Use of Synthetic, Fiber-Reinforced, Initial Shotcrete Lining at Devil's Slide Tunnel Project in California

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Fiber-reinforced shotcrete is widely used as a temporary excavation support in the construction of transportation tunnels and in other civil applications that are performed with the Sequential Excavation Method. Traditionally, steel fibers have been used in tunnel construction; however, the use of synthetic fibers is becoming more common. At the Devil's Slide Tunnel Project, on Highway CA-1 in Pacifica, California, a synthetic fiber mix was used to achieve the contract initial lining performance. The synthetic (polypropylene) fiber was used throughout the excavation phase of the twin highway tunnels and was tested with the round determinate panel test (ASTM C1550) for its capability to absorb energy after shotcrete section failure (flexural strength). The contract required the ASTM C1550 test to produce at least 320 J at 40 mm of deflection after 7 days. This paper discusses the testing program and summarizes its results. The overall performance of the fiber-reinforced shotcrete liner is discussed and evaluated on the basis of its reaction to deformation and its use in the tunnel.

The tunnel project on Highway CA-1 in Pacifica, California, was designed to bypass a slide-prone section of the highway known as "Devil's Slide" (Figure 1). The California Department of Transportation contracted the Kiewit Corporation to construct the two tunnels that would cut through San Pedro Mountain. As a subconsultant to Kiewit, Gall Zeidler Consultants provided integrated, on-site team support services for the conventional Sequential Excavation Method construction and engineering support. The objective of the Devil's Slide project was to construct two parallel, single-lane highway tunnels 2,440 m (8,000 ft) in length, with cross sections of up to 120 m^2 (1,290 ft^2). The tunnels were excavated in faulted and weathered granite diorites and interbedded–conglomerate sandstone, siltstone, and claystone. Tunnel excavation was completed, and the final lining and road work were near completion at the time of this report.

The tunnels were designed to be excavated with the Sequential Excavation Method because (*a*) variable ground was expected during excavation and (*b*) tunnel geometry resembled a modified horseshoe profile. The Sequential Excavation Method uses a thin, flexible, shotcrete lining to permit slight deformation to occur, which allows the rock to carry much of the load. Fiber-reinforced shotcrete (FRS) is commonly used in place of steel-wire mesh for efficiency in the construction process. Steel fiber has been used most commonly. However, the use of synthetic fibers has gained quickly in popularity. The initial liner placed at Devil's Slide used synthetic fibers. This paper discusses the testing of round determinate panel (RDP) (ASTM C1550) at Devil's Slide with specific reference to experience with the Devil's Slide testing program. The results of the testing and the performance of the synthetic fibers are discussed, and some guidance on the use of the fibers is presented. The advantages and disadvantages of synthetic, fiber-reinforced shotcrete are presented as well.

ROUND DETERMINATE PANEL TEST

History and Development

The flexural toughness of FRS can be determined through a variety of internationally recognized methods, including beam tests (ASTM C1018) and the panel test of the European Federation of National Associations Representing Producers and Applicators of Specialist Building Products for Concrete (EFNARC). In 1998, Bernard developed a new method to test flexural toughness (*1, 2*). The new test became known as the RDP test.

Test Standardization

ASTM International C1550-05, "Standard Test method for Flexural Toughness of Fiber Reinforced Concrete (Using Centrally Loaded Round Panel)," is the standard for the RDP test. At least three molded, round, fiber-reinforced shotcrete, or cast concrete, panels are to be produced for testing, two of which must test correctly. To test correctly, a panel must break into three pieces (Figure 2) and be within certain size specifications. ASTM C1550 specifies panel height and diameter at 75 and 800 mm, respectively. A test involves the application of a load to the center of the panel by a hemispherical-ended steel piston. The load is controlled by a programmable logic controller to maintain a constant deflection rate of 4.0 ± 1.0 mm/min. The panel rests on three pivots, evenly spaced around its circumference, and deflection is carried out until a central displacement of at least 40 mm is achieved. The energy absorbed is recorded at deflections of 10, 20, 30, and 40 mm. ASTM C1550 does not expect results to differ by more than 17% from two properly conducted tests of specimens produced from the same batch of shotcrete.

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FIGURE 1 Location of Devil's Slide project (yellow line in red box) on Highway CA-1 in Pacifica, California.

Correlation of RDP to Support Classes

Papworth attempted to correlate the toughness performance levels (TPLs) of Morgan with rock mass quality, Q-system classes, and FRS performance (*3*). The correlation between Morgan's TPLs and the Q-system classes was developed from the description of the ground conditions applicable to the various TPLs and on Papworth's own experience (Table 1). The TPLs were defined by Morgan as follows (*3*):

TPL IV. Appropriate for situations that involve severe ground movement, with cracking expected of the FRS lining, squeezing ground in tunnels and mines, where additional support in the form of rock or cable bolts, or both, may be required;

TPL III. Suitable for relatively stable rock in hard rock mines or tunnels in which low rock stress and movement are expected and the potential for the steel FRS lining to crack is expected to be minor; and

TPL II. Should be used where the potential for stress and movement-induced cracking is considered low (or the consequences of such cracking are not severe) and where the fiber provides mainly thermal and shrinkage crack control and perhaps some enhanced impact resistance.

Morgan's TPLs have their basis in ASTM C1018 beam tests, but panel tests are the preferred method to assess shotcrete for tunnel linings. Thus Papworth correlated the panel-based tough-

FIGURE 2 Panel display of successful break.

TABLE 1 Correlation of Morgan's TPLs to Q-System Rock Classes, and EFNARC and RDP Values (*3*)

Ground Condition		Standard Deflection Criteria	
TPL	Rock Class	EFNARC (joules)	RDP_{40mm} (joules)
IV	F	>1,400	>560
IV	E	>1,000	>400
III	D	>700	>280
II	C	>500	>200

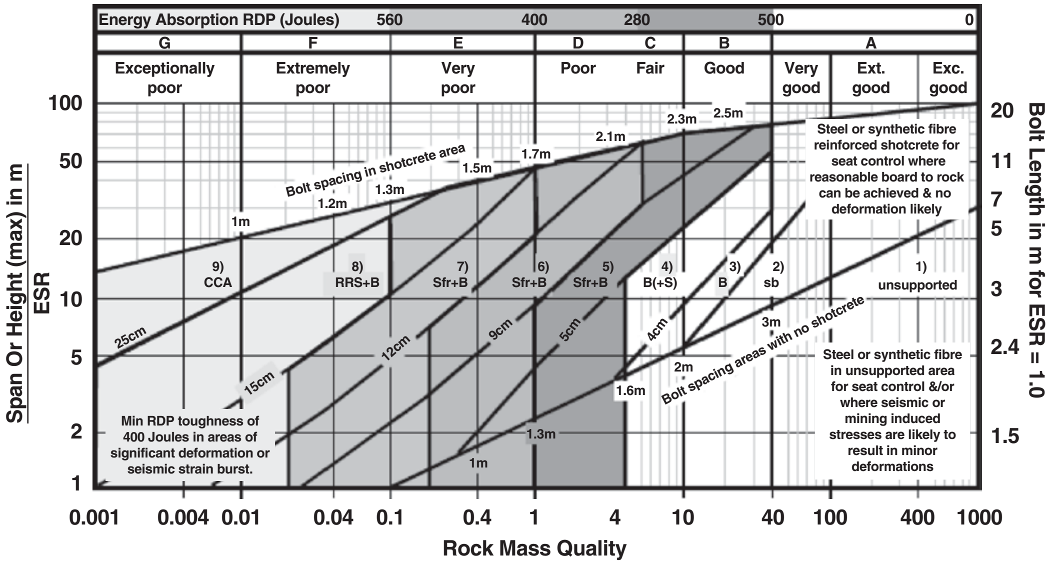

FIGURE 3 RDP values (shaded areas) correlated with Barton Chart (*3*) (ext. = extremely; exc. = exceptionally; CCA = cast concrete lining; RRS+B = reinforced ribs of shotcrete and bolting; Sfr+B = fiber reinforced shotcrete and bolting; B(+S) = systematic bolting and unreinforced shotcrete; B = systemic bolting; and sb = spot bolting).

ness performance recommendations of EFNARC on the basis of Morgan's values of TPL and published performance data (*3*). Papworth was then able to use the EFNARC and RDP correlation equation developed by Bernard (*1*) to develop the RDP values for each of Morgan's TPLs. These values represented test results for panels that were 28 days old.

Papworth took the correlated RDP values shown in Table 1, Column 4, and directly applied them to the Barton Chart (Figure 3), which relates rock mass quality and excavation dimensions and provides recommendations for bolt length, spacing, and shotcrete thickness (*3*).

DEVIL'S SLIDE TUNNELS PROJECT

Contract Requirements

The Devil's Slide contract required use of the RDP test (ASTM C1550) to assess the energy absorption capacity of the FRS. The contract mandated a minimum-average energy absorption value of 320 J at 40 mm displacement, with a shotcrete age of 7 days. This value was established by California Department of Transportation tunnel designer, ILF Consultants, and encompassed all five ground support categories at Devil's Slide. According to ASTM C1140, "Standard Practice for Preparing and Testing Specimens from Shotcrete Test Panels," at least three RDP test panels and one shotcrete box panel for compression test cores were to be produced for every 100 m^3 of material used in the shotcrete initial lining. After the three RDP panels were tested, the energy absorption of the top two was averaged. To pass the test, the average of the top two panels had to surpass the required 320 J.

The preconstruction testing requirements for the compression test cores were as follows:

1. Average strength of six core compressive strength tests on three vertical panels at 24 h: 9.7 MPa minimum,
2. Average strength of six core compressive strength tests on three vertical panels at 7 days: 22.1 MPa minimum, and
3. Average strength of six core compressive strength tests on three vertical panels at 28 days: 28 MPa minimum.

Testing requirements during construction were as follows:

1. Contractor to test three cores for every 100 m^3 of material used in the shotcrete lining; tested for 1- and 28-day strength, respectively; and
2. The required strength values for 1- and 28-day testing remained the same as the preconstruction requirements.

Mix Design and Fiber Selection

Contract documents mandated the use of fiber reinforcement, but either steel or synthetic fibers could be used. Kiewit elected to use synthetic fibers. The initial mix design had a fiber dosage of 5 kg/m^3 of Shogun 48. The dosage rate of Shogun 48 changed throughout the project from 5 kg/m^3 to 7 kg/m^3 and then to 6 kg/m^3. The fiber type was changed to a newer product (Barchip 54), with 1 year left of excavation, and it was dosed at 5 kg/m^3. The initial fiber dosage rate was changed from 5 kg/m^3 to 7 kg/m^3, because the ASTM C1550 tests did not consistently reach 320 J. The rate was reduced to 6 kg/m^3 after the contractor refined the panel shooting and curing process.

RDP Test on Site

Kiewit decided to conduct the RDP test on site after a local facility could not be found to run the tests in a timely manner. Kiewit contracted Lewis Martin of Martin Designs to design and construct an RDP testing machine for use at Devil's Slide. The machine is shown in Figure 4.

FIGURE 4 RDP test machine with panel.

Panel Production

Production of the ASTM C1550 panels began with the circular metal ring forms, which were mounted on a wood pallet. The forms had a diameter and height of 800 and 75 mm, respectively, per ASTM C1550 specifications (Figure 5). The ring forms, and the wooden pallets on which they were mounted, were coated in form oil to allow easy extraction of the shotcrete panel. The forms were taken into the tunnel, where they were filled with shotcrete, along with a box panel from which cores would be taken for compression testing.

FIGURE 5 Metal form for panels mounted on wooden pallet.

The panels were produced after approximately half a concrete truckload was used. When they were sprayed, the panels were propped up at a 45° angle, and the shotcrete nozzle was kept at a distance of approximately 1.5 m from the panels. As soon as the spraying was completed, the excess shotcrete was removed from the top of the forms with a screed. The panels were covered with burlap, plastic, and a curing blanket and left in the tunnel for 20 h.

After 24 to 48 h, the panels were removed from the tunnel and placed in a curing room. The longer they stayed in the tunnel before they were handled, the better the panels performed (as long as they were not disturbed by the excavation process). The temperature of the curing room was maintained at 21° to 32° Celsius, with 95% relative humidity. Approximately 2 to 6 days after production, the panels and their forms were removed from the pallets on which they were mounted, dampened on both sides, covered in wet burlap, and wrapped in plastic. On Day 6, the panels were unwrapped, removed from their metal forms, and left uncovered to dry before they were tested on Day 7.

Panel Tests

Before they were tested, the 90-kg (200-lb) panels were removed from the curing room and placed in the testing apparatus with a hand-operated forklift. Then three diameter and six thickness measurements were recorded for each panel. A panel was removed from the curing room only when it was time for the panel to be tested. During the test, the panel rested on three, evenly spaced pivots. Once the test began, the semispherical steel piston progressed at a rate of 4 mm per minute, and steadily applied a load to the center of the panel. The energy absorption and force applied were hand-recorded by the tester at 10-, 20-, 30-, and 40-mm deflections; however, the machine measured the force continuously every ½ s. Once a test was completed, the panel was removed from the machine, and the three pieces were separated for a fiber count. A 20-cm segment was marked off on the adjoining edges of two of the three breaks. It was within the 20-cm segments that the pulled and torn fibers were counted and recorded. To obtain final measurements of the panels, three thicknesses along the breaks, and one center thickness were recorded. The data were plotted as a load-net deflection curve, with a maximum deflection value of 40 mm. The area under the curve represented the energy absorption of a panel. Its value was entered into a formula and corrected to account for any deviation from ASTM C1550 specifications in thickness or diameter. The corrected values for each panel were averaged to determine whether the tested set surpassed 320 J. The correction formula was as follows:

$$W = W'\left(\frac{t_0}{t}\right)^{\beta}\left(\frac{d_0}{d}\right) \tag{1}$$

where

$\beta = 2.0 - \frac{(\delta - 0.5)}{80}$

W = corrected energy absorption,

W' = measured energy absorption,
t = average thickness (mm),
t_0 = nominal thickness of 75 (mm),
d = average diameter (mm),
d_0 = nominal diameter of 800 mm, and
δ = specified central deflection at which capacity to absorb energy is measured (mm).

RESULTS

The initial panel tests with the 5-kg/m^3 mix produced varied results. Approximately 52% of the tests achieved the required 320 J of energy absorption after correction, for an average of 313 J. Once the fiber dosage was increased to 7 kg/m^3, 91% of the tested panels surpassed 320 J of energy absorption, for an average of 392 J. The fiber dosage at 6 kg/m^3 gave an average of 355 J, and 80% of the tests surpassed the specified 320 J. The Barchip 54 fiber dosed at 5 kg/m^3 gave an average test result of 351 J, and 79% of the tests surpassed the specified 320 J. Figure 6 displays the corrected averages of the panel sets throughout the entire excavation. The Shogun 48, dosed at 6 kg/m^3, and the Barchip 54, dosed at 5 kg/m^3, produced similar results but still had lower averages than the Shogun 48 dosed at 7 kg/m^3. The increased fiber content dosage was not the only reason for the improvement in test results after the switch from Shogun 48 dosed at 5 kg/m^3. The improvement in results is discussed in greater detail in the section that follows.

DISCUSSION OF RESULTS

Impact of Variables on Testing

RDP testing results can be affected by many variables, especially during production testing. Many of the failed tests at Devil's Slide could be attributed to variables unrelated to the quality of the shotcrete or fiber product. The variables encountered at Devil's Slide could be separated into four categories: (*a*) mechanical, (*b*) addition of fiber into the mix, (*c*) panel production, and (*d*) panel curing process.

Mechanical

The biggest mechanical issue was with regard to accelerator dosing. If the shotcrete equipment did not dose the accelerator correctly, the 7-day strength of the panels could vary. Too much accelerator could make the concrete brittle and cause the shotcrete to set too quickly, which would make it difficult to screed the panel to its required thickness. Too little accelerator could result in a low-strength panel at the 7-day strength test. It was important to quickly discover and correct dosing issues during shotcrete operation.

Addition of Fiber into the Mix

Addition of fiber was found to be critical to achieve the needed distribution of fiber in the mix. If the fibers were added to the mix from the bag all at once, they would tend to clump into balls, and the distribution would be poor. The fibers needed to be added in a more

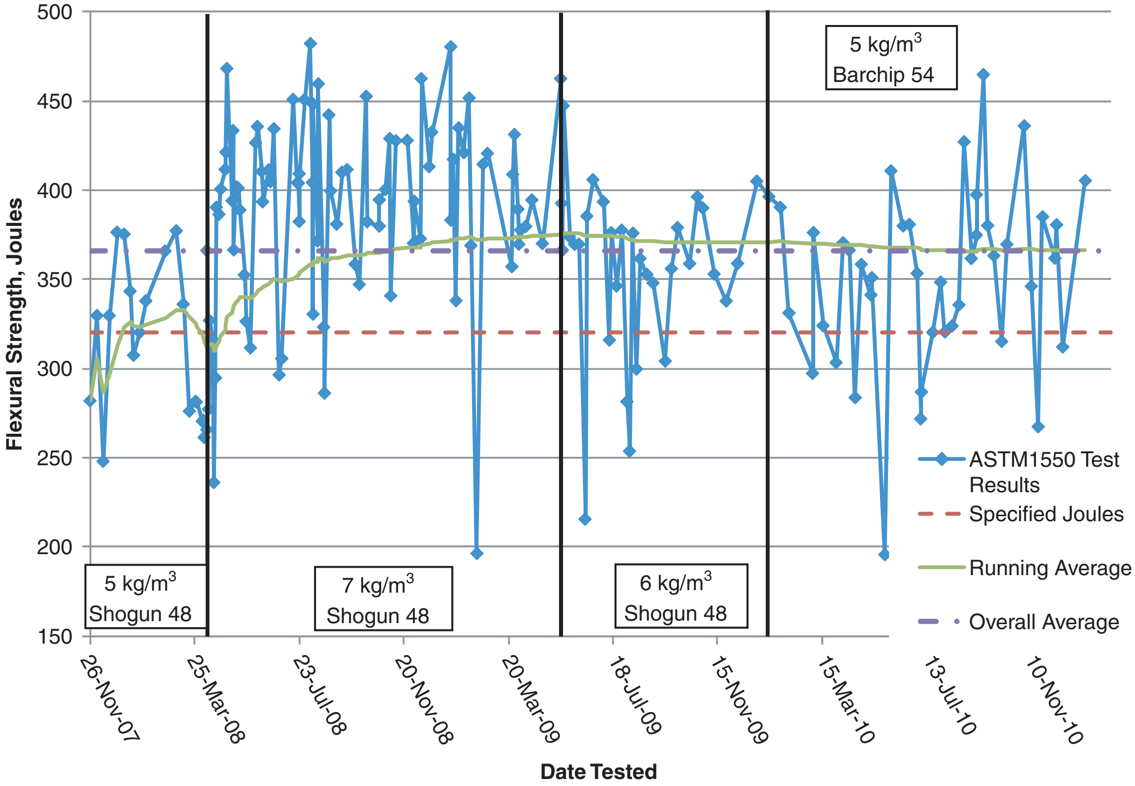

FIGURE 6 Panel energy absorption versus date of testing.

dispersed manner. This was accomplished through the addition of a feeding shoot through which fibers could be poured, and flow down and disperse somewhat before they entered the mix.

Panel Production

Many variables can affect the quality of panel production. For example, the actual shooting of panels can have an effect on panel quality. At Devil's Slide, a 1.5-m distance between the nozzle and the panel produced a better product. The velocity at which shotcrete is applied also can have an adverse effect on the panel fiber count and subsequent energy absorption. This is evident in a comparison of panels produced by hand nozzle (lab testing) versus those produced by a shotcrete robot in the field. Such an effect most likely is the result of the higher velocity in the robot application, which causes the fibers to rebound.

Early in the excavation at Devil's Slide, over a period of nearly a month, almost none of the panels passed the test. The contractor realized that too many people, excluding nozzlemen, were involved in the panel production process. This made it difficult to trace the source of problems in the production process when panels failed. The contractor hired a craft specialist to be trained on the test and to be responsible for the panels from production to testing, which eliminated the involvement of the general crew in the panel production process. With one individual responsible for the panels, the quality greatly improved.

Only a few instances were noted where the shotcrete quality led to low test results. In these cases, low test results were measured with the core compression testing as well. Most of the time, the low results were related to the quantity of the fiber and disturbances during the curing process. In a tightly controlled lab test, the size of the shotcrete panels may not create so many production issues. However, the size of the test panels created many challenges in the field. Although the RDP test was an indication of the quality of the shotcrete, it was not a perfect sample of what actually was applied to the tunnel wall. There were several important differences between shotcrete shot onto panels and shotcrete shot onto rock walls. First, the flexibility of the panels was much higher than that of the rock, which caused vibration and bouncing when the panels were shot. Second, the shotcrete in the panels was thinner than any applied shotcrete in the tunnel. Third, the shotcrete in the panel was screeded and made to be smooth. Last, the shotcrete in the panel was confined to the dimension of the panel, whereas the shotcrete in the tunnel was applied over the whole area of the tunnel wall. Early in the testing program, most of the panels were thicker than 75 mm, which incurred a penalty on the energy absorption value when corrected to compensate for the variation in thickness. The metal form was the correct height to produce the thickness of 75 mm as defined in ASTM C1550, but the panels were still too thick. A set of new forms was fabricated that conformed to the ASTM C1550 specifications with the exception of the height, which was reduced to 72 mm. The panels produced subsequently were much closer to the required 75-mm thickness.

An important production goal was to reduce disturbances to the early-age panels as much as possible. These disturbances included transportation of the panels out of the tunnels and their removal from the wood that backed the pallets and the metal form rings. To assist in panel removal, form oil was applied to the metal form rings and the wooden pallets before a set of panels was shot. Before the contractor implemented the use of form oil, removal of the panel from its metal form often was traumatic, with the potential to create microfractures in the panels. The wooden pallet on which the panel and form were mounted introduced another potential panel disturbance. A pallet with too much flexibility would increase the likelihood that the shotcrete panel would crack or weaken during transport.

Panel Curing Process

Improper curing can have a significant effect on the quality of shotcrete and flexural toughness. Curing issues can arise when the panels are in the tunnel for the first 24 h. During this time in the tunnel at Devil's Slide, the panels could be physically disturbed by equipment, uncovered, moved too early, or sustain some other type of damage or disturbance. The contractor learned that panels tested higher if they were stored on the side of the tunnel opposite the auxiliary fan, so that they did not dry out from too much air flow.

In the curing room, further potential issues arose. If unnoticed, they could have had an effect on the panels. The curing room at Devil's Slide was heated with a radiating heater, and if it was not monitored, room temperature could be too high or too low. If doors were left open for too long, the temperature could quickly drop to unacceptable values until the reestablishment of the correct ambient temperature. The location of the panels with respect to the heater could have had an effect as well. Panels set next to the heater might dry out faster, whereas those farther away might remain moist on the testing day. The panels performed well if they were left in the tunnel for more than 24 h because the tunnel had a good curing atmosphere. However, the longer the panels remained in the tunnel, the greater the chances were that they would be disturbed. The curing room at Devil's Slide is shown in Figure 7.

General Trends

The testing results were analyzed to determine any trends in the data and what variables might have caused them. The most pronounced change in the data was the positive trend in the panel results after the increase of the fiber content from 5 to 7 kg/m^3. This positive trend clearly could be attributed to the increase in the fiber dosage

FIGURE 7 Curing room at Devil's Slide.

and to the quality control measures implemented. However, on initial implementation of the increased dosage, panels still failed with no significant deviation from the previous trend. This observation strongly supported the importance of the quality assurance and quality control changes implemented by the contractor and the need for a strictly controlled environment for panel production and storage.

Further analysis of the 5-kg/m^3 and 7-kg/m^3 dosages allowed comparison between laboratory and field testing. The fiber manufacturer anticipated energy absorption values of 350 J and 490 J for the 5-kg/m^3 and 7-kg/m^3 dosages, respectively. However, the average value achieved for the 5-kg/m^3 dosage panels was 313 J, while the value for the 7-kg/m^3 dosage panels was 392 J. This finding showed how difficult it was to achieve the ideal energy absorption values obtained in lab testing in whose controlled environment the panels were produced with a hand nozzle instead of a shotcrete robot.

An additional inquiry was made to see how the failing panels in the RDP tests compared with the results of the compression tests. The comparison was inconclusive. In most instances, the shotcrete batches that produced RDP test panels that failed also produced sufficiently strong cores. It was concluded that, in general, the failure of a panel could not necessarily be attributed to poor shotcrete strength. A few select panel groups displayed failing results for both RDP and compressive strength tests. Failure of both tests indicated that quality control was an issue with the actual shotcrete and demonstrated that a compression test was a more likely determinant of shotcrete quality than the RDP test.

With respect to the precision of the RDP test, ASTM C1550 states that "the results from two properly conducted tests by the same operator on specimens made from the same batch of concrete are not expected to differ from each other by more than 17%." The standard deviation of the RDP tests at Devil's Slide (Table 2, Column 5) fell within this anticipated deviation.

The standard deviation was calculated for the corrected results for all of the tests of the same fiber type and dosage, and the results are given in Table 2. The results showed that the standard deviation was practically equal for all fiber types and dosage rates. Therefore, the variability in the test data was almost the same for every scenario, and it was to be expected when ASTM C1550 shotcrete panels were tested in the field. In production testing of the Shogun 48 fibers, about 60 J were achieved per kilogram of fiber used in 1 m^3. The Barchip 54 resulted in about 70 J/kg of fiber used. Therefore, the Barchip 54 achieved the anticipated joules per kilogram.

TABLE 2 Standard Deviation and Average for Each Fiber Type and Dosage

Fiber Type	Fiber Dosage (kg/m^3)	No. of Tests	Average (joules)	Standard Deviation (joules)	Joules per kg/m^3
Shogun 48	5	23	313	42	63
Shogun 48	7	85	392	51	56
Shogun 48	6	30	355	42	59
Barchip 54	5	42	352	50	70

NOTE: No. = number.

DEFORMATION

The synthetic, fiber-reinforced shotcrete performed well in areas of deformation and cracking. In some areas of the tunnel, up to 100 mm of deformations were observed. and cracking occurred in the shotcrete liner. The postcrack performance of the synthetic fiber was excellent and kept the cracked concrete from deteriorating and falling out (*4*). The shotcrete liner sustained the deformation and maintained the overall stability of the tunnel.

ADVANTAGES AND DISADVANTAGES

The use of synthetic, fiber-reinforced shotcrete in transportation tunnel construction projects offers many advantages, including the following:

- Flexural strength. Excellent performance is shown in the provision of postcrack flexural strength to the shotcrete.
- Equipment wear. Synthetic fibers produce less wear and tear on equipment than steel fibers.
- Worker safety. Not only do the fibers provide postcrack flexural strength, which creates safe excavations, they are safer to work with (e.g., they are light to lift and they do not pose puncture hazards on the surface of the shotcrete tunnel, which steel fibers can).
- Fire protection. Synthetic fibers can minimize spalling shotcrete as the result of fire damage, because the melting fibers create pore space that can relieve pressure in the shotcrete (*5*).
- Rust. Synthetic fibers will not rust the way steel fibers do.
- Waterproofing. Unlike steel fibers, synthetic fibers do not damage waterproofing membranes, and additional smoothing shotcrete does not need to be applied to cover the fibers before water proofing is installed.

Synthetic fibers also present several disadvantages, such as the following:

- Reinforcement design. No accepted method exists to use synthetic fibers as concrete reinforcement in design. Because the modulus of the fibers is lower than concrete, it is difficult to rely on the fibers as reinforcement in design.
- Creep. Creep is a concern that needs to be addressed in certain long-term applications (*6*).
- Fire protection. The fiber melts at temperatures that are common in tunnel fires. Thus the fibers cannot be relied on for flexural strength after or during fires.

LESSONS LEARNED AND GUIDELINES

The experience gained at Devil's Slide from use of the RDP test on shotcrete panels produced a series of valuable guidelines and lessons learned, which might apply to future projects. They include the following:

1. Numerous variables can affect the outcome of ASTM C1550 production testing.
2. Tight control of panel production must be maintained from shooting to curing.
3. The expertise of the nozzlemen and the method used to spray shotcrete can affect panel quality and testing results.

4. The characteristics of the panels themselves (e.g., flexibility or rigidity, dimensions, early-age disturbance) may affect test results.
5. The method used to mix the fibers should be designed to allow the fibers to be added in a dispersed state.
6. Variability tends to be relatively high in production testing.
7. Experience reduced variability over time and improved overall results at Devil's Slide.
8. Design of the fiber mix should take into account the greater variability in production testing than in laboratory testing.
9. The Shogun 48 resulted in 60 J/kg of fiber, whereas the Barchip 54 resulted in 70 J/kg of fiber.
10. The synthetic fiber performed well when high levels of tunnel deformation were encountered and cracking occurred in the initial lining.

CONCLUSIONS

The RDP test at Devil's Slide demonstrated that (*a*) a controlled environment in which to prepare panels, and (*b*) the expertise of those who were involved in panel preparation and testing, were key to success. Design of the fiber mix for a project should take into account the significant drop in panel energy absorption when testing is done in the field rather than in a highly controlled lab setting. Use of the RDP test is expanding. Demonstrations of its use, such as the experience at Devil's Slide, will help to further the reliability and repeatability of the test. In addition, the use at Devil's Slide of synthetic, fiber-reinforced shotcrete for the initial lining was successful and demonstrated the use of the product for transportation tunnel construction.

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