Release of New ASTM Round Panel Test

Figure 1: Round panel test rig with tested specimen.

by Stefan Bernard

Following a 3-year development period, a new test for post-crack performance assessment of fiber-reinforced shotcrete (FRS) and fiber-reinforced concrete (FRC) based on round panels was passed by ASTM Committee C 09 in June 2002. The standard test method, known as C 1550-02, "Standard Test Method for Flexural Toughness of Fiber-Reinforced Concrete (Using Centrally-Loaded Round Panel)," was published in the 2002 edition of the *Annual Book of ASTM Standards* V. 4.02.[1] Publication of this standard test method is a major development in the fiber-reinforced shotcrete industry. It will, for the first time, permit a both reliable and economical estimation of post-cracking performance for this material.

The use of fibers in shotcrete has become an established form of reinforcement in many sectors of the underground construction industry over the last 20 years. The effective measurement of post-crack performance (toughness) in this material, however, is a problem that has plagued the industry and made the influence of parameters such as fiber type, mixture design, and spraying technique difficult to determine. Much of the difficulty is attributable to the high levels of within-batch variability obtained for even well-prepared sets of FRS samples when beams are used as the basis of toughness assessment. Typical levels of within-batch variability for toughness indices obtained using ASTM C 1018 beams range from 13 to 18%.[2,3] More than18% is common for residual strength obtained using EFNARC beams.[4] The imprecision associated with such high levels of variability has obscured trends in performance development and eroded confidence in the material. Some improvement occurred with the introduction of EFNARC panels in the 1990s,[5,6] but this test suffered its own difficulties associated with seating problems and high costs. Other types of specimens have seen occasional use,[7-10] but the size and expense of these tests have limited their use to special applications.

The first round panel test similar to the C 1550 configuration was undertaken in 1997 as part of an investigation of the influence of support conditions on structural behavior in FRC panels.[11] The potential of this test was recognized by the Roads and Traffic Authority of New South Wales in Australia, which immediately sponsored a comparative study of FRS performance for several commonly available fibers.[12] A specification based on this test[13] was also introduced for shotcrete intended for ground stabilization in association with road works. Interest among fiber manufacturers led to an extended comparative study of post-crack performance based on both beam and panel tests that resulted in performance correlations for several types of toughness tests.[14] This study established the superior repeatability of the round panel test compared with the alternatives and aroused the interest of ASTM Subcommittee C 9.42 as to its possible development as a standard test method. Under the stewardship of Pete Tatnall, and later Matt Miltenberger, this subcommittee appointed the author and Rusty Morgan as co-chairs of a task group to develop the round panel test. Vigorous input and debate within the subcommittee (with special thanks to Nick Carino and Ron Zollo) led to rapid development of the text for the standard, although few changes were made to the actual method of execution relative to the original RTA test.[13]

The test involves the imposition of a point load to the center of a round panel measuring ∅800 x 75 mm (31.5 x 3 in.) centered on three symmetrically arranged pivots located on a 750 mm (29.5 in.) diameter circle (see Fig. 1 to 3 for possible test rig and formwork configurations). The loading piston is advanced at a constant rate of 4 mm/min (0.157 in./min) using either a servocontrolled hydraulic actuator or electro-mechanical screw jack. Post-crack instability is less pronounced in panels supported using this configuration than in beams, but nevertheless can still occur in very brittle specimens; it is therefore important to use

Figure 2: Alternative round panel test rig with specimen under test.

Figure 3: Round panel forms ready for spraying.

a very stiff test rig satisfying the load train stiffness requirements specified within the standard. The test proceeds to a total central deflection of 40 mm (1.6 in.) after which the energy absorbed by the specimen is obtained as the integral under the load-deflection curve. The load-deflection response of a typical steel FRS is shown in Fig. 4 and that of a typical macrosynthetic FRC is shown in Fig. 5. The former characteristically exhibits higher residual load capacity immediately after cracking, while the latter exhibits higher residual capacity when the cracks have opened significantly. The average crack rotation angle φ suffered by the three radial cracks in a C-1550 panel at a given central deflection δ can be found (to within several percent) to be

$$\varphi = \sqrt{3}\frac{\delta}{r} \quad (1)$$

where r is the support radius, normally equal to 375 mm (14.8 in.). Performance at central deflections ranging from 5 to 40 mm (0.2 to 1.6 in.) can be used to judge the suitability of a FRS mixture for a variety of ground support conditions.

The round panel test offers contractors several important advantages over alternative forms of post-crack performance assessment. The most important of these is the low within-batch variability in results, but other advantages include the elimination of saw-cutting from the process of specimen production and the use of easy-to-prepare forms. Extensive testing of FRS based on round panels for tunneling and mining projects in Australia has demonstrated a reduction in QC costs of about 40% compared with the use of beams.[15]

The fact that saw-cutting is eliminated from the process of specimen preparation allows toughness to be assessed as soon as the specimen can support itself after stripping. Tests can therefore be done as little as two hours after spraying, depending on the type and dosage of set accelerator used.[16] This makes the round panel test a useful tool for studying FRS behavior in the first few hours after spraying, thereby helping to understand how the material interacts with the ground and leads to stabilization. If the specimen is carefully screeded before hardening, and the thickness made uniform, the cracking load can also be used to calculate the modulus of rupture of the concrete matrix based on a yield line analysis of structural behavior.[11,17] The stiffness of the panel prior to cracking of the concrete matrix can also be used to determine the quasi-elastic modulus of the matrix.[16] It must be stressed, however, that these matrix properties cannot be determined accurately if the thickness is variable or the panel surface is heavily pitted or otherwise ill-defined.

It is mainly the cracked part of a FRS specimen that is assessed during a toughness test. Therefore it is important to obtain a large cracked section if the test is to produce results that are representative of the material as sprayed. The large size of a round panel specimen compared to beams means that the result more accurately represents the performance of the material produced during spraying. The large area of crack surface generated is also, in part, responsible for the low within-batch variability in post-crack performance achieved using this test. Three radial cracks are formed in almost every specimen leading to a total crack length of 1200 mm (47 in.) compared with between 100 and 150 mm (4 to 6 in.) for most standard beam tests.

The importance of low within-batch variability is reinforced by the following analysis of the confidence possible in the mean result obtained for a set of FRS specimens. Given a within-batch variation for a normally-distributed population of specimens equal to σ, the number of specimens n required to ensure that the error between the

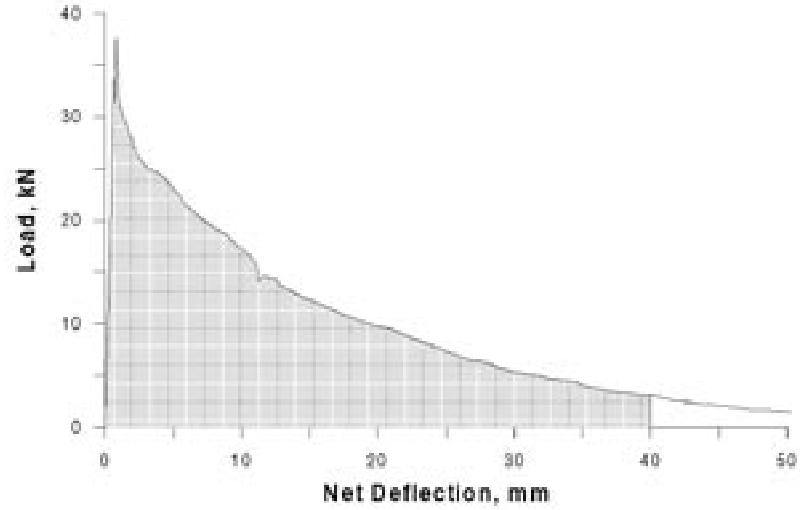

Figure 4: Typical load-deflection curve obtained for a steel fiber-reinforced shotcrete panel with shaded area representing energy absorbed up to 40 mm central deflection.

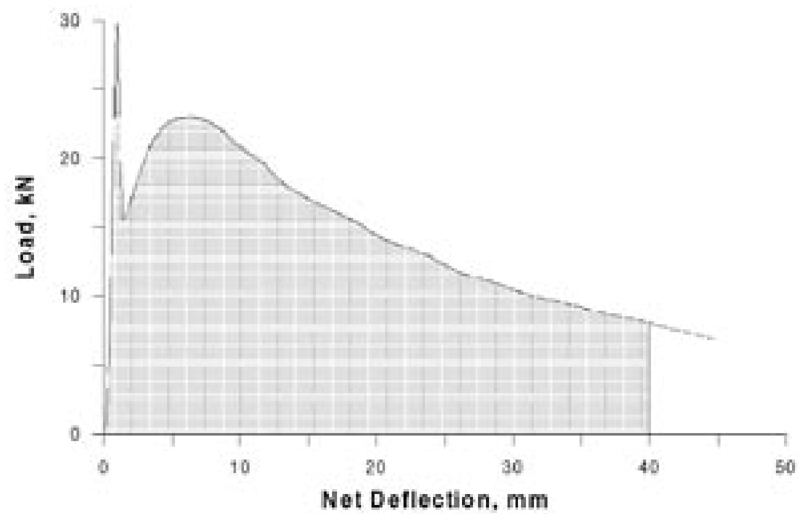

Figure 5: Typical load-deflection curve obtained for a macro-synthetic fiber-reinforced shotcrete panel with shaded area representing energy absorbed up to 40 mm central deflection.

sample mean x and true (population) mean μ does not exceed an amount e, is given by

$$n = \left(\frac{Z_\alpha \sigma}{e}\right)^2 \qquad (2)$$

where Z_α is equal to 1.645 for a 95% confidence interval.[18] For panel-based performance parameters with an average within-batch variation of about 7%,[15] two specimens will yield a maximum likely error between the sample and population mean of e = 8%. To achieve a similar degree of maximum likely error in the residual strength at 3.0 mm central deflection using EFNARC beams, for which the within-batch variation is about 18%, the number of specimens required exceeds 16. Because such a large number of beam tests cannot be undertaken economically, the reliability of QC based on round panel tests effectively cannot be matched using beams.

Field Experience

Field use of the round panel test commenced in Australia soon after RTA procedure T373[13] was introduced in 2000. Several small ground stabilization projects and mines adopted the test for QC of FRS, and extensive use was made of the round panel for research[19] and product development. The first major project to adopt the test as the principal means of QC for toughness of FRS was the M5 East Motorway tunnel project in Sydney,[15] which saw over 800 panels used for QC purposes after EFNARC beams were abandoned because of poor repeatability and high costs. The round panel is now used for almost every QC program in Australia involving FRS linings in mines, shafts, tunnels, and occasional above-ground slope stabilization. The test has also been used for FRS performance evaluation on several projects in Canada and the U.S. (refer to Fig. 6), including at the Inco mine in Sudbury, ON; Falconbridge Mine in Timmins, ON; Noranda at Bathurst, NB; and Barrick Gold in Carlin, NV. Specialist materials suppliers also use the test for internal materials performance assessments.

Continuing Development

Publication of ASTM C 1550 is expected to promote further developmental work into aspects of post-crack performance assessment and FRS design using round panel test data. One of the most important areas of development requiring attention is the use of post-crack performance parameters in FRS lining design. Performance data is presently used as part of observational design during ground stabilization in tunnels and mines. This involves the selection of lining thickness and toughness by an engineer at the work face based on the level of ground instability observed during excavation. While this method is effective for variable ground conditions, the economy and level of conservatism in the resulting lining is unknown.

Greater engineering input is generally required in ground exhibiting more uniform behavior, but probabilistic methods of structural design of the kind widely used for conventional concrete structures[20] do not yet exist for FRS linings. The improved repeatability of performance parameters based on the round panel test will make it possible to introduce characteristic performance specifications and calculate partial safety factors based on a rational risk analysis.

The structural behavior of round panels may one day also be used to determine the behavior of *in-situ* FRS linings of regular geometry. This is a challenging task, however, that will require a great deal of research effort before realization, and this effort is presently in short supply. A considerable period of time is therefore likely to pass before fully rational and technically transparent methods of engineering design become available for FRS linings.

Figure 6: Round panel specimens being sprayed in Canada.

Existing Laboratories

Although the round panel test offers many advantages over other types of toughness tests, it suffers a similar problem to beam testing in that the design of the test rig and control system necessary for undertaking a test is quite sophisticated. The number of laboratories that presently have all the equipment required to undertake this test is therefore limited. Most university-based and many private civil engineering laboratories with servo-controlled hydraulic equipment, however, should be capable of testing round panels, provided a suitable test fixture is fabricated and used with actuators of appropriate size and stiffness. Laboratories that presently have appropriate equipment include TSE in Sydney, Australia; AMEC in Vancouver, Canada; MBT Inc. in Cleveland, Ohio; and Dalhousie University in Nova Scotia, Canada. Facilities are also under development in Sweden and Germany. For further details about testing, contact the author at s.bernard@shotcreteengineers.com.

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