Rock Mech Rock Eng (2013) 46:1237–1246
DOI 10.1007/s00603-013-0380-0

TECHNICAL NOTE

Adhesion Strength at the Shotcrete–Rock Contact in Rock Tunneling

Moorak Son

Received: 14 August 2012 / Accepted: 25 January 2013 / Published online: 16 February 2013

Keywords Rock tunnel · Shotcrete liner · Shotcrete–rock contact · Tensile test · Adhesion strength

1 Introduction

An increasing number of tunnels have been constructed worldwide for a diverse range of infrastructure projects, including highways, subways, railways, and various utilities. As a result, tunnel engineers are increasingly aware of the importance of safe and economic tunnel construction. Peck (1969) addresses the following three issues in terms of tunnel construction: maintaining stability and safety during construction, minimizing unfavorable impacts on third parties, and performing the intended function over the life of a project. Among these issues, the first is directly related to the behavior and stability of the tunnel support system.

In rock tunneling, the New Austrian Tunneling Method (NATM) is a widely used tunneling method in which the shotcrete liner acts as the main support. Shotcrete is sprayed on the tunnel excavation surface very shortly after being excavated and supports the ground load in conjunction with the rock bolt and the steel rib.

Barrett and McCreath (1995) explained the failure modes for the shotcrete liner (Fig. 1). It has been shown that the behavior of the shotcrete liner is highly dependent on the adhesion strength at the shotcrete–rock contact. For example, if this strength is sufficient enough, then the mode of failure may be a direct shear failure. Otherwise, the shotcrete liner may fail under a flexural condition. In addition to the behavior of structural characteristics, sufficient adhesion strength can merge the surrounding ground and the shotcrete liner into a single body, increasing tunnel stability. Therefore, the adhesion strength at the shotcrete–rock contact can influence the failure mode for the shotcrete liner, which, in turn, can impact the overall tunnel stability. This indicates a need for a better understanding of this adhesion strength.

An adhesion strength test method (Swedish Standard 1987) from Sweden drills two circular slots with a double-diamond drill. Here, the inner circular slot is drilled through the substrate and shotcrete, and the test equipment is attached to the shotcrete drill core for the pullout test. The test method can be used only for relatively stiff shotcrete. Brennan (2005) explains a shotcrete bond test method from the International Concrete Repair Institute (ICRI). This method uses a core bit to drill the applied shotcrete and substrate, and then attaches a rigid steel disk to the top of the core by using epoxy. Then, the test equipment applies some tensile load to the disk until it fails. This test method is similar to the direct test of tensile bond strength by the American Concrete Institute (ACI 2004) or the American Society for Testing and Manuals (ASTM 2004). A thin spray-on liner (TSL) has been developed and used in the mining industry since the 1990s. Ozturk and Tannant (2010) compare various adhesion test methods based on TSL and suggest a pulloff test of an elevator bolt (33 mm in diameter) attached to the liner with strong epoxy. This test uses a thin-walled diamond core bit to isolate the test area by overcoring. Ozturk (2012) provides a method for calculating the liner–substrate adhesion

M. Son (✉)
Department of Civil Engineering, Daegu University, Jillyang, Gyeongsan, Gyeongbuk 712-714, South Korea
e-mail: mson@daegu.ac.kr

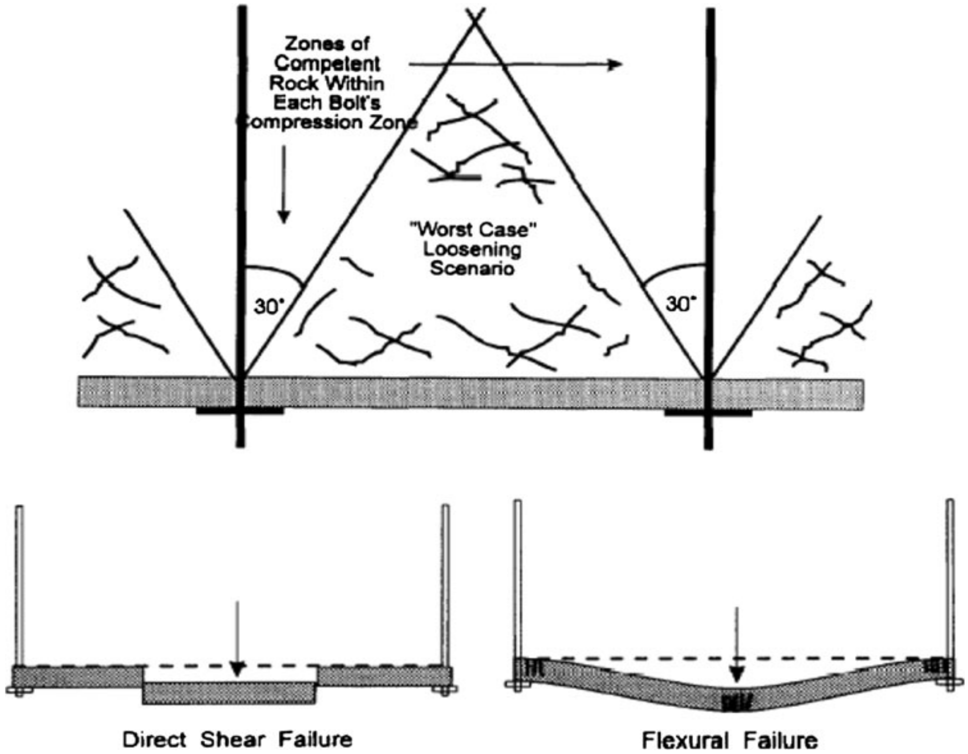


Fig. 1 Modes of failure in the shotcrete liner (Barrett and McCreath 1995)

strength based on the calculation of the energy required to peel the liner away from the substrate.

Kuchta (2002) investigated the effects of a surface treated with high-pressure water on the adhesion strength of shotcrete and found increased strength for the treated surface. Malmgren et al. (2005) examined the effects of age and surface treatment (scaling and cleaning) on the adhesion strength of shotcrete and found much greater adhesion strength for rock surfaces scaled by the water jet compared to those treated with mechanical scaling followed by the cleaning of the rock surface. Ozturk and Tannant (2011) investigated the effects of substrate properties (tensile strength, roughness, and grain size) and surface contaminants (oil and dust) on the adhesion strength and found that surface contaminants reduced the adhesion strength and that, the larger the grain size, the greater the strength of the liner's adhesion to the substrate. In addition, they determined that substrate roughness did not increase the adhesion strength and that the chemical reaction between the rock grain matrix and the liner material was more important in achieving adhesion strength than mechanical interlocking.

This paper focuses on the shotcrete liner sprayed on the rock surface and describes the overall test procedure. The paper compares the results for various test methods, including direct and indirect tensile tests (split and flexure tensile tests). The test procedure and results provide useful information for tunnel construction and maintenance.

Fig. 2 Mold preparation and placement in a tunnel

2 Preparation of Test Specimens

The most ideal and practical method for testing the adhesion strength at the shotcrete–rock contact is either a direct test of the tunnel surface after shotcrete is sprayed or that of core specimens obtained from the tunnel surface. Although such methods are practical and standard in many

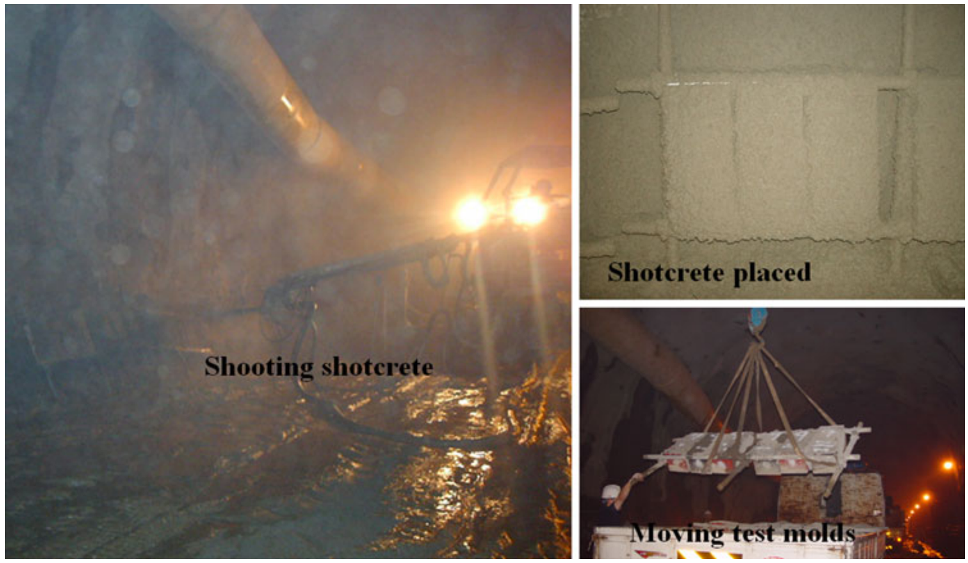


Fig. 3 Placing shotcrete and moving test molds

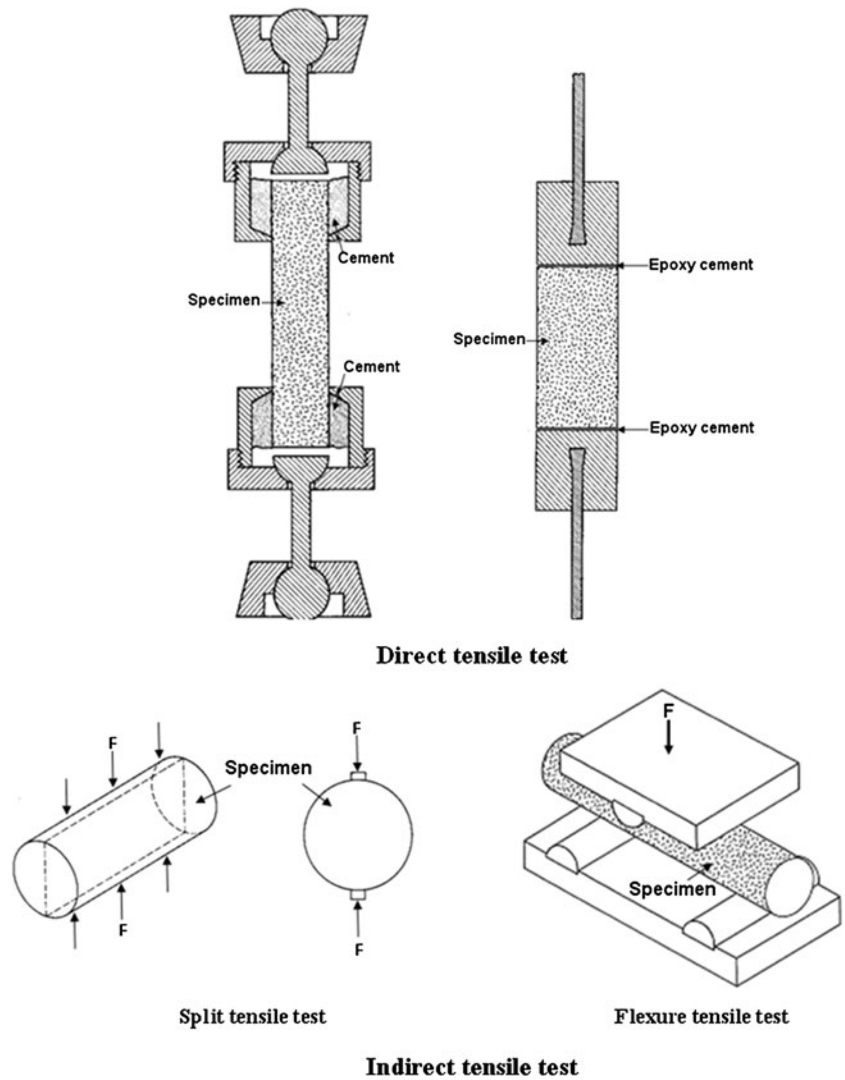
Fig. 4 NX coring for test specimens

countries (e.g., the Swedish Standard SS 13 72 43; 1987), some studies such as Ahn et al. (2004) prepare shotcrete/rock test specimens in a laboratory by placing a rock specimen inside a form and then simply pouring a shotcrete mix on the surface of the specimen to conduct indirect tests such as the split tensile test because of the inconvenience of conducting a field test, the concern over structural integrity as a result of coring, and other reasons. However, test specimens prepared in this way and the indirect test cannot reliably represent the adhesion strength induced by pressurized shotcrete shooting on the rock surface.

For a more realistic condition for shotcrete shooting, a total of 60 steel cube molds (25 cm deep × 50 cm long × 20 cm wide) are prepared for the tests of the adhesion strength and other studies, including the effects of deterioration in harmful environments.

Among these molds, 28 are made to be empty only for shotcrete shooting and the remaining 32 are filled to half its depth with rock specimens for shotcrete shooting on the rock specimen (Fig. 2). The rock is granite, and the rock specimen surface is created by artificial cracking with a chisel to represent roughness and waviness similar to the characteristics in the field. The rock specimens are cut to the size of the mold and placed inside the mold such that the rough and wavy surface is on top. The thickness of the specimen is approximately 10 cm. All molds were taken to a tunnel under construction and placed one by one along the tunnel sidewall near the tunnel excavation face (Fig. 2). Cube molds are installed approximately 50 cm above the tunnel bottom by using the clamped steel pipe frame because the bottom is muddy with water and rock fragments and because some impurities such as soil need to be prevented from becoming mixed with the test specimen during shotcrete shooting. The six molds (three empty and three filled with rocks) are placed together on the same steel pipe frame. After the molds are placed, a shotcrete-shooting machine for tunnel construction is used to spray shotcrete toward the test molds (Fig. 3). After more than 24 h at the site, the test molds are carefully transported to the laboratory. The shotcrete-filled test molds are very heavy, and pipe frames are stuck to the tunnel bottom and wall with the sprayed shotcrete. As a result, it is very difficult to move the test molds by hand, and, therefore, a

Fig. 5 Direct and indirect tensile test methods (after Obert and Duvall 1967)



five-ton crane truck is used to move them (Fig. 3). As shown in the figure, the six test molds on the clamped pipe frame are loaded onto the truck together and carefully moved to the laboratory. The test molds are cured in air over a 28-day period and then cored in NX size for testing their adhesion strength (Fig. 4).

3 Preparation of the Device for a Direct Tensile Test

As shown in Fig. 5, there are, generally, two types of tensile strength tests for rock or concrete specimens: a direct tensile test using epoxy or a particular specimen shape and an indirect tensile test (a split or flexure tensile test). Although existing test methods are widely used, they entail some cumbersome procedures and limitations. For example, in a direct tensile test, the top and bottom of a specimen are cut for a flat surface and then glued using epoxy for testing. This procedure is repeated for each test specimen and, thus, requires a substantial amount of time and effort. In addition, the procedure can have some vibration effects on the surface of the shotcrete–rock contact. Indirect tensile tests are simpler, but the loading mechanism does not reflect real conditions. To minimize the limitations of existing test methods, a device was devised for a direct tensile test. Figure 6 shows its components and assembly. The device makes direct use of a cored specimen without cutting the top and bottom of the specimen. In addition, the device uses compression test equipment instead of equipment for direct tensile testing. The procedure for using the device is as follows: a specimen extracted by a coring machine is placed in the device and clamped with the clamp nut and the clamp adapter sleeve. The sleeve is tapered to prevent the specimen from slipping out of the sleeve when the tensile load is transferred onto the specimen through the clamp system during

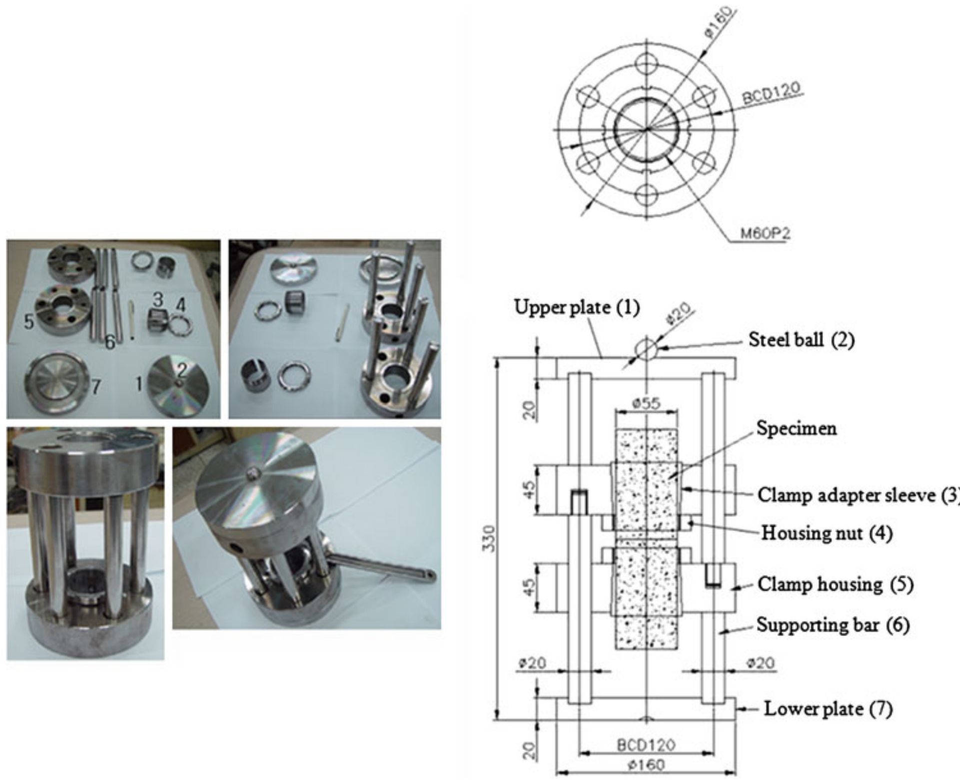


Fig. 6 Devised device for direct tensile test

Table 1 Mix design of shotcrete (wet-mix method)

Maximum size of aggregates (mm)	Slump (mm)	Water–cement ratio (%)	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Accelerator (aluminate)	Superplasticizer (kg/m^3)
13	100	34.8	454	1,127	622	5 % of cement weight	2.24

Steel fiber not included

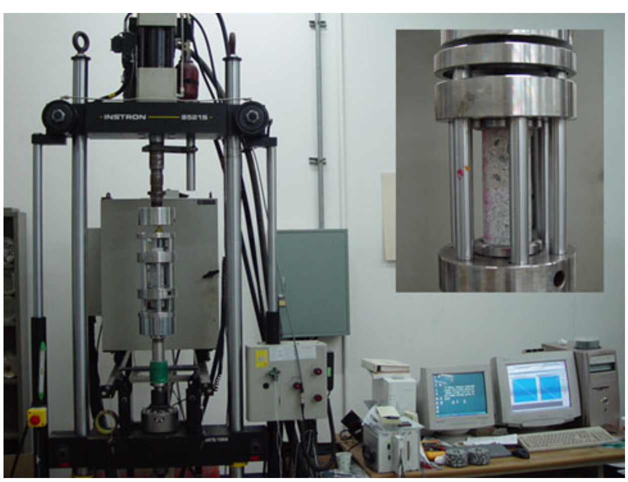


Fig. 7 Test setup for the devised direct tensile test

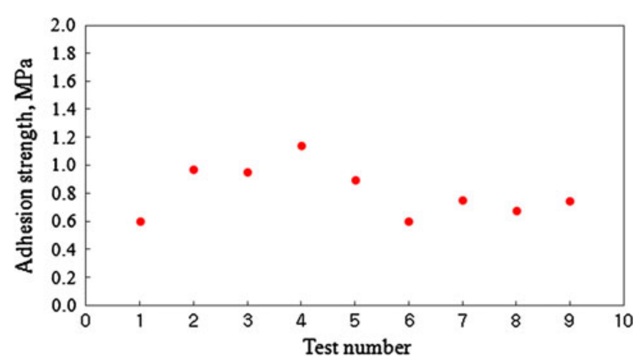


Fig. 8 Results from the devised direct tensile tests

compressive loading. The tapered sleeve increases the grabbing effect by increasing the pressure on the specimen with an increase in the tensile load. After the specimen is clamped in the assembly, the assembly is placed between the top and bottom plates, each of which has a circular groove for interposing loading transfer bars. The top plate has a steel ball on the upper side for preventing loading eccentricity. The compressive load is transferred to loading transfer bars, which push the top and bottom clamp housings, inducing some tensile load on the specimen clamped with the clamp nut and the clamp adapter sleeve. The

Fig. 9 Test setup for the direct tensile tests

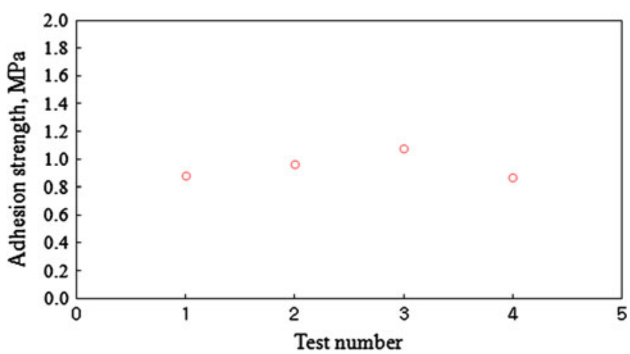
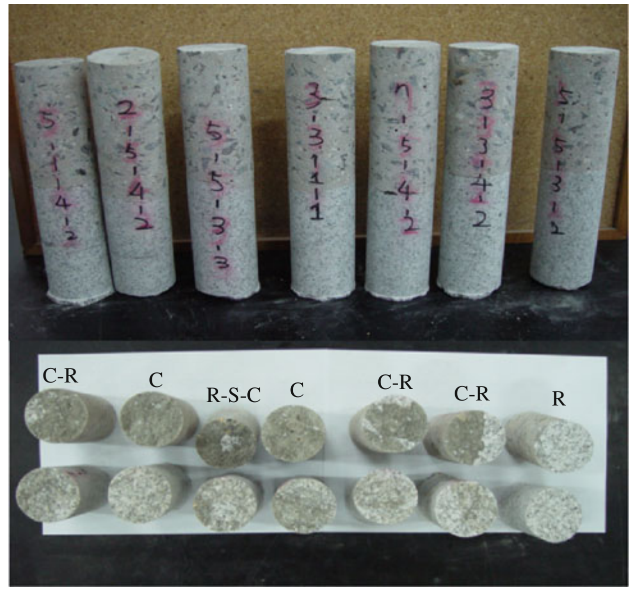


Fig. 10 Results from the direct tensile tests

Table 2 Adhesion strength at the shotcrete–rock contact (Malmgren et al. 2005)

Location	Average adhesion strength (MPa)	No. of tests
Södra Länken, Stockholm, Sweden (wet-mix method)	1.34	78
Grödingebanan, Sweden (wet-mix method)	0.85	78
Grödingebanan, Sweden (dry-mix method)	0.95	48
LKAB's underground mine in Malmberget, Sweden (wet-mix method)	0.39	23

compressive load is increased continuously until the specimen breaks, and this load, obtained by subtracting half of the weight of the device from the total applied load, is the tensile load transferred to the specimen. The direct tensile strength can be calculated from the tensile load. The device is pretested using rock, concrete, shotcrete, and



C: Contact, R: Rock, C-R: Contact-Rock, R-S-C: Rock-Shotcrete-Contact

Fig. 11 Examples of breaking planes of specimens for direct tensile tests

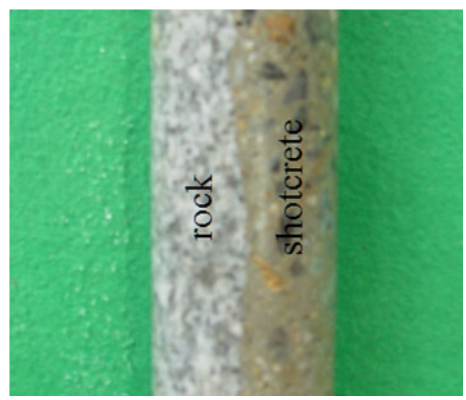


Fig. 12 Specimen cored for the split tensile tests

shotcrete–rock core specimens to verify no slippage during testing, and the results indicate no such slippage.

4 Analysis and Results of the Tensile Strength Tests

For testing the adhesion strength at the shotcrete–rock contact, test specimens are cored in NX size (see Fig. 4). The rock is granite, and Table 1 summarizes the shotcrete properties (wet-mix method). The adhesion strength at the shotcrete–rock contact is tested using four different test methods. Two are direct tensile tests and the other two are indirect tensile tests (split and flexure tensile tests). One of the direct tensile tests is the devised device constructed under a compressive load test machine (Instron) (Fig. 7). Nine specimens are tested by applying a constant strain rate (1 mm/min), and Fig. 8

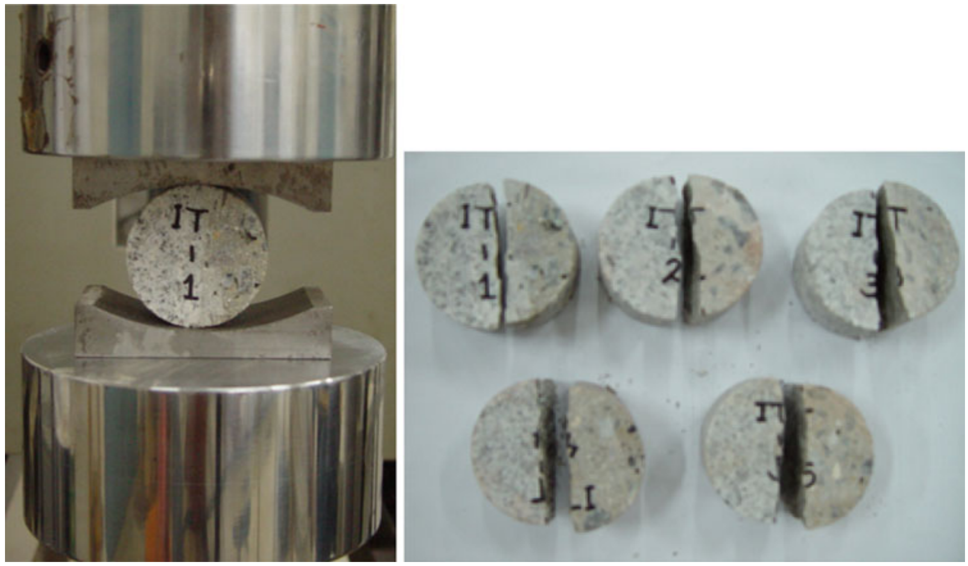


Fig. 13 Test setup and results for the split tensile tests

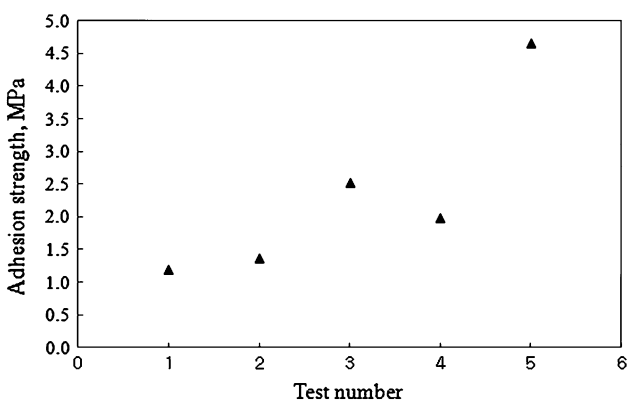


Fig. 14 Results from the split tensile tests

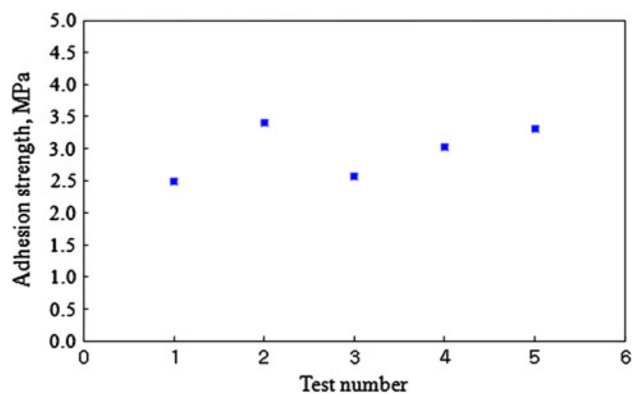


Fig. 16 Results from the flexure tensile tests

Fig. 15 Test setup for the flexure tensile tests

shows the test results. Adhesion strength ranges from 0.60 to 1.14 MPa (average 0.81 MPa). The Swedish Railroad Department (SRD 1991) and the European Federation of National Associations of Specialist Repair Contractors and Material Suppliers (EFNARC 1992) recommend that the adhesion strength at the shotcrete–rock contact for a structural member should be more than 0.5 MPa.

The other direct test method is a general tensile test method in which a circular disk with a hook is glued to the top and bottom surfaces of a specimen with epoxy and the load is applied using a tensile-testing machine (Fig. 9). Four specimens are tested, and Fig. 10 shows the results. The adhesion strength ranges from 0.87 to 1.08 MPa (average 0.95 MPa). This range of adhesion strength is consistent with the test results for the devised device.

Malmgren et al. (2005) investigated the results (Table 2) for the adhesion strength at the shotcrete–rock contact by

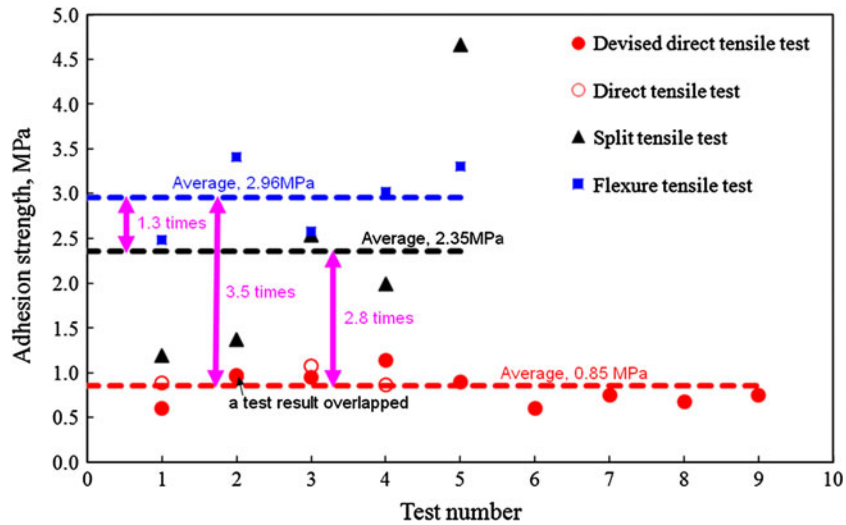


Fig. 17 Comparison of the test results from different test methods (regardless of the location of breaks)

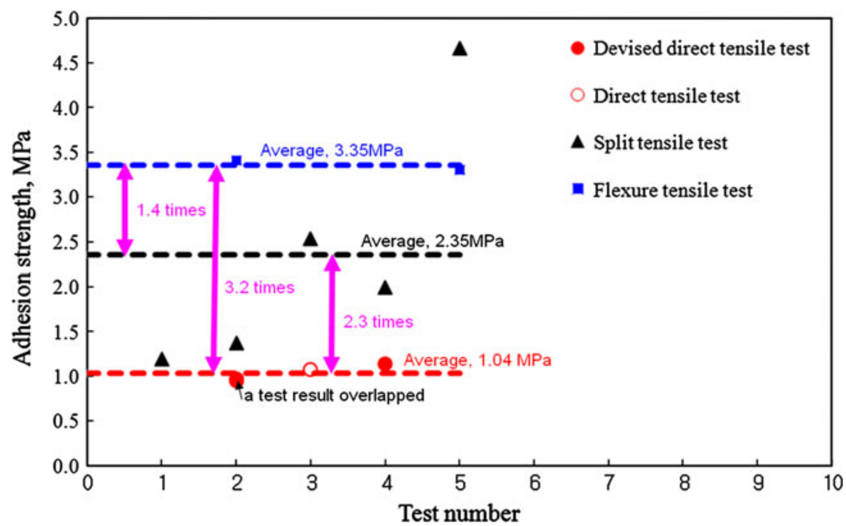


Fig. 18 Comparison of the test results from different test methods (the location of breaks is contact only)

measuring it in tunnels and mining sites in Sweden using a test method (Swedish Standard 1987). As shown in the table, the average adhesion strength for different locations ranges from 0.39 to 1.34 MPa, and the overall average strength and its range are consistent with the test results in this paper. The variation of the adhesion strength from this study and the field measurement is attributable to several factors, such as the rock surface (roughness and cleanness), existing micro- or macrocracks near the rock surface, and rock/shotcrete properties. This paper's results provide support for this explanation. Before the test, the location of a break is assumed to be at the shotcrete–rock contact. However, among the 13 specimens in the direct tensile test, only four break at the shotcrete–rock contact area. On the other hand, two break at the rock near the contact; one at the shotcrete; four at the contact area and rock; one at the contact area and shotcrete; and one at the rock, shotcrete and contact area (Fig. 11). The break at the rock is presumed to be a result of some invisible microcracks in the rock near the contact, which reduce the rock's tensile strength.

Karlsson (1980) investigated break locations based on the adhesion strength results obtained from 228 tests for gneiss and 11 tests for granite, and found that only 32 % of the breaks occurred at the shotcrete–rock contact area, whereas the remaining 68 % occurred at various locations: the rock (17 %), the shotcrete (17 %), the contact area and rock (20 %), the contact area and shotcrete (2 %), the rock and shotcrete (6 %), the rock, shotcrete, and contact area (1 %), and others (5 %). This paper's results are consistent overall with these findings.

In addition to the direct tensile tests, two indirect tensile tests are conducted to measure the adhesion strength at the shotcrete–rock contact. One of these indirect tests is the split tensile test. Here, the test specimens are prepared by coring a shotcrete–rock block horizontally to include the shotcrete–rock contact (Fig. 12), and five tests are conducted with specimens 55 mm in diameter and 27.5 mm in length (Fig. 13). The specimens nearly break along the contact and Fig. 14 shows the test results. As shown in the figure, the adhesion strength varies widely from 1.20 to 4.66 MPa (average 2.35 MPa).

The other indirect test is the flexure tensile test. Here, five tests are conducted with specimens 55 mm in diameter and 218 mm in length, and the beam span is 180 mm (Fig. 15). Three specimens break at the contact area and rock, and two at the contact area. The adhesion strength ranges from 2.48 to 3.31 MPa (average 2.96 MPa) for the five flexure tensile tests (Fig. 16).

The results for each test method are compared. Figure 17 shows all the test results regardless of the break location, and Fig. 18 shows the results only for breaks at the contact. Based on this comparison, the adhesion strength is greater for indirect test methods than for direct methods. The results for the average adhesion strength for the split and flexure test methods are approximately 2.8 times (2.3 times for breaks only at the contact) and 3.5 times (3.2 times for breaks only at the contact) higher, respectively, than those for the direct test methods. The average strength for the flexure test method is 1.3 times (1.4 times for breaks only at the contact) greater than that for the split test method. The results for the two direct test methods are similar to each other. The results of a comparison of the indirect tensile test methods (split and flexure tensile tests) indicate a wider range of adhesion strength for the split tensile test than for the flexure tensile test. This may be attributable to the characteristics of the shotcrete–rock contact surface, including the roughness of the rock surface and the waviness of the shotcrete–rock contact line.

Based on the comparison of the results for various test methods, the adhesion strength at the shotcrete–rock contact depends highly on the test method, and the adhesion strength results of the indirect tensile tests should not be directly employed for the analysis of tunnel stability.

Akazawa (1953) compared the tensile strength results between flexure and direct tests and found that the adhesion strength is approximately 2.4 times greater for the flexure tensile test than for the direct tensile test. Obert and Duvall (1967) found that the tensile strength is generally greater for the split test than for the direct test. Tourenq and Denis (1970) investigated the ratio of the adhesion strength for the split tensile test to that for the direct tensile test by varying the size of preexisting fissures in the specimen and found a ratio ranging from 1.0 to 10. Goodman (1989) mentioned that the tensile strength is greater for the split test than for the direct test and attributes this to preexisting fissures in the specimen. In addition, he compared flexure and direct tensile tests and suggested that the adhesion strength for the flexure tensile test, which is based on simple beam theory, is approximately two to three times greater than that for the direct tensile test. The results of this paper are generally consistent with the findings of previous studies but provide a more specific and direct comparison of test specimens.

5 Conclusions

To better understand the tunnel support system and provide some useful information for tunnel support design and construction, this paper tests the adhesion strength at the shotcrete–rock contact by using various methods. The paper describes the overall test procedure and compares the test results. The results are summarized as follows.

A device for directly testing the adhesion strength at the shotcrete–rock contact is devised and developed. The device makes direct use of a cored specimen without cutting its top and bottom. In addition, the device uses the equipment for a compressive test, not for a direct tensile test. The test results for the device are consistent with those for the general direct tensile test method. Therefore, the devised device can be used to conduct a direct tensile test of various core specimens more effectively and conveniently by using general compression load test equipment.

The limited test results indicate that the adhesion strength is greater for indirect test methods than for the direct methods. The results for the average adhesion strength for split and flexure test methods are approximately 2.8 times (2.3 times for breaks only at the contact) and 3.5 times (3.2 times for breaks only at the contact) greater, respectively, than those for direct test methods. The average adhesion strength is 1.3 times (1.4 times for breaks only at the contact) greater for the flexure test method than for the split test method. The results for the two direct test methods are similar to each other. The results are generally consistent with the findings of previous studies but provide a more specific and direct comparison of test specimens. Nevertheless, these results, which are based on limited tests, need to be updated with more data.

The difference in adhesion strength can be attributed to several factors, including the status of the rock surface (roughness and cleanness), preexisting micro- or macro-cracks near the rock surface, and rock/shotcrete properties. The results provide some evidence that breaks can occur at various locations: the shotcrete–rock contact area, the rock, the shotcrete, the contact area and rock, the contact area and shotcrete, the rock and shotcrete, and the rock, shotcrete, and contact area.

A comparison of indirect tensile test methods (the split and flexure tensile tests) indicates that the adhesion strength varies more widely for the split tensile test than for the flexure tensile test. This can be attributed to the characteristics of the surface of the shotcrete–rock contact, including the roughness of the rock surface and the waviness of the shotcrete–rock contact line.

Based on a comparison of the results for the various test methods, the adhesion strength at the shotcrete–rock contact is highly dependent on the test method, and, therefore, the adhesion strength results of the indirect tensile tests should not be directly employed in analyzing the stability or safety of tunnel structures that interact with the surrounding ground. From this paper's results, it is suggested that direct test methods should be used for measuring the adhesion strength at the shotcrete–rock contact.

References

Ahn KC, Shin JK, Kim JD, Won KY, Kim TG (2004) Support design with measuring the adhesion strength of shotcrete. Conference proceeding, Korean Society for Rock Mechanics (KSRM), p 31–45

Akazawa T (1953) Tension test method or concrete. Union of Testing and Research for Materials and Structures, No. 16

American Concrete Institute (ACI) (2004) ACI 506.4R-94. Guide for the evaluation of shotcrete. ACI Committee 506. 15

American Society for Testing and Materials (ASTM) (2004) ASTM C1583/C1583M-04. Standard test method for tensile strength of concrete surfaces and the bond strength or tensile strength of concrete repair and overlay materials by direct tension (pull-off method)

Barrett SVL, McCreath DR (1995) Shotcrete support design in blocky ground: towards a deterministic approach. Tunn Undergr Space Technol 10(1):79–89

Brennan E (2005) Testing shotcrete for bond. Shotcrete Magazine, Winter 2005, pp 18–19

European Federation of National Associations of Specialist Repair Contractors and Material Suppliers (EFNARC) (1992) Draft specification for sprayed concrete

Goodman RE (1989) Introduction to rock mechanics. Wiley, New York

Karlsson L (1980) Sprutbetongens vidhäftning mot bergunderlag. Byggforskningsrådet. Report No. R69 (in Swedish)

Kuchta ME (2002) Quantifying the increase in adhesion strength of shotcrete applied to surfaces treated with high-pressure water. SME Preprint 0235. SME Annual Meeting, Phoenix

Malmgren L, Nordlund E, Rolund S (2005) Adhesion strength and shrinkage of shotcrete. Tunn Undergr Space Technol 20(1):33–48

Obert L, Duvall WI (1967) Rock mechanics and the design of structures in rock. Wiley, New York

Ozturk H (2012) Work of adhesion of thin spray-on liners. Rock Mech Rock Eng 45:1095–1102. doi:10.1007/s00603-012-0238-x . Published online 15 March 2012

Ozturk H, Tannant DD (2010) Thin spray-on liner adhesive strength test method and effect of liner thickness on adhesion. Int J Rock Mech Min Sci 47:808–815

Ozturk H, Tannant DD (2011) Influence of rock properties and environmental conditions on thin spray-on liner adhesive bond. Int J Rock Mech Min Sci 48:1196–1198

Peck RB (1969) Deep excavations and tunneling in soft ground. In: Proceedings of the 7th International Conference on Soil Mechanics and Foundation Engineering, State-of-the-Art, Mexico City, p 225–290

Swedish Railroad Department (1991) Tender document on railway tunnel project Grödingebanan-SödertaljeSydGerstaberg, "Hallandsåsen." Swedish Railroad Department, Stockholm

Swedish Standard (1987) SS 13 72 43. Concrete testing—hardened concrete-adhesion strength (in Swedish)

Tourenq C, Denis A (1970) The tensile strength of rocks. Lab de Ponts et Chaussees, Paris, Research Report 4 (in French)