts (Fig. 1) proved that a complete explanation on the stages of a pull-out test curve can be described by the shear behaviour of the grouting agent i.e. the cement annulus. Following this conclusion the importance of determining the mechanical properties of Portland cement grout was revealed. Although numerous researches have been performed on the mechanical properties of concrete, less work has been focused on the mechanical properties of cement grout without any aggregates. Such examples are the research by Domone and Jefferis [4] and also studies performed by Hyett et al. [5] and Hutchinson and Diederichs [6] with emphasis on the corresponding effects on cable bolting performance.

As clearly shown in Fig. 1, there is an exposed area of cement captured within the ribs of the bar and within the deformed structure of the cable. During pull, these grout bridges must shear on the predefined plane determined by the geometry of the reinforcement. The

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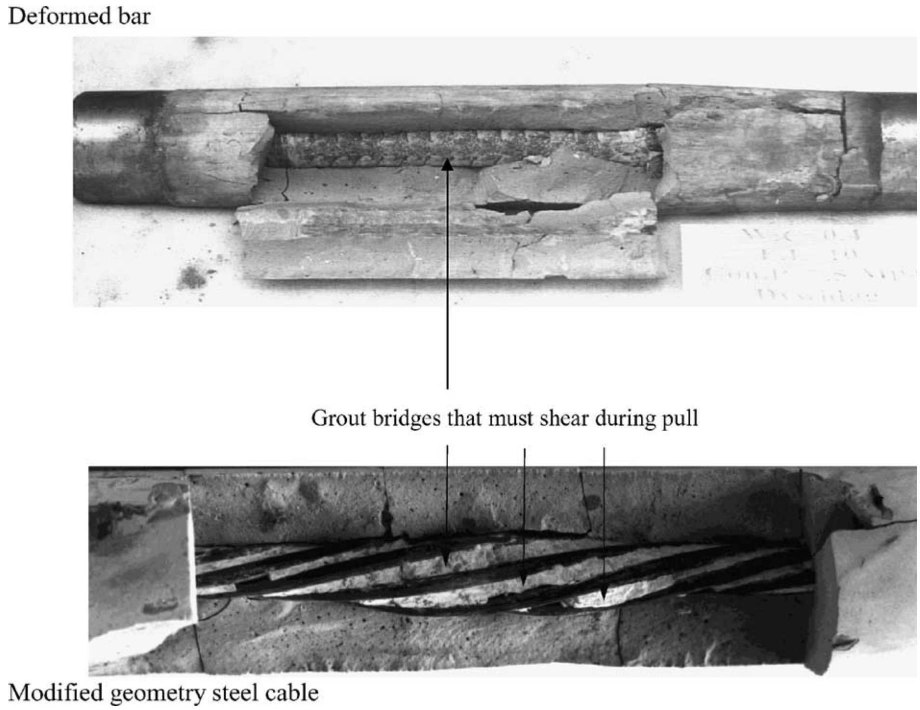


Fig. 1. An open view of a cable bolt (top) and a deformed bar (bottom) sample after pull test.

mechanism here is therefore shearing across the grout annulus and this has a significant effect on the overall response of the reinforcement.

Since in the tested samples, grout was forced to fail on a "predefined" shear plane (the interface between reinforcement and cement), obtaining shear parameters of the grout (C and ϕ) from triaxial tests (in which the cement annulus behaves more ductile and barrels at failure instead of generation of a distinct shear plane) is not recommended. Therefore, direct shear test set-up seemed to be a better representative of failure mechanism.

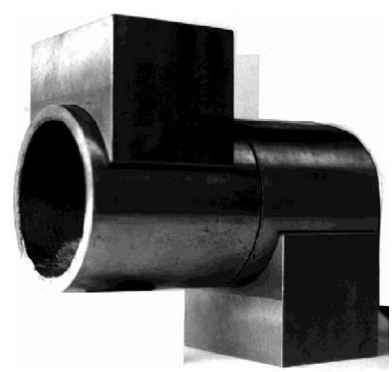


Fig. 2. Designed shear box for the experiments.

2. Experimental program

Shear tests were performed on grout cylinders 100 mm in diameter and 200 mm in length. Samples were poured at 0.4 and 0.5 w:c ratio grouts and were tested after 28 days of curing. A shear box was designed and manufactured to facilitate the shearing of the sample while a hydraulic jack was applying a normal stress to the specimen (Fig. 2). In these tests the normal pressure was varied from 2–50 MPa to investigate the dependency of the shear strength on this. The number of tests performed at each normal pressure is summarized in Table 1. The samples had a uniaxial compressive strength of 50.6 and 40.3 MPa for 0.4 and 0.5 w:c ratio grouts respectively.

Table 1
Number of shear tests for each normal pressure

	2 MPa	5 MPa	10 MPa	20 MPa	30 MPa	40 MPa	50 MPa
0.4	1	3	3	4	4	2	3
0.5	4	4	4	4	3	3	–[a]

[a] Normal stress exceeded the UCS of the grout.

Fig. 3. The components of the direct shear test. (1) MTS loading frame, (2) stationary head, (3) actuator head, (4) hydraulic jack for normal load, (5) steel blocks, (6) rollers, (7) shear box, (8) bearing plates.

A stiff MTS loading frame (4000 kN) was used to apply the shear displacement with a hydraulic jack bearing against its walls applied the normal pressure to the sample (Fig. 3). The magnitude of this pressure had to be controlled and kept constant during each test. To ensure that the normal pressure remains constant as well as to measure the dilation (or contraction) of the shear plane during test a second hydraulic jack was placed in a second MTS machine (under load control condition) and connected directly to the jack (Fig. 4). This means that in response to the sample dilation (or contraction) during shear test, the second MTS relaxes (or compresses) the jack to accommodate a volume of oil proportional to the sample's dilation (or contraction). Thus, during the test, oil migrates from the cell to the jack, ensuring constant load in the jack (and as a result, constant normal pressure on the shear plane). Using this arrangement, the normal pressure was kept constant within 0.5% accuracy. In this arrangement, the volume change associated with the movement of the second MTS actuator facilitated the calculation of the sample's dilation.

3. Results and discussions

In Fig. 5, a sample is shown before and after shearing. In this, a rough horizontal shear plane is formed under low normal stress (i.e. 2 MPa) and also inclined tension cracks are created in the two halves of the sample. The results are summarised in Fig. 6. Some of the most important features of these results are:

- Higher shear stresses are obtained from stronger grout (0.4 w:c) as one would expect. The dilation results are similar for both grouts but greater contraction is obtained for 0.5 w:c grout.
- The shear strength increases with increasing normal pressure, but not linearly.
- Typically, a rapid rise of shear stress to a maximum value (τ_p) is followed by a gradual decrease to

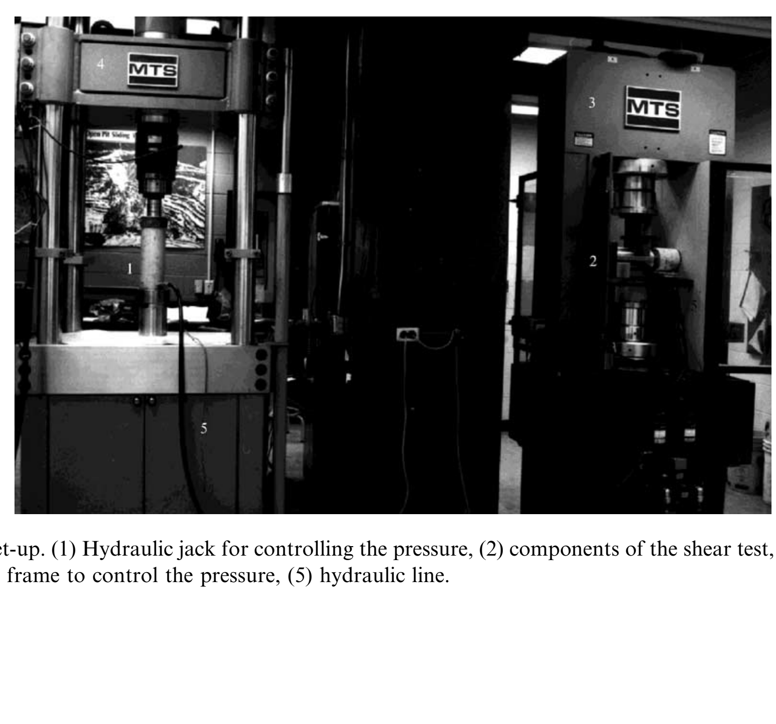
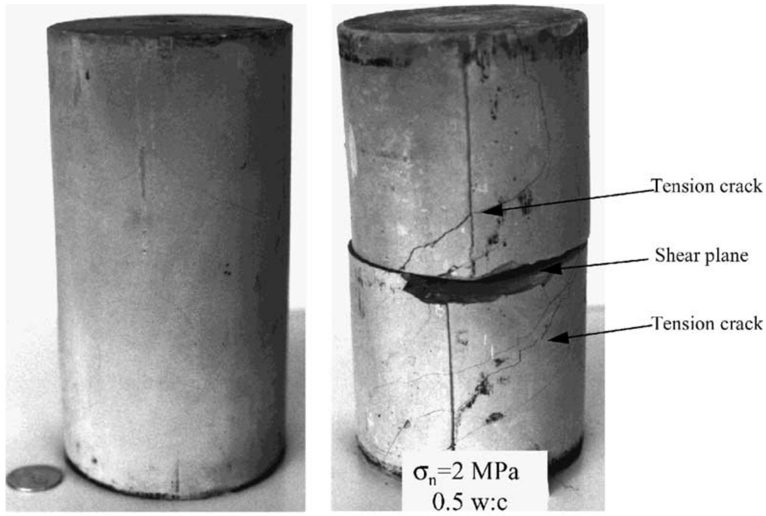


Fig. 4. The direct shear test set-up. (1) Hydraulic jack for controlling the pressure, (2) components of the shear test, (3) MTS loading frame to shear the samples, (4) MTS loading frame to control the pressure, (5) hydraulic line.



Before test After test

Fig. 5. A sample before and after shear test.

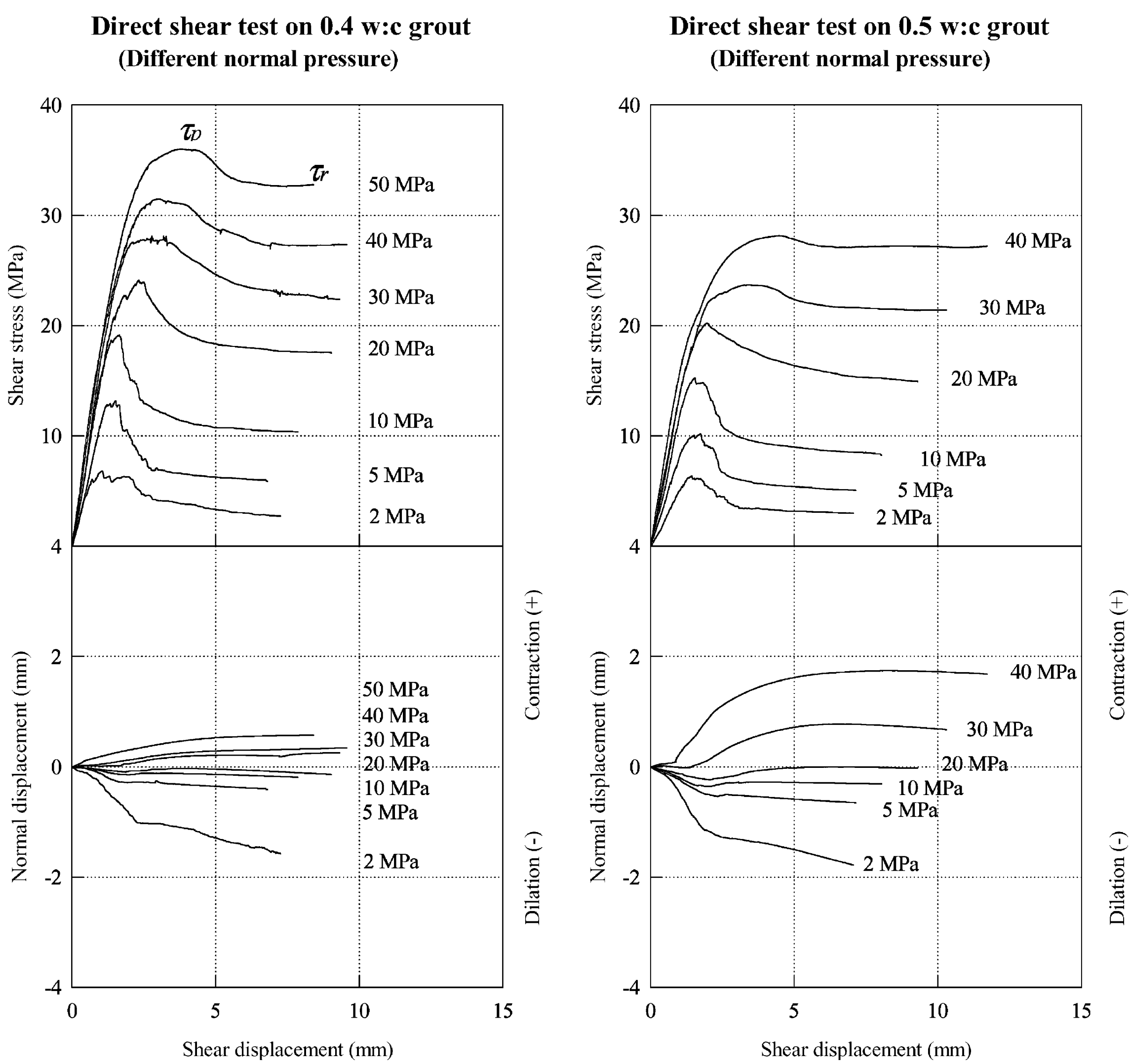
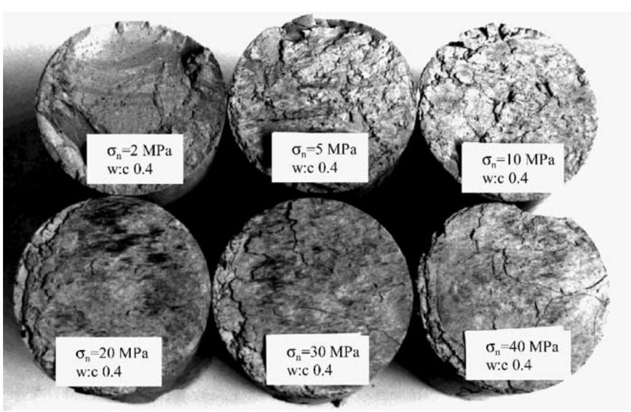


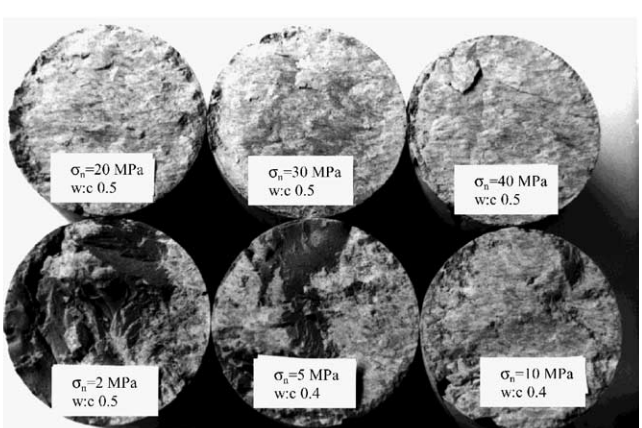
Fig. 6. Results of direct shear tests on 0.4 (left) and 0.5 (right) w:c ratio grouts.

a residual level (τ_r) after large shear displacements. Similar to the shearing of a rock joint, the maximum rate of dilation (ratio of lateral displacement to the axial displacement) closely coincides with the mobilisation of peak shear strength and vanishes at the residual stage. The amount of dilation depends on the surface roughness, the strength of the cement grout and also the level of normal stress. At higher normal stresses, the irregularities are sheared off and dilation decreases, resulting in a curved peak shear stress plot. This behaviour is reflected both in lower gradients of the dilation graphs as well as in the pictures taken from the samples after the test (Fig. 7).
- The peak shear displacement is greatly influenced by the normal stress and shifts to the right at higher stresses.

Plotting the results in shear stress–normal stress space shows that the relation between both peak and residual shear strength and normal stress is not linear (Fig. 8).



w:c samples 0.4



w:c samples 0.5

Fig. 7. Comparison between the formed shear planes at different normal pressures. 0.4 (top) and 0.5 (bottom).

This non-linearity is more pronounced for low normal stresses, implying that the use of linear Mohr–Coulomb failure criteria for the cement annulus is only justifiable at high normal stresses.

The non-linearity observed in the tests have been previously addressed by other researchers for concrete such as Untrauer and Henry [7], Robins and Standish [8], Navaratnarajah and Speare [9] and Malvar [10,11]. For example, a square root function was found appropriate by Untrauer and Henry [7]. The same type of function provides a reasonable fit to the peak and residual stresses obtained for a 0.4 w:c ratio grout (solid lines in Fig. 8) and takes the form of:

$$\begin{aligned} \tau_p &= 3.33 + 4.25\sqrt{\sigma_n} \\ \tau_r &= 3.9\sqrt{\sigma_n} \end{aligned} \quad (1)$$

however, for the 0.5 w:c ratio grout, a linear function provides a better fit to the residual stress data. These equations are:

$$\begin{aligned} \tau_p &= 0.65 + 4.33\sqrt{\sigma_n} \\ \tau_r &= 0.72\sigma_n \end{aligned} \quad (2)$$

A linear fit to the data for results at normal stresses higher than 5 MPa returns values for cohesion and friction angle (summarised in Table 2) comparable to those reported by Hyett et al. [5].

The triaxial test results performed by Moosavi [2] are compared with the direct shear test results for 0.4 and 0.5 w:c ratio grouts in Fig. 9. Shear strength results obtained from direct shear tests are always lower than those achieved from triaxial ones. This is most likely due to the different boundary conditions in the two testing systems. In triaxial tests, the sample is always under compression during the test but in direct shear tests tensile cracks can generate in two halves (Fig. 5) which will contribute to the early development of the shear plane. This effect becomes more significant at lower normal stresses which is reflected in Fig. 9 by a notable divergence between the two data set below 10 MPa normal stress. Although in some applications it might be more accurate to use the triaxial results, for the problem under investigation (with a predefined shear plane) the direct shear test results seem more realistic.

A direct shear test was also performed at 30 MPa normal pressure on a 0.4 w:c sample with a pre generated saw-cut plane. The objective was to determine the angle of friction of the grout. Slip started at about 10 MPa shear stress with a friction angle of 18.5° (Fig. 10). As in the general case for smooth surfaces, the so called "stick-slip" phenomenon was observed. The shear stress steadily increases up to a point at which a sudden slip occurs between the surfaces, which subsequently lock together. Following the initial slip, the shear stress

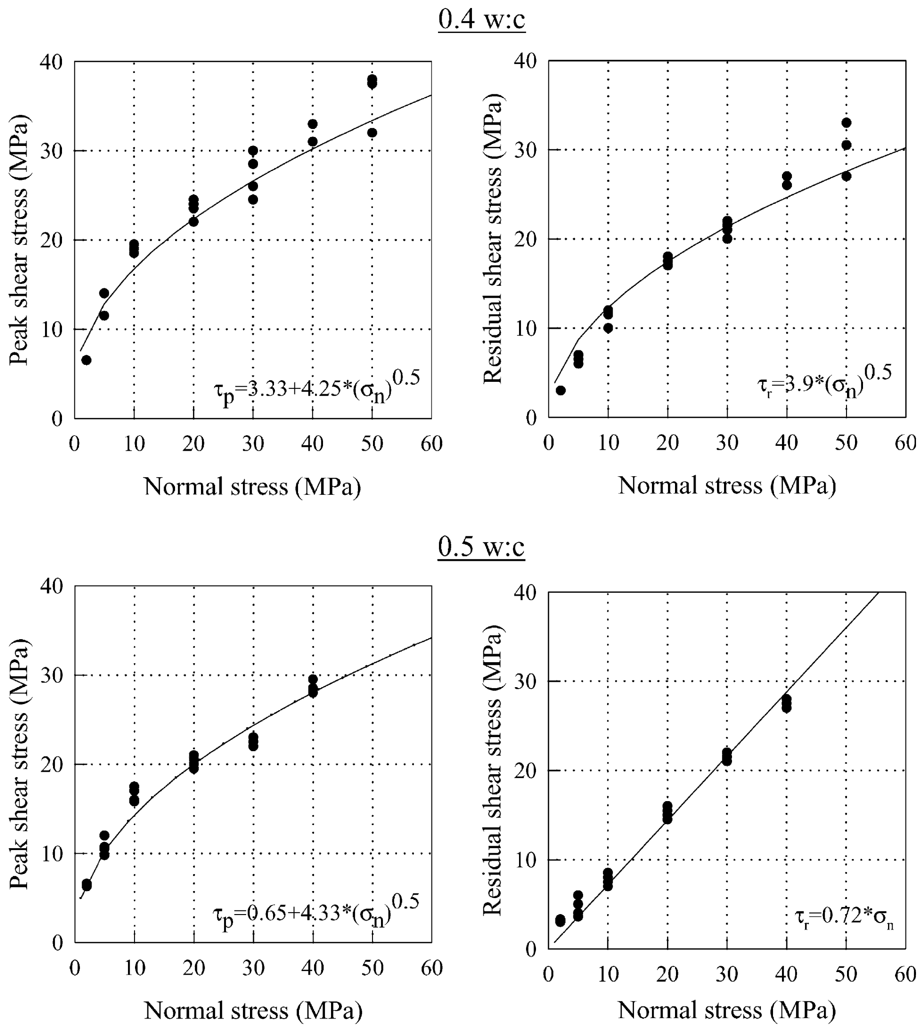


Fig. 8. Shear stress–normal stress relation for 0.4 and 0.5 w:c grouts.

Table 2
Cohesion and friction angle of the grout

w:c	Cohesion (MPa)		Friction (°)	
	Peak	Residual	Peak	Residual
0.4	15.3	5.6	22.3	28.3
0.5	11.2	2	22.8	32.4

gradually increases which is attributed to the continuous damage to the shear plane. As expected, minimal dilation was observed.

4. Conclusions

1. Thicker grouts and higher normal stresses increase the shear strength of the grout, as one would expect. The increase with normal pressure is nonlinear.
2. Although the dilation is similar for 0.4 and 0.5 w:c grouts, with increasing normal pressure, more contraction is observed in thinner grout samples.
3. The slope of the shear stress–shear displacement curve is almost independent of the level of normal stress, but the peak shear strength occurs at higher shear displacements.
4. Due to the non-linear shape of the τ–σ_n curve, specially at lower normal pressures, a linear Mohr–Coulomb failure criteria can be used only at high normal stresses. The equations given in the paper

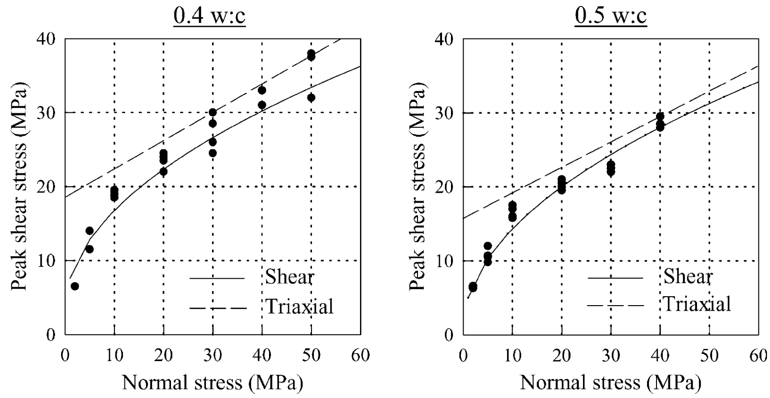


Fig. 9. Comparison between obtained results from triaxial and direct shear tests.

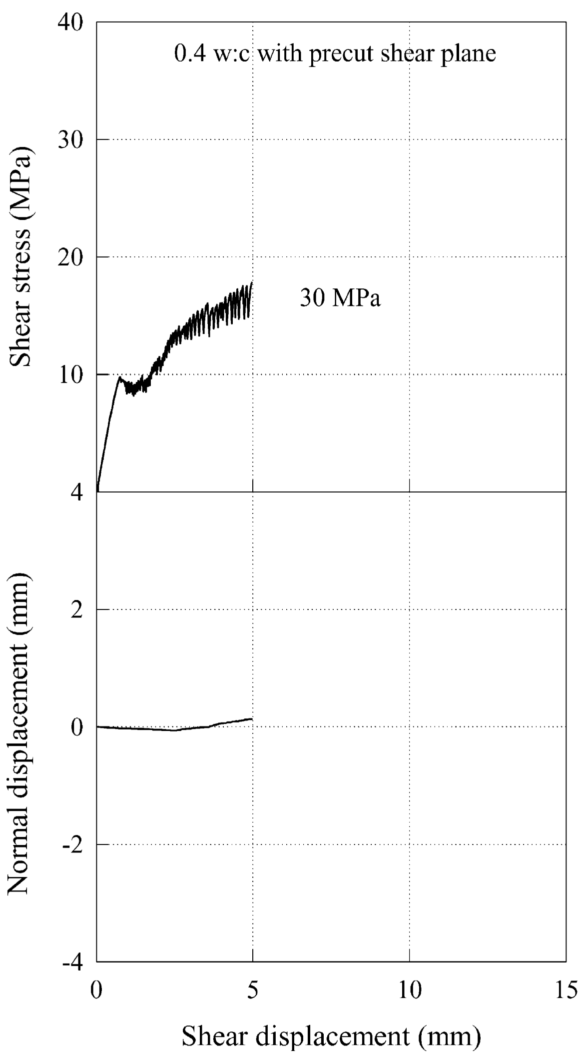


Fig. 10. Direct shear test on a sample with a precut shear plane (0.4 w:c and 30 MPa normal pressure).

can be used to estimate the instantaneous values of C and ϕ parameters at any specific level of normal stress.

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References

[1] Hoek E, Brown ET. Underground Excavations in Rock. UK: Institution of Mining and Metallurgy; 1980.
[2] Moosavi M. Load distribution along fully grouted cable bolts based on constitutive models obtained from a modified Hoek cell. PhD thesis, Canada, Queen's University, 1997.
[3] Moosavi M, Jafari A, Khosravi A. A laboratory study on bond failure mechanism in deformed rock bolts using a modified Hoek cell. Second Asian Rock Mechanics Symposium (ARMS), China, 2001.
[4] Domone PLJ, Jefferis SA. Structural Grouts. London: Chapman and Hall; 1994. 222 pp.
[5] Hyett AJ, Bawden WF, Coulson AL. Physical and mechanical properties of normal Portland cement pertaining to fully grouted cable bolts. In: Proceedings of Rock Support in Mining and Underground Construction. Rotterdam: Balkema; 1992. p. 341–8.
[6] Hutchinson DJ, Diederichs M. Cable bolting in underground hard rock mines. Canada: Geomechanical Research Center; 1995.
[7] Untrauer RE, Henry RL. Influence of normal pressure on bond strength. ACI Journal Proceedings 1965;62(5):577–86.
[8] Robins PJ, Standish IG. Effect of lateral pressure on bond of reinforcing bars in concrete. In: Bond in Concrete, Proceedings of the International Conference Paisley College of Technology, Scottland. Essex: Applied Science Publishers; 1982. p. 262–72.
[9] Navaratnarajah V, Speare PR. Theory of transfer bond resistance of deformed reinforcing bars in concrete under lateral pressure. Magazine of Concrete Research 1987;139(140):161–8.
[10] Malvar LJ. Bond reinforcement under controlled confinement. ACI Materials Journal 1992:593–601.
[11] Malvar LJ. Tensile and bond properties of GFRP reinforcing bars. ACI Materials Journal 1995:276–85.