EXPERIENCE WITH SYNTHETIC FIBER REINFORCED INITIAL SHOTCRETE LINING AT THE DEVIL'S SLIDE TUNNEL PROJECT

ERFAHRUNGEN MIT SYNTHETISCHEN FASERN IM SPRITZBETON TUNNELAUSBAU AM DEVIL'S SLIDE PROJEKT

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The conventional tunnel design of the Devil's Slide Tunnel project near San Francisco, California anticipates relatively large deformation in weak rock conditions. To ensure adequate shotcrete initial lining performance, the Contract Documents address the shotcrete flexural strength and its capability to absorb energy post shotcrete section failure using the Round Determinate Panel (RDP) test. To meet the specified requirements of RDP values in excess of 320 joules at 40 mm deflection the Contractor elected to use polypropylene fibers for shotcrete reinforcement. The paper proposes a general overview of shotcrete testing using the RDP test, correlation of deformation performance to rock mass deformation and practical experience with this product, in particular the associated testing.

Für den bergmännischen Vortrieb des Devil's Slide Tunnels nahe San Francisco, Kalifornien, werden relative hohe Ausbauverformungen erwartet. Um eine entsprechende Spritzbetonsicherung sicher zu stellen, sind im Vertragswerk die Anforderungen an die Biegezugfestigkeit und die Energieabsorbtionsfähigkeit für den gerissenen Spritzbeton festgelegt. Als Testmethode legen die Vetragsdokumente den „Round Determinate Panel Test" fest. Um den vertraglichen Anforderungen gerecht zu werden, müssen Werte von mindestens 320 Joules bei einer Verformung von 40 mm erzielt werden. Dieser Beitrag bietet einen allgemeinen Überblick über die Testergebnisse, Vergleiche zwischen den Testergebnissen und tatsächlich gemessenen Gebirgsverformungen und die allgemeinen Versuchserfahrungen.

1. Introduction

The Devil's Slide Tunnels project on CA-1 in Pacifica, California is designed to bypass a slide-prone section of CA-1 known as Devil's Slide. The California Department of Transportation (CALTRANS) has contracted Kiewit to construct the two tunnels which will cut through San Pedro Mountain. Gall Zeidler Consultants is a sub-consultant to Kiewit, providing integrated on-site team support services for the conventional (NATM) construction and engineering support. The Devil's Slide Tunnels are two (2) parallel, single-lane highway tunnels with a total length of 2440 m (8000 ft), with cross sections of up to 120 m^2 (1290 ft^2). The tunnels will be constructed in faulted and weathered granite diorites and interbedded conglomerates/sandstones/siltstones/claystones. Tunnel excavation is ongoing and experience with Fiber Reinforced Shotcrete (FRS) has been gained in ground support categories I, II and III to date.

2. Round Determinate Panel (RDP) test

2.1 History & development

The flexural toughness of FRS can be determined using a variety of internationally recognized methods, including Beam tests (ASTM C1018) and the EFNARC panel test [4]. In 1998, Dr. E. S. Bernard developed a new method to test flexural toughness while at the University of Western Australia, Sydney [2, 3]. The new test is known as the Round Determinate Panel (RDP) test.

2.2 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 3 molded round fiber reinforced shotcrete or cast concrete panels are to be produced for testing, from which 2 must test correctly. To test correctly, a panel must break in 3 pieces as shown in Figure 1 and be within certain size specifications. ASTM 1550 specifies a height and diameter of the panels of 75 mm and 800 mm respectively. Testing involves the application of a load to the center of the panel by a hemispherical-ended steel piston. The load is controlled by a PLC to maintain a constant deflection rate of 4.0 ± 1.0 mm/min. The panel rests on 3 pivots evenly spaced around its circumference and deflection is carried out until a central displacement of at least 40.00 mm is achieved. The energy absorbed is recorded at 10, 20, 30, and 40 mm deflection. ASTM C1550 does not expect results from two properly conducted tests of specimens produced from the same batch of shotcrete to differ by more than 17%.

Figure 1: Panel displaying a successful break

2.3 Correlation of RDP to support classes

In his paper, "Design Guidelines for the use of Fiber Reinforced Shotcrete in Ground Support," F. Papworth attempts to correlate the Toughness Performance Levels (TPL) by D. R. Morgan with the Q-system classes and FRS performance [4]. Table 1 is a modified table displaying the Standard Deflection Criteria of Papworth's correlation in which the TPLs are defined by Morgan as follows [4]:

1) TPL IV – Appropriate for situations involving severe ground movement, with an expectation for cracking of the SFRS lining, squeezing ground in tunnels and

mines, where additional support in the form of rock bolts and/or cable bolts may be required.

2) TPL III – Suitable for relatively stable rock in hard rock mines or tunnels where low rock stress and movement is expected and the potential for cracking of the SFRS lining is expected to be minor.

3) 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 is providing mainly thermal and shrinkage crack control and perhaps some enhanced impact resistance.

Morgan's TPL's are based on ASTM C1018 beam tests; however, results from panel tests are the preferred way for the assessment of shotcrete for tunnel linings so the EFNARC panel-based toughness performance recommendations were developed based on Morgan's TPL and published performance data. Using these EFNARC performance recomendations and an RDP correlation developed by Dr. Bernard [2], Papworth created the correlations shown in table 1. It is important to note that these values represent test results for panels 28 days in age.

Tab. 1: Correlation of Morgan's TPLs to Q-System rock classes, and EFNARC and RDP values (regarding to Papworth [4])

Ground Condition		Standard Deflection Criteria	
TPL	**Rock Class**	**EFNARC (Joules)**	**RDP_{40mm} (Joules)**
IV	F	>1400	>560
	E	>1000	>400
III	D	>700	>280
II	C	>500	>200

The Norwegian Concrete Association (NCA) attempted to correlate Energy Absorption from the RDP test with the Q-System developed by Barton (see Figure 2). [4]

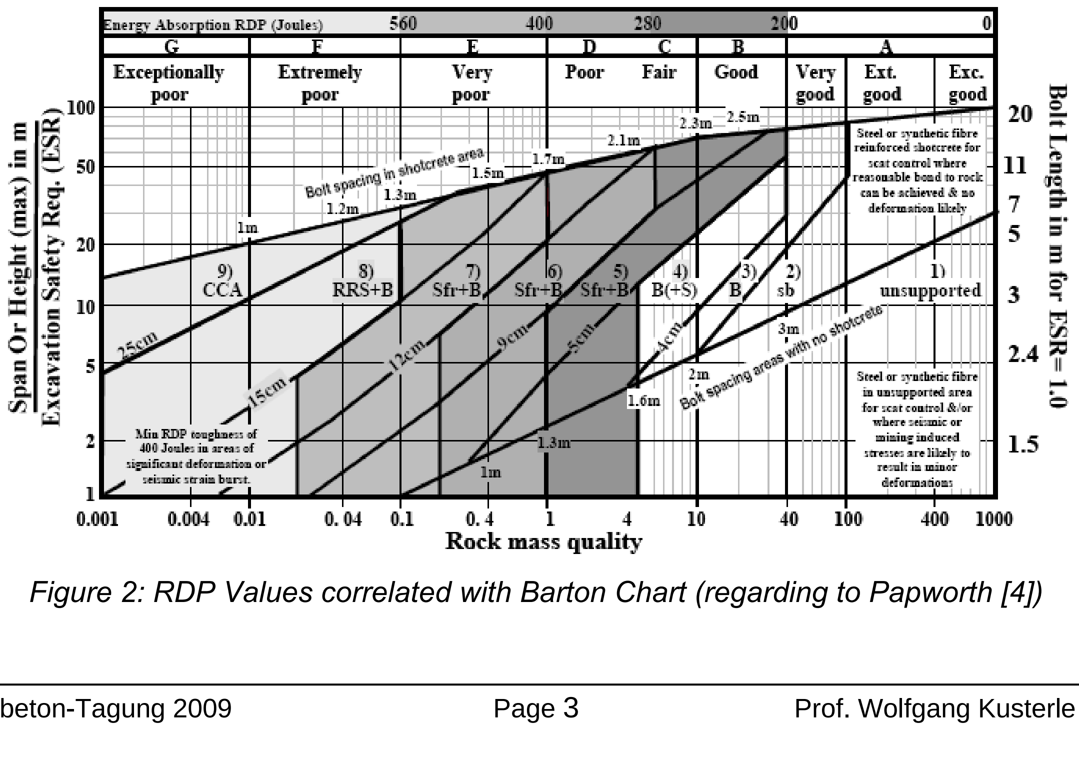

Figure 2: RDP Values correlated with Barton Chart (regarding to Papworth [4])

3. Devil's Slide tunnels project

3.1 Contract requirements

The Devil's Slide Tunnels project documents required the use of the RDP test as per ASTM 1550 to assess the energy absorption capacity of the fiber reinforced shotcrete. The contract mandates a required minimum average energy absorption value of 320 Joules at 40 mm displacement at a shotcrete age of 7 days. This value was established by CALTRANS' tunnel designer, ILF Consultants, and encompasses all 5 ground support categories at Devil's Slide. At least 3 RDP test panels and 1 box panel for compression test cores are to be produced for every 100 m^3 of material used in the shotcrete initial lining. After testing the 3 panels, the energy absorption of the top two are averaged. The average of the top two panels must surpass the required 320 Joules in order for the test to pass.

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

- *a)* Avg. strength of 6 core compressive strength tests on 3 vertical panels, at 24 hours: 9.7 MPa minimum.
- *b)* Avg. strength of 6 core compressive strength tests on 3 vertical panels, at 7 days: 22.1 MPa minimum.
- *c)* Avg. strength of 6 core compressive strength tests on 3 vertical panels, at 28 days: 28 MPa minimum.

Testing requirements during construction are as follows:

- *a)* Contractor to test 3 cores for every 100 m^3 of material used in the shotcrete lining, tested for 1 and 28 day strength respectively.
- *b)* Required strength values for 1 and 28 day testing remain the same as pre-construction requirements.

3.2 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 current fiber dosage is 7 kg/m^3; however, in the initial mix design a fiber dosage of 5 kg/m^3 was used. The 5 kg/m^3 dosage was chosen based on an anticipated fiber performance of 70 J/kg, resulting in 350 Joules energy absorption.

However, RDP testing results were not consistently reaching 350 Joules. Hence, the Contractor increased the dosage to the current level of 7 kg/m^3, with anticipated energy absorption of 490 Joules.

3.3 The Round Determinate Panel Test at Devil's Slide Tunnels project

Kiewit decided to conduct the RDP test on-site after being unable to locate a local facility capable of running the tests in a timely manner. Kiewit contracted Lewis Martin of Martin Designs to design and construct a RDP testing machine for Devil's Slide. The machine is shown in Figure 3.

Figure 3: Round Determinate Panel Test machine with panel (Picture: Timothy O'Brien)

3.3.1 Panel production
Production of the panels begins with the circular metal ring forms which are mounted on a wood pallet. The forms have a diameter and height of 800 and 75 mm respectively as per ASTM 1550 specifications (see figure 4). The ring forms and the wooden pallets on which they are mounted are coated in form oil to allow easy extraction of the shotcrete panel. The forms are taken into the tunnel where they are filled with shotcrete along with a square panel for cores.

The panels are produced after approximately half a concrete truck load has been used. When spraying, the panels are propped up at a 45 degree angle and the shotcrete nozzle is kept at approximately 1.5 meters distance from the panels. As soon as spraying is completed, the excess shotcrete is removed from the top of the forms using a screed. The panels are covered with burlap, plastic, and a curing blanket and left in the tunnel for 20 hours.

After 20 hours, the panels are removed from the tunnel and placed in a curing room. The temperature of the curing room is maintained at 21° to 32° Celsius with 95% relative humidity. Approximately 2 days after production, the panels and their forms are removed from the pallets on which they are mounted, dampened on both sides, covered in wet burlap, and wrapped in plastic. On the 6th day, the panels are unwrapped, removed from their metal forms, and left uncovered to dry before testing on day 7.

Figure 4: Metal form for panels mounted on wooden pallet (Picture: Jeramy Decker)

3.3.2 Testing the panels

Before testing, the 90 kg (200 lb) panels are removed from the curing room and placed in the testing apparatus using a hand operated forklift. Then 3 diameter and 6 thickness measurements are recorded for each panel. A panel is removed from the curing room only when it is time for the panel to be tested. For the test the panel rests on the three evenly spaced pivots. Once the test begins, the semi-spherical steel piston progresses at a rate of 4 mm per minute, steadily applying a load to the center of the panel. The energy absorption and force applied are hand recorded by the tester at 10, 20, 30 and 40 mm deflection, however, the machine measures the force continuously every ½ second. Once testing is completed, the panel is removed from the machine, and the 3 pieces are separated for a fiber count. A 20 cm segment is marked off on the adjoining edges of 2 of the 3 breaks. It is within the 20 cm segments that the pulled and torn fibers are counted and recorded. Final measurements of the panels involve recording total of 3 thicknesses along the breaks and 1 center thickness. The data is plotted as a Load-Net Deflection curve with a maximum deflection value of 40 mm. The area under the curve represents the energy absorption of a panel. The energy absorption value is entered into a formula and corrected to account for any deviation from the ASTM 1550 specifications in thickness or diameter. The corrected values for each panel are averaged to determine whether the tested set surpasses 320 Joules. The correction formula is as follows [1]:

$$W = W' (t_0 / t)^{\beta} (d_0 / d) \quad \text{where } \beta = 2.0 - (\delta - 0.5) / 80 \qquad (1)$$

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

4. Results

The initial panel tests with the 5 kg/m^3 mix produced varying results with approximately 64% of the individual panels tested falling below the required 320 Joules energy absorption after correction. Once the fiber dosage was increased to 7 kg/m^3 approximately 80% of the panels tested surpassed 320 Joules energy absorption. Figure 5 displays the corrected averages of the panel sets for the 5 kg/m^3 and 7 kg/m^3 fiber dosages. The positive trend that has developed since increasing the fiber dosage to 7 kg/m^3 can clearly be seen. The changed fiber content was not the only reason for this positive trend; however, this will be discussed in greater detail below.

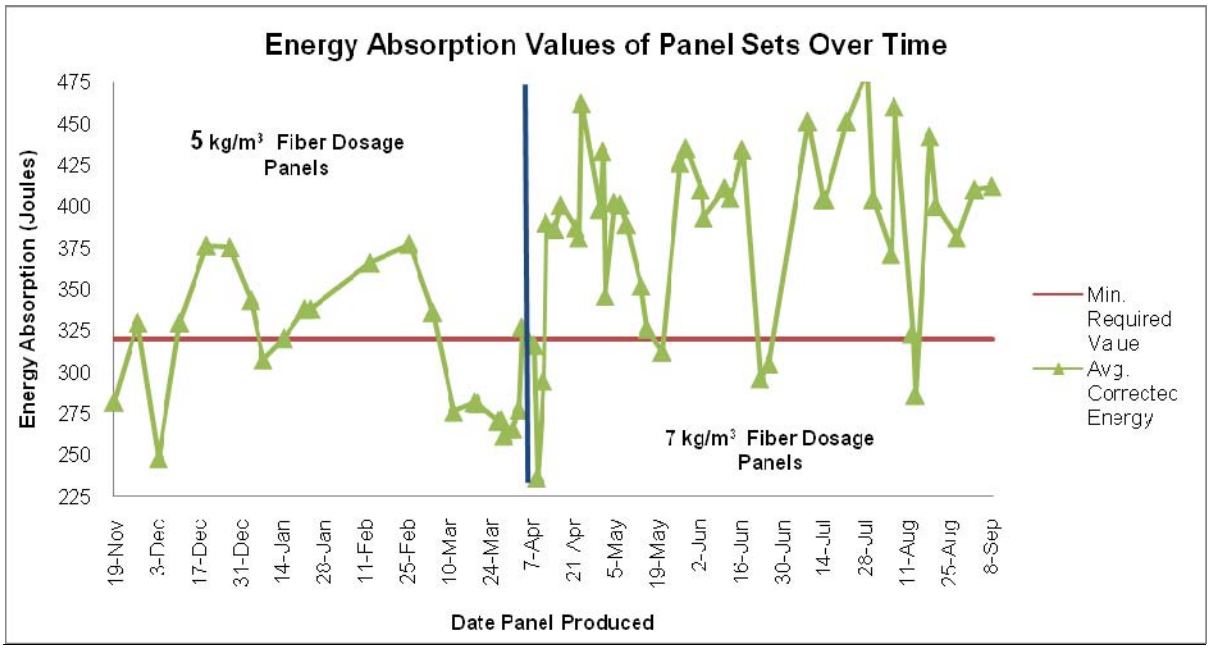

Figure 5: Panel energy absorption vs. date of testing

5. Discussion of results

5.1 Impact of variables on testing

RDP testing results can be affected by many different variables, especially during production testing. Many of the failed tests at Devil's Slide can be attributed to variables that are not related to the quality of the shotcrete or fiber product. The variables encountered at Devil's slide can be separated into 3 categories: (1) mechanical, (2) panel production, and (3) panel curing process.

5.1.1 Mechanical

Two mechanical problems have been encountered that have influenced the testing results. The first problem is in regards to the shotcrete robot. An issue within the machine was discovered, which lead to incorrect dosing of the accelerator. If the machine is not dosing the accelerator correctly, the 7 day strength of the panels can vary. Too much accelerator could make the concrete brittle in addition to causing the shotcrete to set too quickly, making it difficult to screed the panel to its required thickness. Too little accelerator will potentially yield a low-strength panel at the 7 day strength test. The Contractor has taken proper measures to correct the issue, however, it is important to persistently evaluate and calibrate the shotcrete robot to avoid such problems.

5.1.2 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 it was found that maintaining a 1.5 meter distance between the nozzle and the panel produces a better product. The velocity at which the shotcrete is applied can also have an adverse effect on the panel fiber count and subsequently energy absorption. This is evident when comparing panels produced by hand nozzle (lab testing) versus those produced by a shotcrete robot in the field.

During the period of nearly a month, almost none of the panels were passing 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 be responsible for the panels from production to testing, eliminating the involvement of the general crew in the panel production process. With one individual responsible for the panels the quality greatly improved.

Early in the testing program, it was observed that the majority of the panels were thicker than 75 mm, incurring 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 1550, but the panels were still too thick. A set of new forms was fabricated conforming to the ASTM 1550 specifications with the exception of the height, which was reduced to 72 mm. The panels now produced are much closer to the required 75 mm thickness.

An important goal in panel production is to reduce disturbances to the early-age panels as much as possible. These disturbances include transportation of the panels out of the tunnels and removal of the panels from both the wood backing pallets and metal form rings. To assist in panel removal, form oil is applied to the metal form rings and the wooden pallet before shooting a set of panels. Before the Contractor implemented the use of form oil, removing the panel from its metal form could often be traumatic, potentially creating micro-fractures in the panels. The wooden pallet on which the panel and form are mounted introduces another potential cause for panel disturbance. A pallet that has too much flexibility will increase the likelihood for causing cracks in or weakening of the shotcrete panel during transport. The Contractor has recently begun looking into switching to more rigid steel plates.

5.1.3 Panel curing process

Improper curing can have a significant effect on the quality of shotcrete and their flexural toughness. Curing issues can begin when the panels are in the tunnel for the first 20 hours. During this time in the tunnel, the panels could be physically disturbed by equipment, un-covered, moved to early, or they sustain some other type of damage or disturbance.

Once in the curing room, there are further potential issues that, if go unnoticed, can have an effect on the panels. The curing room at Devil's Slide is heated using a radiating heater, however, if not monitored, there is the possibility of too high or too low room temperatures. If doors are left open for too long the temperature can quickly drop to unacceptable values until the re-establishment of the correct ambient temperature. Placement of the panels within the room with regards to their location compared to the heater can have an effect as well. Panels right next to the heater may dry out quickly compared with those further away which still may be moist on the testing day. The curing room at Devil's Slide is shown in figure 6.

Figure 6: Curing room at Devil's Slide (Picture: Timothy O'Brien)

5.2 General trends in results

The testing results were analyzed to determine any trends in the data and what variables may be causing these trends. The most pronounced change in the data is the positive trend in the panel results after the increase of the fiber content (figure 5). This positive trend can clearly be attributed to both the increase in the fiber dosage, as well as the quality control measures implemented. However, it is interesting to note that upon initial implementation of the increased dosage panels were still failing with no significant deviation from the previous trend. This observation strongly supports the importance of the QA/QC changes implemented by the Contractor and the need for a strictly controlled environment for panel production and storage.

Looking further into the 5 kg/m^3 and 7 kg/m^3 dosage, these results provide an interesting comparison between laboratory and field testing. The fiber manufacturer anticipated energy absorption values of 350 Joules and 490 Joules 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 310 Joules, while the value for the 7 kg/m^3 dosage panels is 388 Joules. It is important to note that these are averages of the corrected values for the 2 best panels for all the sets. The average for the panel sets inclusive of the 3rd panel was approximately 20 Joules less for both the 5 kg/m^3 and 7 kg/m^3 panels. This is an interesting observation as it shows the difficulty in achieving the ideal energy absorption values obtained in lab testing, which allows for a much more controlled environment including the production of the panels using a hand-nozzle instead of a shotcrete robot.

An additional inquiry was made into how failing panels compare to their compression test results. The results were inconclusive as in most instances shotcrete batches that produced failing panels produced sufficiently strong cores. From this information one can conclude that generally the failure of a panel cannot necessarily be attributed to poor shotcrete strength. A few selected panel groups displayed failing results in the RDP tests and compressive strength tests. The failure of both tests indicated that there was a QC issue with the actual shotcrete. This demonstrates that the compression production testing is likely to be adequate to determine whether there are shotcrete quality problems.

In discussing the precision of the RDP test, ASTM 1550 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% [1]." In most instances of test results at Devil's Slide this expectation has been met, however, occasionally two panels will produce results within 17% of one another, while the third panel is either much higher or much lower than the other two.

The standard deviation was calculated for the corrected results inclusive of all of the tested 5 kg and 7 kg/m^3 panels. The 5 kg/m^3 panels have a standard deviation of 54 Joules while the 7 kg/m^3 panels have a standard deviation of 71 Joules. However, once the most outlying test is taken out to compute the test average the standard deviation for the 5 kg and 7 kg results drop to 47 and 59 Joules respectively.

The averages for this test data of the 5 kg/m^3 and 7 kg/m^3 panels are 311 and 388 Joules respectively. Applying the ± 8.5% test variation to these averages produces an expected data range between 285 and 337 Joules for 5 kg/m^3 panels and 322 and 454 Joules for 7 kg/m^3 panels. The application of the standard deviation of the official test data to the averages produces a data range between 257 and 365 for 5 kg/m^3 panels and 355 and 421 for 7 kg/m^3 panels.

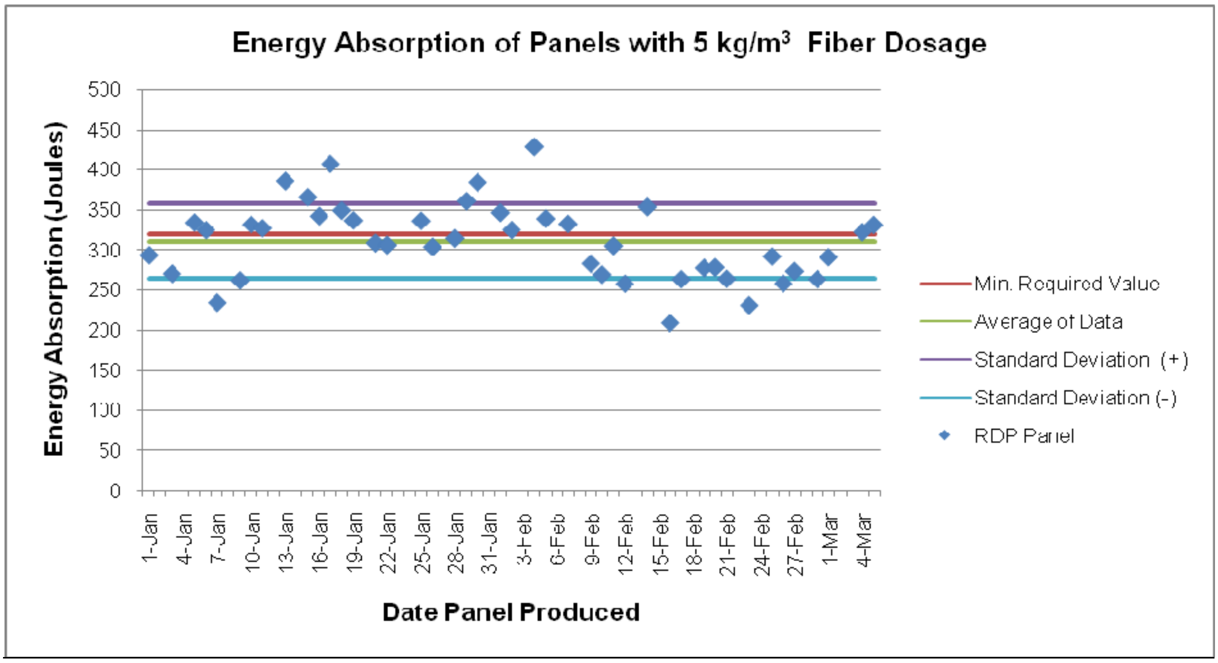

Figure 7: Energy absorption data for 5 kg/m^3 fiber dosage

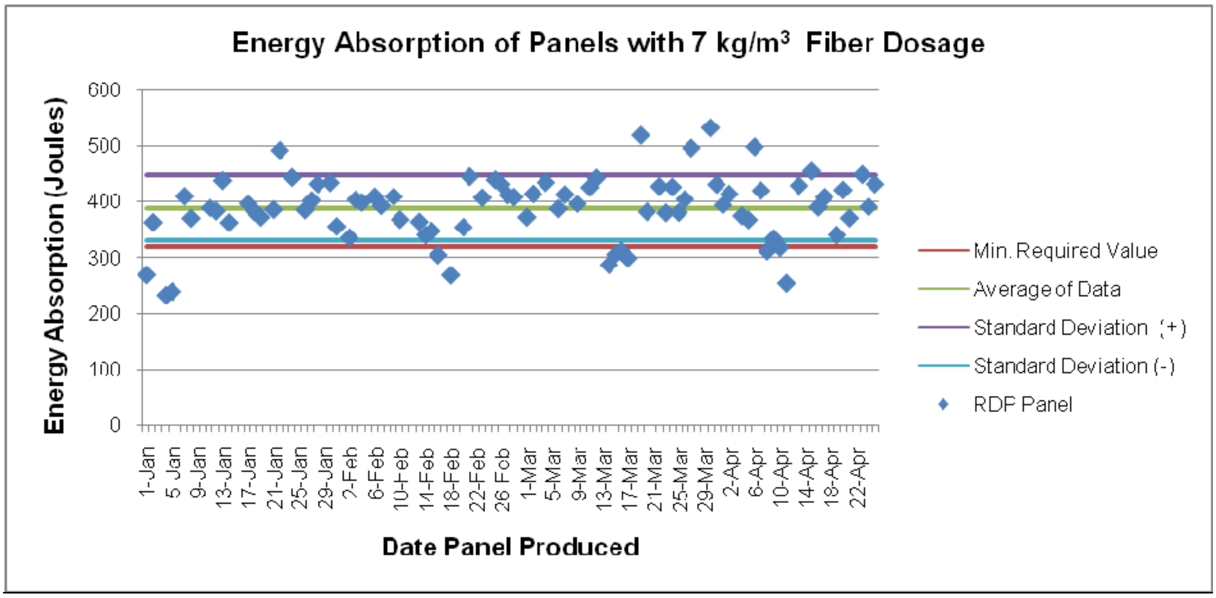

Figure 8: Energy absorption data for 7 kg/m³ fiber dosage

6. Deformation performance and rock mass deformation

Thus far, excavation has proceeded through ground support category I, II and III rock material. The majority of recorded deformation values have remained within the predicted levels for ground support categories I, II and III. A few locations have experienced deformation values ranging between 8 and 10 cm. However, shotcrete performance has been excellent thus far, including those sections that have experienced the greater deformation. The true test will begin once excavation proceeds through the weak ground support category IV and V rock material. Once excavation reaches this weaker material, additional analysis of the shotcrete performance can begin.

7. Lessons learned

a) Numerous variables can affect the outcome of ASTM C1550 production testing.
b) Tight control of the panel production must be maintained from shooting to curing.
c) The experience of the nozzleman and the method of shotcrete spraying can affect the panel quality and testing results.
d) The panels themselves (flexibility/rigid, dimensions, early age disturbance) may have an affect on the testing results.
e) The variability tends to be relatively high in production testing.
f) Experience has tended to reduce the variability over time and improve overall results at Devil's Slide
g) Design of the fiber mix should take into account the variability in production testing as compared to laboratory testing.

8. Conclusions

The experience with the Round Determinate Panel test at Devil's Slide has demonstrated that a controlled environment for the preparation of panels along with experience on the part of those involved in panel preparation and testing is key to successful testing. Design of the fiber mix for a project should take into account the significant drop in panel energy absorption when tested in the field in comparison to highly controlled lab testing. This test is ever expanding in its use on projects and experiences with it such as at Devil's Slide are important to further the reliability and repeatability of the Round Determinate Panel test.

9. References

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