A PRACTICAL METHOD OF MEASURING SHOTCRETE ADHESION STRENGTH

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ABSTRACT

The National Institute for Occupational Safety and Health (NIOSH) is conducting research to develop safe practices for the use of shotcrete as ground support in underground mines, particularly mines operating in weak host rock. As part of this research, tests were conducted with a commercial poly-fiber reinforced shotcrete mix to develop a practical means of measuring shotcrete adhesion strength. Full-scale tests were conducted in a test frame equipped with concrete panels having three distinct surface roughness profiles. Adhesion test fixtures either embedded or epoxied in the shotcrete were overcored into the underlying concrete, and direct tensile tests were conducted to determine the bond strength of the shotcrete cores to the substrate after a selected shotcrete curing interval (1, 3, 7, 14, 28, or 90 days). Measured adhesion strengths typically ranged from 0.5 to 2.0 MPa depending on the curing age of the shotcrete samples. This paper presents the results of these tests, describes the portable test system components, and addresses some of the design issues encountered in the development of a rugged and reliable method for determining shotcrete adhesion strength in underground mines.

INTRODUCTION

Historically, a significant percentage of the injuries and fatalities that occur in underground mines are caused by falls of ground (Fig. 1). To protect mine personnel from ground fall hazards, particularly in underground mines where the host rock is weak (RMR<40), research is being conducted by the National Institute for Occupational Safety and Health (NIOSH) to develop safe practices for the use of shotcrete as ground support.

Shotcrete is a specially blended, cement-based product that is pneumatically sprayed at a high velocity on the exposed surfaces of underground openings to provide ground support. In underground hard rock mines in the western U.S., shotcrete is generally used as an integral part of a ground support system consisting of multiple components. When ground conditions are poor, and the host rock is weak, as in many of the underground gold mines in Nevada, extensive ground support is required. In these situations, shotcrete is typically applied in conjunction with other ground support elements such as bolts and mesh, but it may also be used with spiling or cemented rockfill for extremely weak ground. In raveling and highly fractured ground, shotcrete is mainly used to provide surface support or skin control between the roof bolts which serve as the primary ground support elements. By supporting the rock near the surface of the mine opening, shotcrete helps prevent degradation of other ground support components and bridges the span between the rock bolts, thereby supporting the loose material that typically causes many of the small ground falls [1]. Shotcrete holds by adhesion, strengthens the rock by preventing relative movements at the shotcrete/rock interface, and acts as a "super mesh" by providing a stiff retaining component with substantial bending or flexural capacity [2].

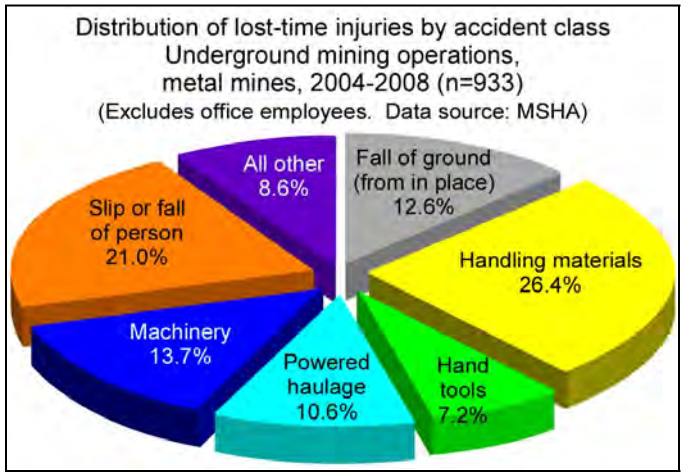

Figure 1. 2004-2008 Underground metal mining injuries by accident class, MSHA.

When shotcrete is used as an integral part of a mine's ground support system, it is important to know the strength properties of the in-place shotcrete. Besides conventional strength parameters, such as the shotcrete's flexural, compressive, or tensile strength, the adhesion or bond strength of the shotcrete to the host rock must also be known in order to adequately determine the shotcrete's ability to support the immediate ground near the surface of the mine opening. Consequently, the adhesion strength of the shotcrete is a necessary parameter for ground support design.

Researchers have found that shotcrete applied in underground mines primarily fails in adhesion, and that this initial debonding of the shotcrete from the underlying substrate is followed by a subsequent failure in flexure as the shotcrete bends under the weight of additional loading from loose material (Fig. 2) [3,4]. In another study, two basic types of shotcrete failure modes were identified through a mapping program at the Kiirunavaara Mine in Kiruna, Sweden (Fig. 3).

Laboratory tests in Sweden have indicated that the primary failure of a good quality shotcrete lining on hard rock is adhesion failure [3]. As discussed by Thomas [7], the crown of an underground opening presents the worst condition for shotcrete stability because the shotcrete is loaded by its own self weight from the moment it is sprayed. Further research has identified a more complete listing of possible shotcrete failure modes, particularly for cases where shotcrete is used in conjunction with roof bolts (Fig. 4).

Good bond strength depends on a number of factors including proper surface preparation [5,9], adequate compaction between the shotcrete and substrate [10], and also compatibility of the shotcrete with the host rock. Studies have indicated that the type of rock mineralogy can affect the bond strength [11]. For example, the adhesion of shotcrete to weak geologic formations such as shales and mudstones is frequently poor [12]. Experience has also shown that shotcrete bond strength can be poor in rock that is structurally weak in tension, or in other words, rock that is highly foliated, closely bedded, or spalling [2,5].

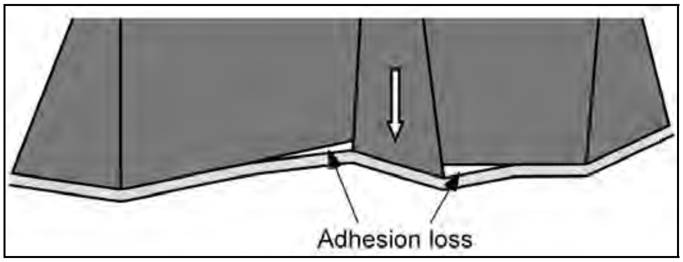

Figure 2. Flexural failure of shotcrete resulting from insufficient adhesion strength (after Kuchta, 2002).

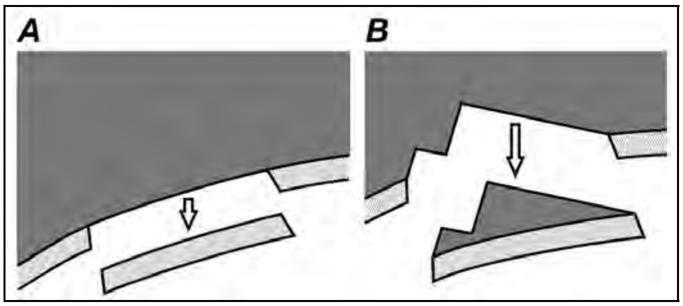

Figure 3. Two basic types of shotcrete failure modes. A: Fallout of only shotcrete indicating poor adhesion; B: fallout of shotcrete and rock indicating zones of weak rock (after Malmgren & Svensson, 1999).

As mentioned by Spearing [12], key elements of a shotcrete quality control program should include design compliance for bond and strength as well as sprayed thickness. As a result, the ability to determine the bond strength or adhesion of the shotcrete is a key component of mine design and ground control methodology [13]. A more thorough understanding of the in-situ strength properties of shotcrete, particularly the bond strength of shotcrete to the host rock, will lead to improvements in ground support practices, thereby preventing falls of ground and reducing mine roof fall accidents.

BACKGROUND

Adhesion strength of sprayed shotcrete is generally determined by a simple pull test known as the tensile bond strength test. As shown in Figure 5, a direct tensile load is applied to a core drilled through the shotcrete into the underlying substrate. The tensile load at failure is then measured to determine the adhesion or bond strength of the shotcrete to the underlying substrate material. Depending on where the core breaks, the tensile strength at failure can represent the actual adhesion strength of the shotcrete or an assumed lower limit of this adhesion strength. If the core fails in the shotcrete or substrate rather than at the bond surface or interface, the adhesion strength of the shotcrete is then known to at least exceed the measured tensile strength of the failed core.

Various test methods have been developed using this basic test configuration. For example, a standard test was established for the U.S. concrete industry in which the direct tensile load is applied through a steel disk that is glued to the top of the shotcrete core [14,15]; an adhesion test method was developed in Sweden (SS 13 72 43) whereby a direct tensile load is applied to a test core using a friction grip or core sleeve [16]; and Canadian experiments have been reported in which shotcrete is applied over drilled pucks to determine adhesion strengths [17]. In the U.S., commonly specified direct tensile strength values for shotcrete applied to properly prepared concrete substrates range from 0.69 to 1.00 MPa, (100 to 145 psi) [10]. In Sweden, the bond strength is commonly required to be a minimum of 0.5 MPa (73 psi) between shotcrete and rock, 1.0 MPa (145 psi) between different shotcrete layers, and 1.5 MPa (218 psi) for shotcrete applied to repair concrete [16]. Values that have been typically reported for the adhesion strength of shotcrete applied to host rock in underground mines range from about 0.2 to 1.5 MPa (29 to 218 psi) [4,6,8,9,18,19].

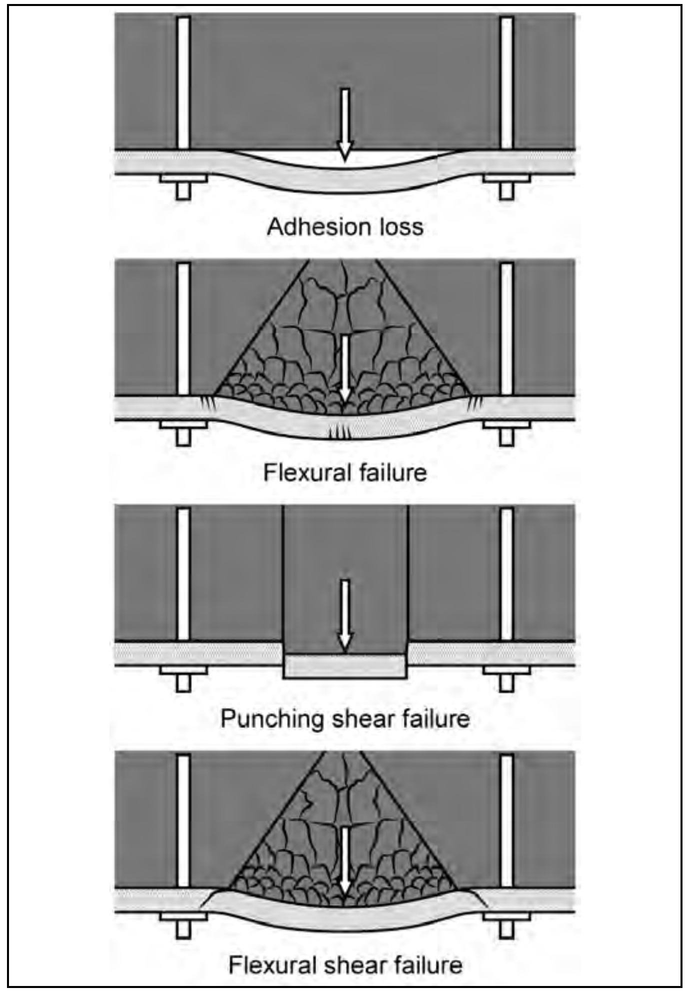

Figure 4. Schematic of shotcrete loading and failure modes (after Morton et al., 2008; Barrett and McCreath, 1995).

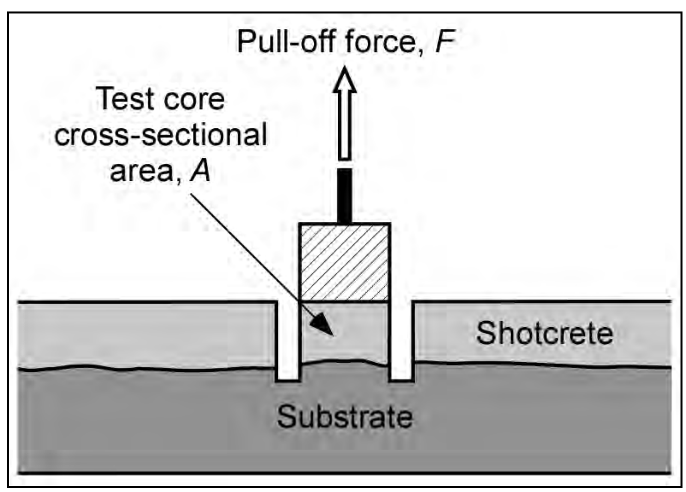

Figure 5. Simplified schematic of a tensile bond strength test (after ACI 506.4R, 2004).

Although a number of adhesion test methods have been developed, no universal procedure has been adopted or used extensively by the mining industry. Usually, the adhesion test equipment is unavailable or too expensive, complicated, or fragile for extended use underground. Some of the test methods are not practical for typical mining conditions because they require special surface preparation, gluing, or curing time to allow the shotcrete to gain sufficient strength before a test can be conducted. As a result, the adhesion strength of shotcrete is seldom measured in underground mines, even though this strength parameter plays a major role in the stability of the shotcrete, particularly during the early stages of curing. To develop a more integrated design approach for the use of shotcrete as ground support, further information is needed regarding the shotcrete's in-place strength properties (e.g., magnitude, parameter relationships, strength gain with curing time, etc.). Therefore, a practical method needs to be developed so that a typical underground miner or foreman can use a standard set of rugged and reliable tools in conjunction with simple test procedures to measure the adhesion strength of the in-place shotcrete.

RESEARCH AND DEVELOPMENT

To develop a practical method of measuring shotcrete adhesion strength in underground mines, NIOSH researchers conducted several series of direct tensile tests with shotcrete applied to concrete test panels. The focus of these experimental tests was to select light weight, portable, and robust equipment that would be suitable for use underground and to develop a simple set of test procedures so that shotcrete adhesion strengths could be measured by mine personnel. Concrete was used for these tests to provide a substrate material of known quality and consistent strength properties, thus eliminating the influence of many confounding factors that would normally be present underground, such as varying rock type, geologic structure, discontinuities, blasting-induced fracturing, loose material, mud, dust, and oil (Fig. 6).

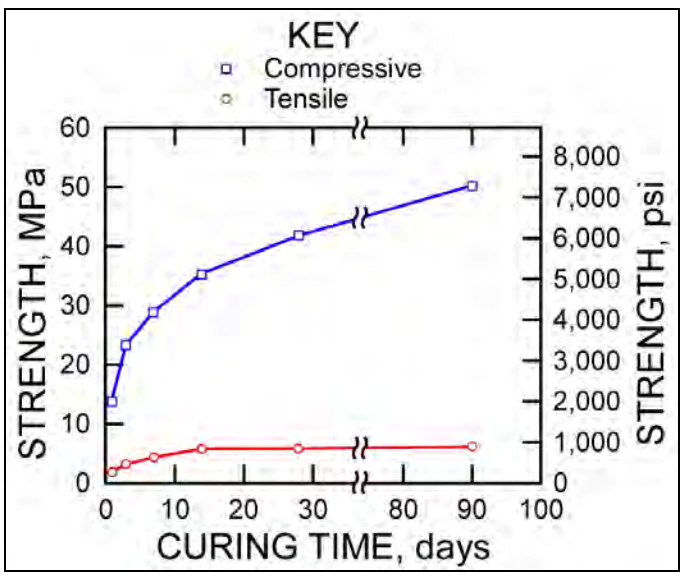

Figure 6. Average unconfined compression and splitting tensile strengths for the concrete substrate (n=36).

To investigate the influence of substrate surface roughness, the concrete was cast in special forms to produce test panels with three visually distinct surface textures or surface roughness profiles (Fig. 7).

After the concrete panels had cured for several days, they were attached to a test frame that simulated the dimensions of a typical underground opening, and a commercial shotcrete mix commonly used in western hard rock mines was applied to the panels using a dry mix process and an Aliva-252.1 shotcrete machine equipped with a hopper and pre-dampener (Fig. 8). For consistency, the same brand of poly-fiber reinforced shotcrete (SCAPF) was used for all of the tests along with similar preparation methods and spraying procedures.

Figure 7. Concrete panels cast with three distinct surface roughness profiles.

Figure 8. Simulated Underground Mine Test Frame.

During the development of a mine-worthy adhesion test system, five separate series of direct tension tests were conducted using a logical progression of adhesion test fixtures or pull anchors (Fig. 9). For an initial series of tests, an expanded metal anchor was manually held in place with a hollow rod (preformed aluminum conduit) as the shotcrete was applied to the test panel. Not only was it difficult to core drill around this particular anchor and center the fixture in the test core, but it also appeared that flexing of the expanded metal during the pull test may have caused some of the test cores to break near the fixture. As a result, the next two series of tests were conducted with pull anchors consisting of a 44.5-mm- (1.75-in-) or 38-mm- (1.5-in-) diameter metal washer welded to a coupling nut. Although it was easier to core drill around this fixture and center the metal washer in the test core, it was difficult to maintain the position of the fixture perpendicular to the concrete surface while the shotcrete was applied. This tended to produce voids in the shotcrete near the anchor and also caused the pulling axis angle to deviate from the longitudinal axis of the test core.

The first three series of adhesion tests were conducted with concrete panels mounted either vertically to a side wall or overhead in an arch position on the test frame (Fig. 10). Extra precautions were taken during the next two series of tests to more closely control the spatial orientation of the pull anchor in relation to the test core and substrate surface. Concrete panels for the fourth and fifth series of tests were sprayed with shotcrete while they were propped against the test frame at approximately a 45° angle. Adhesion tests were then conducted with the panels after they were placed in a horizontal position so that the core drill and pulling fixture could be positioned more precisely. To hold the adhesion fixture perpendicular to the substrate surface, the fourth series of adhesion tests were conducted with a pull anchor consisting of a 35-mm- (1.375-in-) diameter metal washer welded to a coupling nut and connected to a long section of all-thread that was in turn secured to a rigid metal grid bolted to the panel. Although the diameter of the metal washer did not appear to affect the adhesion strength measurements, more closely controlling the orientation of the pull anchor reduced eccentric loading and thus, produced more consistent and repeatable test results.

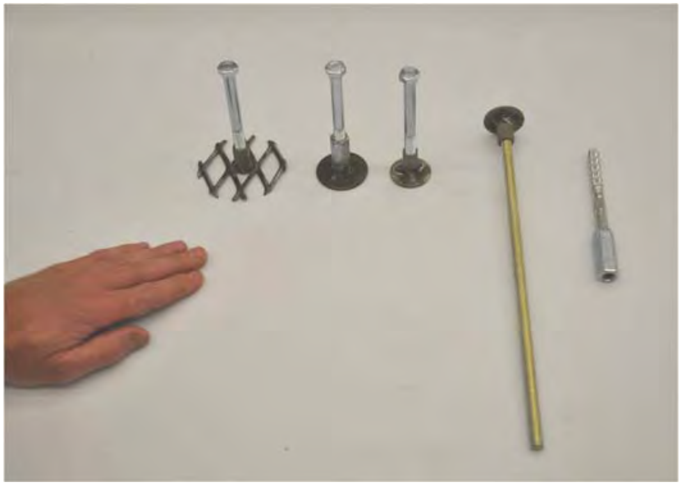

Figure 9. Pull anchors investigated during the development of a direct tensile test system for determining shotcrete adhesion strength.

Figure 10. Drilling an adhesion test core on a vertical surface.

One of the main disadvantages of the pull anchors used in the first four series of adhesion tests was that the anchor had to be held in place either manually or with a mounting grid while the shotcrete was sprayed on the substrate. This interfered with the shotcrete application process, produced voids in the shotcrete at the location of the test fixture, and caused subsequent problems with eccentric loading if the test fixture was not held perpendicular to the surface of the substrate. Further problems with eccentric loading were encountered if the core drill and/or the pulling fixture were not positioned and oriented correctly over the pull anchor. To address these issues, experiments were conducted to develop an alternative technique in which a threaded metal stud was glued in the applied shotcrete and then used as a pull anchor during a direct tensile test. To center the pull anchor in the test core and align the longitudinal axes of the pull anchor, test core, and pulling fixture; a drilling method was adapted from the Swedish friction grip test, whereby three parallel concentric holes are drilled from a single drill set-up (Fig. 11). The base of the pulling fixture was also redesigned to seat in the kerf of the outer drill hole.

Utilizing these modifications, a fifth and final series of adhesion tests was conducted with another set of horizontal test panels. The improved drilling method and revised pulling fixture automatically centered and aligned the pull anchor with the test core and pulling fixture, thereby limiting eccentric loading. Because the pull anchor is installed after the shotcrete is applied, the shotcrete application process is not disrupted, and mine personnel are not exposed to unsupported ground while establishing the position of the anchor. Furthermore, because the adhesion test site is not predetermined, a desired location for conducting the test can be specifically selected by the mine staff, such as in a problem area where poor shotcrete adhesion strength is suspected. The final version of the shotcrete adhesion test system that was developed through these tests is shown in Figure 12. Further tests will be conducted using this system in underground mines to determine if the equipment can withstand typical mining conditions and to obtain suggested improvements from industry personnel.

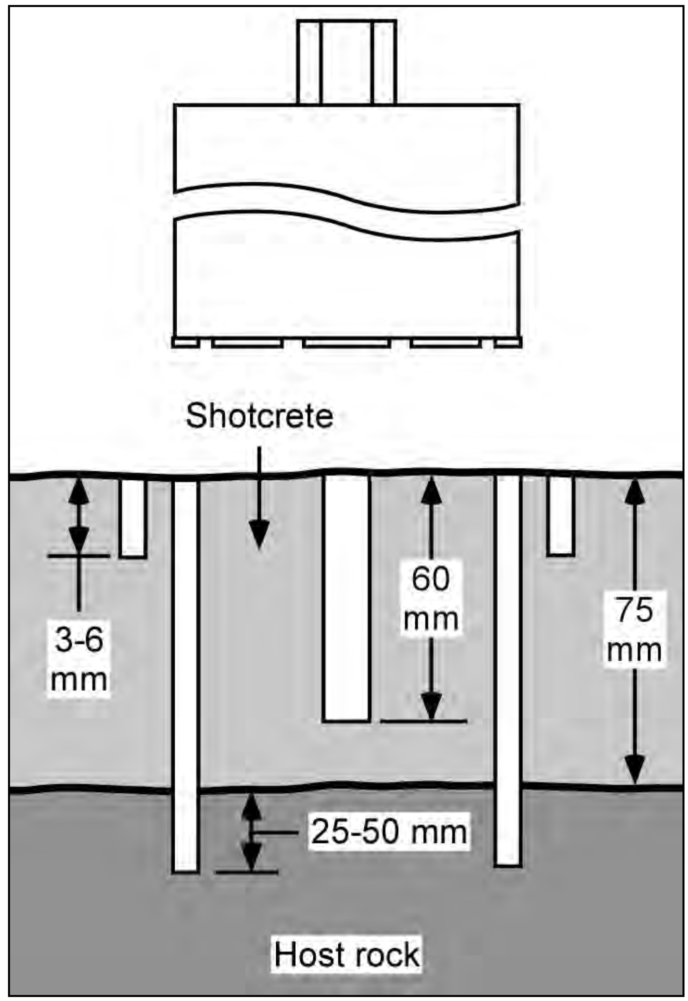

Figure 11. Schematic showing a vertical cross-section of the drill holes for a tensile bond strength test.

Overall, the results of these developmental tests were fairly consistent with adhesion strengths ranging from 0.15 to 2.22 MPa (22 to 322 psi). A total of almost 200 adhesion tests were conducted with only five test cores failing prematurely, either during core drilling or while setting up the pulling apparatus. All of these failures occurred during the first three series of tests before centering of the anchor fixture and eccentricity of the pulling axis were controlled more closely. As the test series progressed and the experimental development continued, there was generally less variability in the measured adhesion strengths (Fig. 13). The spread in the test results illustrates the variability inherent in adhesion testing and demonstrates the importance of quality control measures not only for casting the concrete panels, preparing the interface surface, and applying the shotcrete, but also for operating the adhesion test equipment and consistently following well defined test procedures.

Figure 12. Field expedient direct tensile test system.

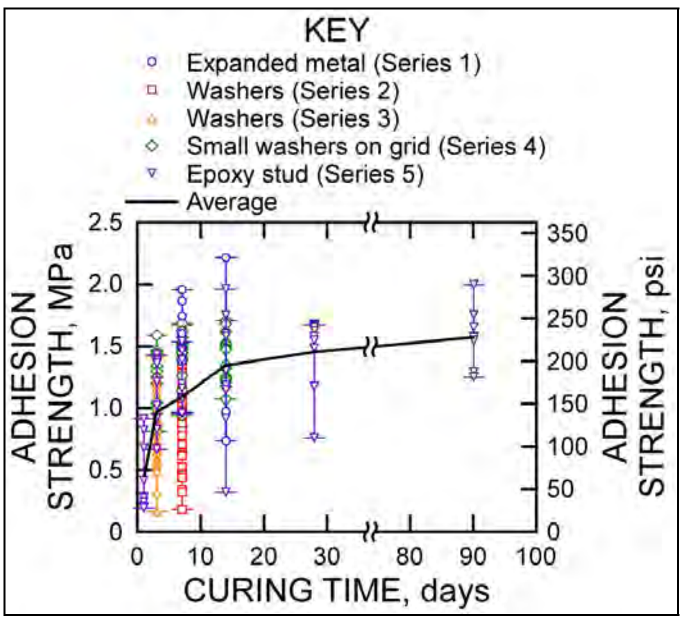

Figure 13. Adhesion strength versus shotcrete curing time for various anchor configurations (n=185).

As mentioned earlier, typical values that have been reported for the adhesion strength of shotcrete in underground mines range from about 0.2 to 1.5 MPa (29 to 218 psi). Direct tensile tests that were conducted using the epoxy stud method gave adhesion strengths that were within a similar range, about 0.2 to 2.0 MPa (29 to 290 psi). Consequently, this test method appears to provide a credible means of measuring shotcrete adhesion strength.

One of the primary factors that must be controlled in any shotcrete investigation is the quality of the applied product which is governed to a large extent by the application technique and the skill of the operator [7,20]. For the adhesion tests conducted in test series 1-5, water was sprayed on the test panels to clean and moisten the concrete prior to applying shotcrete. While further measures were taken to control the quality of the applied shotcrete, obvious defects were observed in some of the panels and test cores. No attempt has been made here to discard anomalously low strength values caused by poor shotcrete quality; instead all of the results from the completed tests have been reported.

CONDUCTING A SHOTCRETE ADHESION TEST

Unlike other methods, this shotcrete adhesion test system consists of readily available and relatively inexpensive components, primarily a small stand-mounted core drill and a pulling unit equipped with a precision pressure gage (Figs. 12 & 14). These robust and reliable components are portable and can be used to measure shotcrete adhesion strength in either the rib or back of an underground opening (Fig. 10).

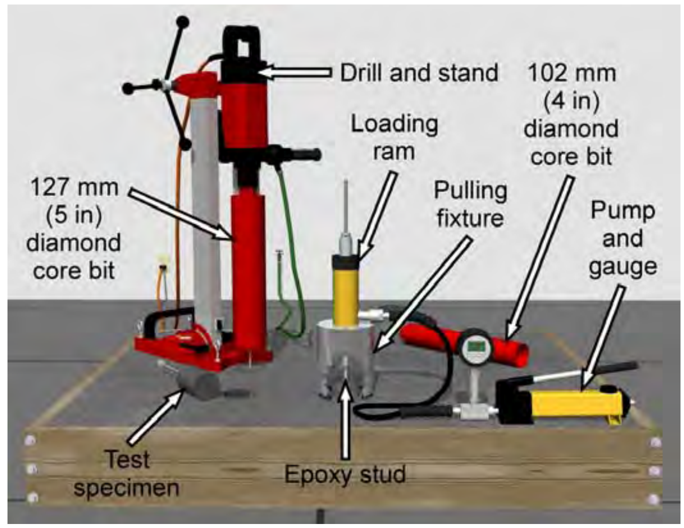

Figure 14. Schematic of direct tensile test system for determining shotcrete adhesion strength.

Once a desired test site has been selected, a hand-operated rotary percussive drill is used to drill a 16-mm x 51-mm (0.625-in x 2-in) hole for anchoring the drill stand. After installing a 13-mm- (0.5-in-) diameter threaded stud and expansion anchor in this hole, the drill stand is leveled and secured in position. Three holes are then drilled from this single drill set-up ensuring that all of the holes are parallel and concentric (Fig. 11). First, an 11.1-mm- (0.4375-in-) diameter hole is drilled dry into the shotcrete using a rotary percussive bit to a depth of about 60 mm (2.375 in), assuming a shotcrete thickness of 75 mm (3 in). Next, the hole is cleaned, filled with a quick setting 2-part epoxy adhesive, and a 9.5-mm- (0.375-in-) diameter pull anchor is inserted. After the epoxy has initially set or gelled (approx. 15 min), a 102-mm- (4-in-) diameter diamond core bit is used to wet drill a second hole through the shotcrete and to a depth of about 25-50 mm (1-2 in) into the underlying substrate. Finally, a 127-mm- (5-in-) diameter diamond core bit is used to wet drill a shallow kerf for seating the base of the pulling fixture, typically to a depth of about 3-6 mm (0.125-0.25 in) depending on the irregularity of the shotcrete surface (Fig. 15).

After the epoxy has fully set (30-60 min), a threaded extension rod is connected to the pull anchor with a coupling nut, and the pulling fixture is carefully placed over the core sample with the base of its reaction ring positioned in the kerf of the outer drill hole. The hydraulic hose from the hand pump is then connected to the loading ram, and the ram is cycled a few times to remove any extraneous air from the system. Next, a collet and a split-nut are connected to the threaded extension rod to serve as a mechanical stop for the pulling fixture's ram. To conduct a test, the pressure gage is zeroed, and an increasing tensile load is applied to the core sample through a slow and steady movement of the pump handle until the core breaks. Test duration varies depending on the tensile strength of the test core (typically 30 sec to 2 min).

The ultimate tensile force applied to the test core is determined by converting the maximum hydraulic pressure value, saved on the pressure gage's digital display, to the maximum tensile force acting normal to the core's failure surface. To simplify analysis of the test results, the tensile force is assumed to act in a direction parallel with the longitudinal axis of the test core, and the area of the failure surface is assumed to be equivalent to the cross-sectional area of the test core. Prior to conducting our tests, the hydraulic pump and loading ram were calibrated in a laboratory test machine equipped with a certified load cell. The hydraulic components were tested at several load values over the range of the rated capacity of the loading ram, thus providing a direct comparison between the hydraulic pressure reading on the pump's digital pressure gauge and the corresponding load or force reading measured by the test machine's load cell. Using a simple linear regression equation obtained from this calibration procedure, the actual force exerted by the hydraulic ram can be accurately determined from the measured hydraulic pressure. Equation 1 shows the simple linear relationship between measured hydraulic pressure and applied tensile load for the hydraulic components used in our tests.

Figure 15. Parallel and concentric drill holes with extension rod connected to epoxied stud.

$$F_t = (2.7181)\, p - 10.058 \tag{1}$$

where F_t = tensile force
and p = hydraulic pressure

The maximum tensile stress at failure is then calculated using Equation 2.

$$\sigma_T = F_T / (d^2 / 4) \tag{2}$$

where σ_T = ultimate tensile stress
F_T = ultimate tensile force
and d = diameter of test core

To aid in the interpretation of the test results, the failure surface on the test core should be examined along with the bottom of the drill hole, and the failure location should be recorded as a percentage of the shotcrete, interface, and substrate that are exposed on the tensile failure surface (Fig. 16). In addition, the overall depth of the 102-mm-(4-in-) diameter drill hole should be noted along with the length of the test core and the thickness of the shotcrete layer so that drilling depth(s) for the pull anchor and/or test core can be adjusted, if necessary for further tests.

DISCUSSION OF TEST RESULTS

Results of direct tensile tests using the epoxy-stud pull anchor are shown in Figure 17 for poly-fiber reinforced shotcrete applied to concrete test panels. The substrate panels were positioned at about a 45° angle when the shotcrete was applied. Later, they were placed in a horizontal position, and a sequential series of adhesion tests were conducted after the shotcrete had cured for 1, 3, 7, 14, 28, and 90 days.

Figure 16. Adhesion test specimen showing a tensile failure surface located predominantly in the concrete substrate.

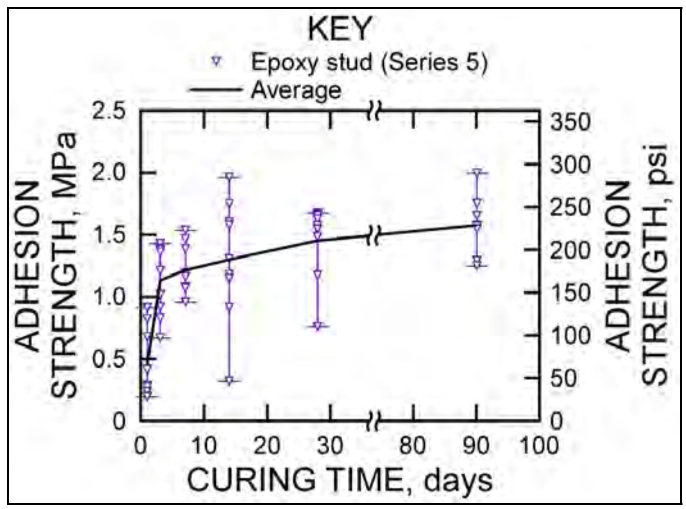

Figure 17. Adhesion strength versus curing time for direct tensile tests using the epoxy stud fixture (n=54).

Average adhesion strength values increased with shotcrete curing age and ranged from 0.44 MPa (64 psi) after 1 day of curing to 1.58 MPa (229 psi) after 90 days of curing. The range of these results are comparable to previously published values for the adhesion of shotcrete to concrete test panels [5,6] and are within the normal range of bond strengths specified for shotcrete applied to concrete substrates [10,16]. In contrast with other methods that require a relatively stiff shotcrete in order to conduct adhesion tests [9], shotcrete adhesion strengths were successfully measured after only 1 day of curing using the epoxy stud anchor. Average adhesion strength increased markedly between 1 and 3 days of curing, from 0.44 to 1.13 MPa (64 to 164 psi) or in other words, from 28 to 72 pct of the average 90-day adhesion strength (Fig. 17). These test results may have important ramifications in terms of safe re-entry times for underground openings that have been recently sprayed with shotcrete and warrant further testing to determine if adhesion strengths can be measured at earlier shotcrete curing times using this method.

It is important to know the early-age strength characteristics of shotcrete in order to conservatively determine when the applied shotcrete is capable of providing ground support and thus, when it is safe to re-enter a sprayed area. Adhesion strength is especially important during the early stages of curing because the shotcrete must be securely bonded to the host rock and held in place until the material can gain sufficient internal strength to resist further loading. Measuring adhesion strength in terms of curing time helps identify when the bond strength of the shotcrete is sufficient to support more than its own self weight. However, because it is difficult to sample and test a weakly consolidated material such as freshly sprayed shotcrete, the strength properties of early age shotcrete are usually related to some direct or indirect measure of its compressive strength. Adhesion strength gain with shotcrete curing time has been identified in other studies, and this trend has been related to an increase in the shotcrete's compressive strength over time [1,9].

Rather than comparing the bond strength of the shotcrete to some measure of its compressive strength, it may be more appropriate to compare adhesion with tensile strength, particularly if a direct tensile test is used to determine adhesion strength. In Figure 18, the results of the epoxy-stud adhesion test series are plotted together with average concrete tensile strengths obtained from splitting tensile tests with cast concrete samples from the substrate test panels and also with shotcrete tensile strengths estimated from unconfined compression and splitting tensile tests with cored samples of similar shotcrete. The concrete test panels had generally cured for over 28 days before they were sprayed with shotcrete, so the average tensile strength of the concrete should have ranged from at least 4.8 to 6.2 MPa (700 to 900 psi) when the adhesion tests were conducted. Although adhesion strength closely follows the strength gain trend estimated for tensile strength of the shotcrete, the results of the adhesion tests are much lower in magnitude (Fig. 19).

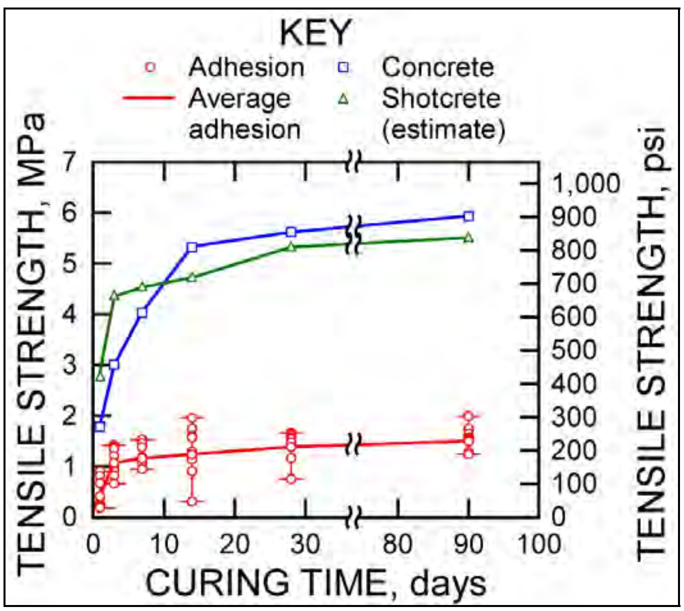

Figure 18. Comparison of adhesion and splitting tensile test results.

These lower strength values are at least partially caused by inherent differences between the two types of tests and the complexity of testing composite samples. During a direct tensile test, failure occurs at the weakest element in the test specimen. Unlike other tests such as a flexural test, the entire volume of a direct tensile test specimen is subjected to the maximum stress; therefore, the probability of a weak element occurring in the test specimen and influencing the test results is relatively high [21]. For a direct tensile test with a composite material, this issue is compounded because the weakest element can occur in any of the individual materials or at their interfaces. Therefore in a shotcrete adhesion test, a tensile failure can occur in the shotcrete, at the bond interface (contact surface), in the substrate, or in a combination of these locations. For concrete, splitting tensile tests provide more uniform results and give strengths that are 5 to 12 pct higher than those obtained from direct tensile tests [21]. Further testing is needed to clearly define the relationship between the adhesion strength at the bond surface and the tensile strength of the shotcrete.

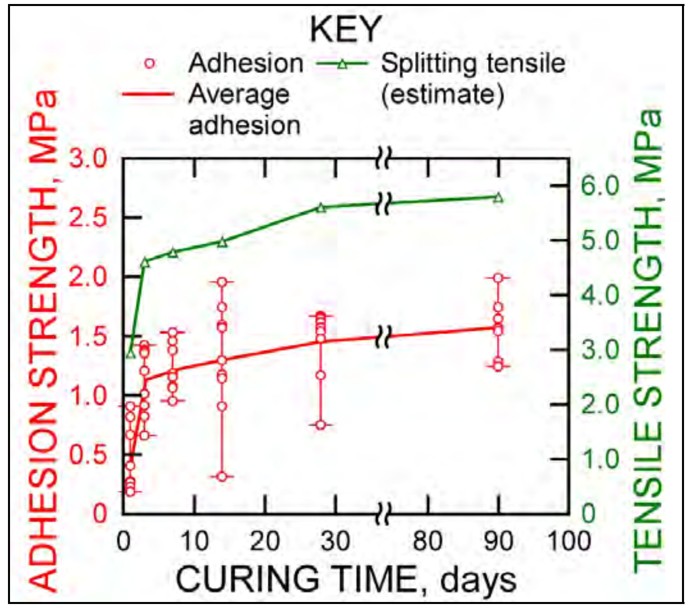

Figure 19. Comparison of adhesion strength and estimated shotcrete tensile strength.

If a high quality shotcrete is applied using correct procedures and the bond surface is prepared properly (i.e., clean and free from loose materials, mud, dust, or oil with sufficient roughness and moisture to permit a good bond), the location of the tensile failure should depend on the relative difference between the tensile strength of the shotcrete and that of the substrate. Results reported for shotcrete adhesion tests in underground mines indicate that the majority of the tensile failures occurred in the host rock or at the contact surface with the host rock [5,9,22]. In contrast, the majority of the tensile failures in our tests occurred in the shotcrete, more than likely because the shotcrete had not yet developed sufficient strength with curing time to match the tensile strength of the concrete (Figs. 18 & 20). As our test series progressed, the consistency of the concrete, shotcrete, and test procedures were controlled more closely. This was reflected some what in the predominant locations of the tensile failure surfaces, which averaged 64 pct in the shotcrete, 23 pct at the interface, and 13 pct in the concrete for the entire test series and 81 pct, 19 pct, and 0 pct respectively, for the final epoxy stud test series.

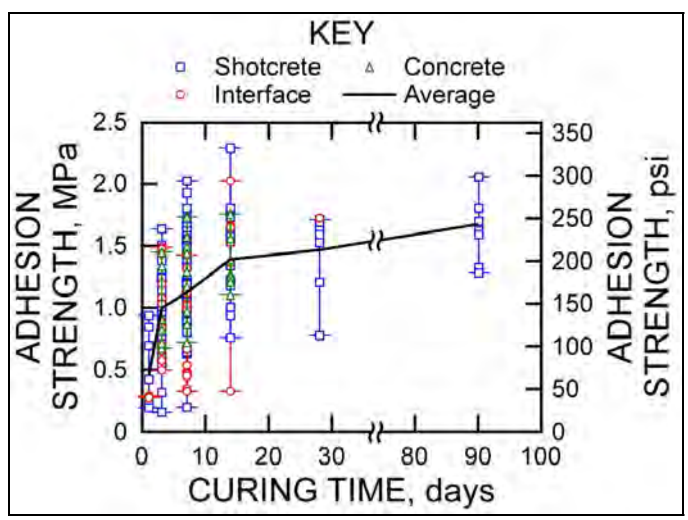

Figure 20. Predominant location of the tensile failure surface for shotcrete adhesion tests with concrete panels (n=185).

According to Swedish Standard SS 13 72 43, the result of the direct tensile test is reported as adhesion strength if more than 80 pct of the tensile failure surface is located at the interface (bond surface). Otherwise, the test result represents a lower limit for adhesion strength. In other words, the actual adhesion strength at the bond surface is larger than a tensile failure that occurs at some other location (shotcrete, host rock, or some combination of locations). Using this criterion, only 4 pct of our tests failed at the bond surface (8 of the 185 total tests). This restriction produced significantly lower adhesion strengths than the average adhesion strength curves shown in Figures 13 and 17-21. By averaging the entire test results, a more consistent and representative value was reported for adhesion strength because anomalously low values for tensile failures at the bond surface were not given an undue weight in the data analysis.

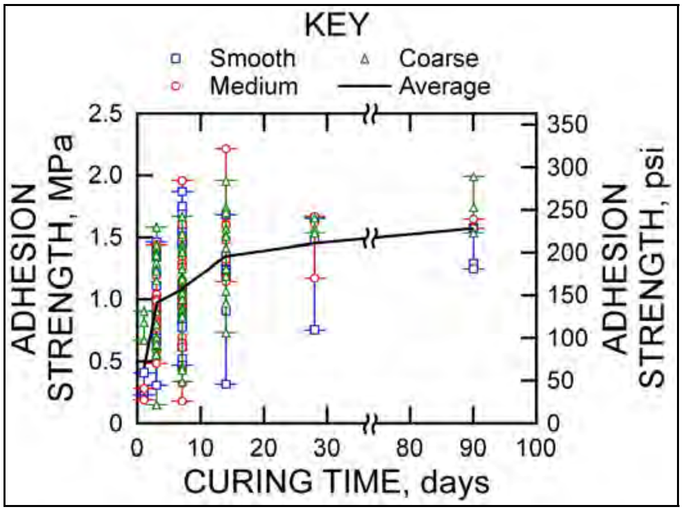

Figure 21. Shotcrete adhesion test results indicating the substrate surface roughness of the concrete panels (n=185).

To investigate the effect of substrate surface roughness on adhesion strength, the concrete test panels were cast to produce three visually distinct surface textures, referred to as smooth, medium, and coarse (Fig. 7). A representative profile of each surface was measured and compared to a joint roughness coefficient chart [23] to obtain the following JRC values, respectively: 6-8, 16-18, and 14-16. Because the surface profile of the panels was measured over a distance of approximately 30 cm (12 in), the JRC value for the medium panel was larger than that of the coarse panel. As shown in Figure 21, the surface roughness of the concrete panels did not appear to significantly affect the adhesion strength of the test cores. Neglecting curing time, the average adhesion strength for all of the tests conducted on the smooth, medium, and coarse panels were respectively, 1.07 MPa (155 psi), 1.09 MPa (158 psi), and 1.15 MPa (167 psi). These limited results indicate the complexity of relating large scale differences in surface roughness to adhesion strength measurements collected over a much smaller surface area. Further tests need to be conducted with test panels having a more uniform surface roughness that is scaled in a consistent manner with respect to the cross-sectional area of the test cores.

CONCLUSIONS

NIOSH researchers have developed a portable direct tensile test system consisting of readily available, inexpensive components that can be used in conjunction with simple test procedures to determine the adhesion strength of shotcrete in underground mines. Several series of direct tensile tests were conducted with this equipment to determine the adhesion strength of poly-fiber reinforced shotcrete applied to concrete test panels using a dry mix process and machinery. Results of these full-scale field tests suggest the following conclusions:

The components of the adhesion test system are robust, light weight, and reliable, and when used in accordance with simple test procedures produce consistent and credible results. Further shotcrete adhesion strength testing is merited using this equipment in vertical as well as overhead positions under actual mining conditions.

Depending on shotcrete curing age, average adhesion strength values derived from these direct tensile tests ranged from 0.44 to 1.58 MPa (64 to 229 psi). These results are comparable to previously published adhesion strengths from similar studies and are within the normal range of bond strengths specified for shotcrete applied to concrete substrates.

Using epoxy stud pull anchors, direct tensile tests were successfully conducted after the shotcrete had only cured for 1 day. Test results indicated a substantial increase in shotcrete adhesion strength between 1 and 3 days of curing (approximately a 44-pct increase in terms of the average 90-day adhesion strength). This gain in adhesion strength appeared to closely reflect a similar trend for tensile strength gain with curing time.

During a direct tensile test, the test core fails at its weakest location. As a result, these tests can provide important information about the quality and tensile strength of the applied shotcrete and the strength and competency of the underlying host rock, as well as the adhesion or bond strength of the shotcrete to the rock.

This paper is not a guideline just a statement regarding shotcrete adhesion strengths measured by NIOSH researchers. Mine staff should conduct their own site specific tests using due diligence and available standards to determine the strength properties of their shotcrete. This information can then be used to design a ground control plan that specifically addresses the conditions at their mine.

The findings and conclusions presented in this document have not been formally disseminated by the National Institute for Occupational Safety and Health and should not be construed to represent any agency determination or policy and mention of any company name or product does not constitute endorsement by NIOSH.

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