Specification of Shotcrete Toughness

by Roland Heere and Dudley R. (Rusty) Morgan

Fiber-reinforced shotcrete has become an established material for ground support in tunnelling and mining applications as well as in new construction and infrastructure repair. Designers and specifiers frequently require such shotcrete to maintain some quantifiable postcrack strength or toughness. Until the newly published round panel test method (ASTM C 1550-03)[1] becomes more widely used, North American designers and specifiers will likely continue to refer to toughness parameters as determined by the beam test method (ASTM C 1018).[2] The following sections discuss various toughness parameters associated with this beam test and their significance.

Beam Toughness Parameters

Toughness Indices and Residual Toughness Factors

In the current ASTM C 1018-97 standard and previous versions of this standard (first published in 1984), the use of toughness indices I_x and residual toughness factors $R_{x,y}$ is required. Proposed revisions to this standard (likely to be published in 2004) will make these toughness indices and residual toughness factors obsolete. The authors concur with this decision of the ASTM committee on the following grounds:

- The often-specified I_5 and I_{10} indices, and related factors like $R_{5,10}$ or $R_{10,30}$, are frequently meaningless because their calculation is heavily influenced by the geometry of any unstable postcrack section of the load-deflection curve.[3] In other words, the calculation of these indices is often based on specific test results not always reliably measurable with testing machines available to commercial testing laboratories;
- The calculation of the toughness indices, and consequently the residual toughness factors, are significantly influenced by the deflection to first crack. Beams with similar geometries and similar postcrack load-deflection curves can show markedly different I_x and $R_{x,y}$ values if their deflection to first crack is not the same; and
- The area under the load-deflection curve before first crack significantly influences the calculation of the I_x and $R_{x,y}$ values. Even though this area has little direct relation with the actual toughness (that is, resistance to load after first crack) of fiber-reinforced shotcretes, it strongly influences the calculated I_x and $R_{x,y}$ values.

Note that the issues described herein are mainly of concern for commercial testing laboratories. Some of the high-end servocontrolled universal testing machines available to research laboratories greatly reduce these problems, but such machines are beyond economical reach for most commercial testing laboratories serving the construction industry.

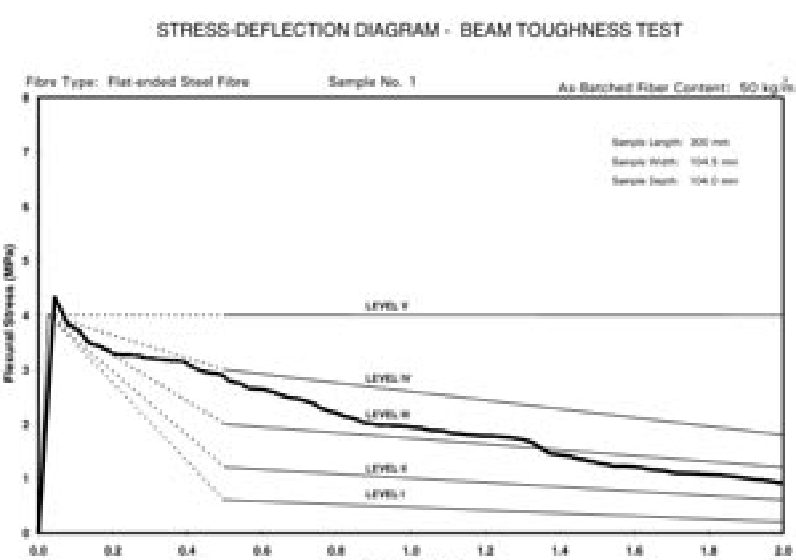

Figure 1: Steel fiber-reinforced shotcrete—TPL II or III?

Toughness Performance Level

Morgan, Chen, and Beaupré[3] established the toughness performance level template method for defining shotcrete toughness in 1995. The Austrian "Sprayed Concrete Guideline"[4] has since adopted these same templates for characterization of fiber-reinforced shotcrete toughness. Designers now frequently refer to such templates in project specifications. A frequently used specification in shotcrete for ground support, for instance, is a toughness performance level (TPL) III at a nominal flexural strength of 4 MPa (571 psi).

The TPL templates were established at a time when shotcrete was almost exclusively reinforced with steel fibers. Consequently, the templates typically compare very well with the particular stress-deflection curves of high-quality steel fiber-reinforced shotcretes. Such curves are generally characterized by a linear rising load-deflection curve segment between origin and first crack, followed by either a small after-first-crack drop or, at very high fiber addition rates, a rise of the curve, and finally an approximately monotonously falling curve segment, as shown in Fig. 1. Modern synthetic fiber-reinforced shotcrete, by contrast, frequently develops different stress-strain behavior. Figure 2 shows an example. Even though the first segment of the curve, from the origin to first crack, appears to be similar to that for steel fiber-reinforced shotcrete, thereafter we frequently see a relatively pronounced drop in stress over a longer range of deflection, after which the stress tends to increase again, before, in some cases, a second, less pronounced drop occurs.

Due to the characteristics of some synthetic fibers to develop "strain hardening," they do not generally fit well into the existing toughness templates that were developed based on steel fiber performance. A strict application of the existing templates' definition may penalize some synthetic fibers, as they may be assigned to a lower TPL due to the characteristic post-crack drop, even though their toughness performance at higher deflections might be excellent. This is a limitation of the TPL method with synthetic fiber reinforced shotcretes.

Residual Flexural Strength (aka Japanese Toughness Factor) and R_e-Value

Two less frequently specified parameters, which the authors consider suitable for some specifications, are the residual flexural strength (better known under the term Japanese toughness factor[5] and the R_e-value.

The first parameter essentially represents the average flexural strength of the specimen between zero load and 2 mm (0.08 in) center point deflection as shown in Fig. 1. It thus represents the ability of the specimen to absorb deformation energy, irrespective of whether the specimen has steel or synthetic fiber reinforcement.

The second parameter R_e is the ratio of residual flexural strength to first crack strength, expressed as a percentage. It shows, in normalized terms, how much of the first crack load the specimen can on average sustain after it has cracked. Some specifiers, especially in Europe, use R_e values.

The two aforementioned parameters can be useful, as they represent the toughness performance of the shotcrete averaged over the full range of test deflections, rather than at only one or two discreet points of the test beam load-deflection curve.

Residual Load Factor and Toughness (as Per Proposed Revision to ASTM C 1018)

Currently, the ASTM C 09.42 committee is balloting revisions to the ASTM C 1018 beam toughness test. Two toughness performance parameters are proposed: residual load factor and toughness.

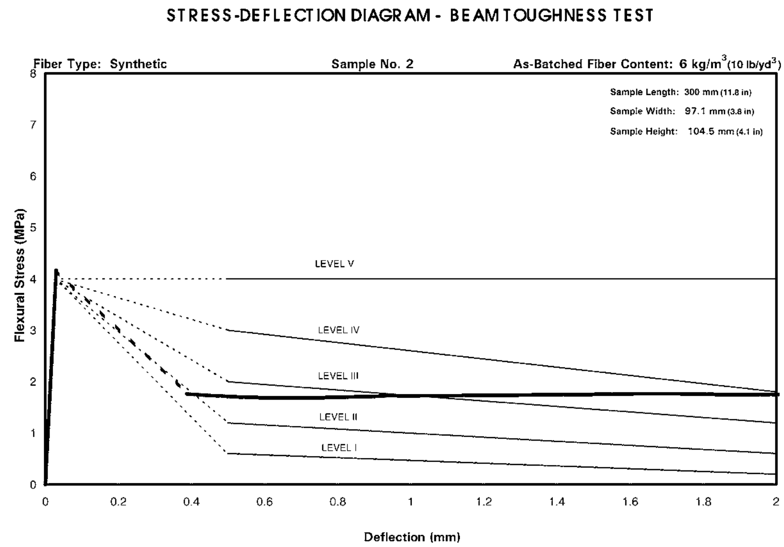

Figure 2: Synthetic fiber-reinforced shotcrete—TPL II or III?

The residual load factors (R_{600} and R_{150}) are defined as the ratio of residual load at certain specimen center point deflections ($L/600$ and $L/150$, with L = specimen load span for R_{600} and R_{150}, respectively) versus first crack load. These residual load factors, in combination with the flexural strength, will thus be convenient tools to describe the postcrack load bearing capacity of the fiber-reinforced material tested. This toughness parameter has similarities to the TPL method but appears to be equally suitable for steel as well as synthetic fiber reinforcement.

The specimen toughness (T_{150}) is, in the current draft of the standard, defined as the area under the load-deflection curve between 0 and $L/150$ center point deflection. In other words, it is the total mechanical energy absorbed by the specimen in the test. This parameter is useful for comparing the toughness of steel with synthetic fiber-reinforced concretes and shotcretes.

Discussion

The authors are frequently asked to interpret toughness test results and decide whether a particular fiber-reinforced shotcrete meets the specified performance. Such decisions are generally easily made when steel fiber-reinforced shotcretes are involved, as their stress versus deflection curve typically fits the TPL templates well. The stress versus deflection curve for synthetic fiber-reinforced shotcretes, however, frequently crosses one, and in some cases even two, template lines, and arguments may arise as to which TPL has been achieved. To simplify this task, the authors have reviewed their database of ASTM C 1018 test results and previous decisions with respect to assigning TPLs. In addition, they have determined the minimum theoretical residual flexural strengths associated with any given TPL. Based on this review, the authors propose

Table 1: Proposed relationship between TPL and residual flexural strength

TPL	Residual flexural strength as a fraction of the design flexural strength	Residual flexural strength of shotcrete with nominally 4 MPa flexural strength, MPa
V	> 100%	> 4.0 (571 psi)
IV	> 67 to 100%	> 2.7 to 4.0 (385 to 571 psi)
III	> 47 to 67%	> 1.9 to 2.7 (271 to 385 psi)
II	> 25 to 47%	> 1.0 to 1.9 (143 to 271 psi)
I	> 10 to 25%	> 0.4 to 1.0 (57 to 143 psi)

the following recommended relationship between TPL and residual flexural strength, as shown in Table 1.

This table has proven helpful in selecting an appropriate TPL for some borderline cases, where the shape of the stress versus deflection curve from the toughness testing of synthetic fiber-reinforced shotcrete does not decisively support the selection of a particular TPL. Two examples of toughness test results are shown in Fig. 1 and 2. Both these stress-deflection diagrams show specimens that do not clearly meet a certain TPL. When comparing their residual flexural strengths (2.08 and 1.97 MPa [297 and 281 psi] for samples 1 and 2, respectively) with the recommended values in Table 1, however, both results are assigned a TPL III.

Summary and Conclusions

With the tabulation presented in Table 1 showing the relationship between TPLs and residual flexural strengths (that is, Japanese toughness factors), the authors hope to provide useful guidance to help resolve some uncertainties about the compliance of specimens tested with toughness specifications. Once the revised ASTM C 1018 standard has been published, we will attempt to establish relationships between the new toughness parameters and current TPLs. This should aid in correlating existing published data to the toughness parameters in the proposed revised ASTM C 1018 standard.

References

1. ASTM C 1550-03, "Standard Test Method for Toughness of Fiber Reinforced Concrete (Using Centrally Loaded Round Panel)," ASTM International, West Conshohocken, PA.

2. ASTM C 1018, "Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading)," ASTM International, West Conshohocken, PA.

3. Morgan, D. R.; Chen, L.; and Beaupré, D., "Toughness of Fiber Reinforced Shotcrete," *ASCE Shotcrete for Underground Support VII*, Telfs, Austria, June 11-15, 1995, pp. 66-87.

4. Östrreichischer, B., "Sprayed Concrete Guideline, Application and Testing," 1999.

5. JSCE-SF4, "Method of Test for Flexural Strength and Flexural Toughness of Fiber Reinforced Concrete," Japan Society of Civil Engineers, V. 3, 1984, pp. 58-61.

ACI member Roland Heere graduated with an engineering degree from TH Leipzig, Germany, and completed his MASc at the University of British Columbia in 1995. He has over 10 years of experience in civil engineering in Europe and Canada. He is working as a senior materials engineer at Metro Testing Laboratories Ltd. in Vancouver, Canada. Heere has extensive experience in shotcrete and concrete technology and has been involved in numerous experimental and production applications of high-performance shotcretes. His professional interest includes the optimization of fiber-reinforced shotcrete technology.

Dudley R. (Rusty) Morgan is Chief Materials Engineer with AMEC Earth & Environmental Ltd. He is a civil engineer with over 35 years of experience in concrete and shotcrete technology and the evaluation and rehabilitation of infrastructure. Morgan is a Fellow of the Canadian Academy of Engineering and the American Concrete Institute (ACI), and he is Secretary of ACI Committee 506, Shotcreting. He is a member of several ACI, ASTM International, and Canadian Standards Association (CSA) technical committees, and he is a founding member of the American Shotcrete Association. Morgan has provided consulting services on concrete and shotcrete projects throughout North America and around the world.