Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading)[1]

This standard is issued under the fixed designation C 1018; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method evaluates the flexural performance of toughness parameters derived from fiber-reinforced concrete in terms of areas under the load-deflection curve obtained by testing a simply supported beam under third-point loading.

NOTE 1—Toughness determined in terms of areas under the load-deflection curve is an indication of the energy absorption capability of the particular test specimen, and, consequently, its magnitude depends directly on the geometrical characteristics of the test specimen and the loading system.

1.2 This test method provides for the determination of a number of ratios called toughness indices that identify the pattern of material behavior up to the selected deflection criteria. These indices are determined by dividing the area under the load-deflection curve up to a specified deflection criterion, by the area up to the deflection at which first crack is deemed to have occurred. Residual strength factors that represent the average post-crack load retained over a specific deflection interval as a percentage of the load at first crack are derived from these indices.

NOTE 2—Index values may be increased by preferential alignment of fibers parallel to the longitudinal axis of the beam caused by fiber contact with the mold surfaces or by external vibration. However, index values appear to be independent of geometrical specimen and testing variables, such as span length, which do not directly affect fiber alignment.

1.3 This test method provides for the determination of the first-crack flexural strength using the load corresponding to the point on the load-deflection curve defined in 3.1.1 as first crack, and the formula for modulus of rupture given in Test Method C 78.

1.4 Values of flexural toughness and first-crack flexural strength stated in inch-pound units are to be regarded as the standard. Values of toughness indices and residual strength factors are independent of the system of units used to measure load and deflection.

1.5 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

C 31 Practice for Making and Curing Concrete Test Specimens in the Field[2]

C 42 Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete[2]

C 78 Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)[2]

C 172 Practice for Sampling Freshly Mixed Concrete[2]

C 192 Practice for Making and Curing Concrete Test Specimens in the Laboratory[2]

C 670 Practice for Preparing Precision and Bias Statements for Test Methods for Construction Materials[2]

C 823 Practice for Examination and Sampling of Hardened Concrete in Constructions[2]

3. Terminology

3.1 *Definitions of Terms Specific to This Standard:*

3.1.1 *first crack*—the point on the load-deflection curve at which the form of the curve first becomes nonlinear (approximates the onset of cracking in the concrete matrix).

3.1.2 *first-crack deflection*—the deflection value on the load-deflection curve at first crack.

3.1.3 *first-crack strength*—the stress obtained when the load corresponding to first crack is inserted in the formula for modulus of rupture given in Test Method C 78.

3.1.4 *first-crack toughness*—the energy equivalent to the area under the load-deflection curve up to the first-crack deflection.

3.1.5 *toughness*—the energy equivalent to the area under the load-deflection curve up to a specified deflection.

3.1.6 *toughness indices*—the numbers obtained by dividing the area up to a specified deflection by the area up to first crack.

NOTE 3—Values of 5.0, 10.0, and 20.0 for I_5, I_{10}, and I_{20} respectively, as defined below, correspond to linear elastic material behavior up to first crack and perfectly plastic behavior thereafter (see Appendix X1).

[1] This test method is under the jurisdiction of ASTM Committee C-9 on Concrete and Concrete Aggregates and is the direct responsibility of Subcommittee C09.42 on Fiber-Reinforced Concrete.

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[2] *Annual Book of ASTM Standards*, Vol 04.02.

3.1.6.1 *toughness index* I_5—the number obtained by dividing the area up to a deflection of 3.0 times the first-crack deflection by the area up to first crack.

3.1.6.2 *toughness index* I_{10}—the number obtained by dividing the area up to a deflection of 5.5 times the first-crack deflection by the area up to first crack.

3.1.6.3 *toughness index* I_{20}—the number obtained by dividing the area up to a deflection of 10.5 times the first-crack deflection by the area up to first crack.

3.1.6.4 *residual strength factor* $R_{5,10}$—the number obtained by calculating the value of 20 ($I_{10} - I_5$).

3.1.6.5 *residual strength factor* $R_{10,20}$—the number obtained by calculating the value of 10 ($I_{20} - I_{10}$).

4. Summary of Test Method

4.1 Molded or sawn beams of fiber-reinforced concrete are tested in flexure using the third-point loading arrangement specified in Test Method C 78. Load and beam deflection are monitored either continuously by means of an X-Y plotter, or incrementally by means of dial gages read at sufficiently frequent intervals to ensure accurate reproduction of the load-deflection curve. A point termed first crack which corresponds approximately to the onset of cracking in the concrete matrix is identified on the load deflection curve. The first-crack load and deflection are used to determine the first-crack flexural strength and to establish end-point deflections for toughness calculations. Computations of toughness and toughness indices are based on areas under the load-deflection curve up to the first-crack deflection and up to the specified end-point deflection.

5. Significance and Use

5.1 The first-crack strength characterizes the behavior of the fiber-reinforced concrete up to the onset of cracking in the matrix, while the toughness indices characterize the toughness thereafter up to specified end-point deflections. Residual strength factors, which are derived directly from toughness indices, characterize the level of strength retained after first crack simply by expressing the average post-crack load over a specific deflection interval as a percentage of the load at first crack. The importance of each depends on the nature of the proposed application and the level of serviceability required in terms of cracking and deflection. Toughness and first-crack strength are influenced in different ways by the amount and type of fiber in the concrete matrix. In some cases, fibers may greatly increase the toughness, toughness indices, and residual strength factors determined by this test method while producing a first-crack strength only slightly greater than the flexural strength of the plain concrete matrix. In other cases, fibers may significantly increase the first-crack strength with only relatively small increases in toughness, toughness indices, and residual strength factors.

5.2 The toughness indices and residual strength factors determined by this test method reflect the post-crack behavior of fiber-reinforced concrete under static flexural loading. The absolute values of toughness determined to compute the toughness indices are of little practical significance since they are directly dependent upon geometrical variables associated with the specimen and the loading arrangement.

NOTE 4—In applications where the energy absorption capability of a structural concrete element is important, it may be possible to obtain some indication of its performance by testing a specimen equivalent to the element in terms of size, span, and mode of loading.

5.3 In determining which toughness index is most appropriate as a measure of material performance for a specific application, the level of serviceability required in terms of cracking and deflection shall be considered, and an index appropriate to the service conditions shall be selected in accordance with the rationale described in 9.6 and in Appendix X1.

5.4 Values of toughness indices, residual strength factors, and first-crack strength may be used for comparing the performance of various fiber-reinforced concretes during the mixture proportioning process or in research and development work. They may also be used to monitor concrete quality, to verify compliance with construction specifications, or to evaluate the quality of concrete already in service.

NOTE 5—Values of toughness index at different ages may not be comparable.

5.5 Values of toughness indices, residual strength factors, and first-crack strength obtained using the 14 by 4 by 4 in. (350 by 100 by 100 mm) preferred standard size of molded specimen may not necessarily correspond with the performance of larger or smaller molded specimens, concrete in large structural units, or specimens sawn from such units, because of differences in the degree of preferential fiber alignment parallel to the longitudinal axis of the specimen. For molded specimens, they tend to increase as the degree of preferential fiber alignment increases.

5.5.1 Preferential fiber alignment is likely to occur in molded specimens when fibers in the vicinity of the mold surfaces tend to align in the plane of the surface, and is most pronounced in specimens of small cross-section containing long fibers.

5.5.2 In thin concrete sections, such as overlays and shotcrete linings, fibers tend to align in the plane of the section, so in-place performance is best evaluated using either molded or sawn specimens of depth equal to the thickness of the section. Consequently, toughness indices, residual strength values, and first-crack strengths for thin sections may differ from those for standard molded specimens of nominally identical concrete.

5.5.3 External vibration promotes preferential alignment of fibers parallel to the vibrating surface of the form or screeding device used, while internal vibration does not have this effect. Consequently, toughness indices, residual strength values, and first-crack strengths for identical concrete specimens prepared using the two kinds of vibration may differ.

5.5.4 Preferential fiber alignment is negligible in mass concrete because the aligning effect of mold surfaces is absent and because internal vibration is often used, so toughness indices, residual strength values, and first-crack strengths for standard molded specimens may differ from those for sawn specimens of nominally identical concrete.

NOTE 6—The degree of preferential fiber alignment may be less for fibers that are flexible enough to be bent by contact with aggregate particles or mold surfaces than for fibers rigid enough to remain straight during mixing and specimen preparation.

6. Apparatus

6.1 *Testing Machine*—The testing machine shall be capable of operating in a manner which produces a controlled and constant increase of deflection of the specimen. A testing arrangement where specimen net mid-span deflection is used to control the rate of increase of deflection using a closed-loop, servo-controlled testing system shall be used. Testing machines that use stroke displacement control or load control are not suitable for establishing the post-crack portion of the load-deflection curve. The loading and specimen support system shall be capable of reproducing third-point loading on the specimen without eccentricity or torque. The system specified in Test Method C 78 is suitable.

NOTE 7—Load-deflection curves produced from closed-loop testing systems may show substantial toughness for non-fibrous concrete in the post-crack deflection area up to a deflection of 5.5 times the first-crack deflection. Values of toughness indices I_5 and I_{10} and residual strength $R_{5,10}$, should be used with caution, as they may not accurately reflect the contribution of fibers to post-crack toughness at these deflections.

6.2 *Deflection-Measuring Equipment*—Devices such as electronic transducers or electronic deflection gages shall be located in a manner that ensures accurate determination of the net deflection at the mid-span exclusive of any effects due to seating or twisting of the specimen on its supports. Two alternative arrangements for measuring net mid-span deflection have evolved. In the first arrangement three electronic transducers or similar digital devices mounted on a supporting frame are positioned along the centerline of the top surface of the test specimen, one at the mid-span and one at each support (Fig. 1). The average of the support deflections is electrically subtracted from the mid-span deflection. The second arrangement employs a rectangular jig which surrounds the specimen and is clamped to it at the supports (Fig. 2). Two transducers or similar digital devices mounted on the jig at mid-span, one on each side, measure deflection through contact with appropriate brackets attached to the specimen. The average of the measurements represents net mid-span deflection.

6.3 *Data Compilation System*—An X-Y plotter coupled directly to electronic outputs of load and deflection is the simplest acceptable means of expediently and accurately obtaining the relationship between load and net mid-span deflection, subsequently termed the load-deflection curve. A data acquisition system capable of digitally recording load and deflection at least every second and plotting it is also suitable.

NOTE 8—Accurate determination of the areas under the load-deflection curve subsequently needed for computation of toughness indices is only possible when the scales initially chosen for load and deflection are reasonably large. A load scale on which 1 in. (25 mm) corresponds to a flexural stress of the order of 150 psi (1 MPa), or no more than 20 % of the estimated first-crack strength, is recommended. For the preferred 14 by 4 by 4 in. (350 by 100 by 100 mm) specimen size, where first-crack deflection is of the order of 0.002 in. (0.05 mm), a deflection scale on which 1 in. (25 mm) corresponds to about 10 % of the estimated end-point deflection for I-20 is recommended. When testing is continued to a higher end-point deflection, the scale may have to be reduced to avoid excessively large load-deflection plots. With some plotting equipment it is possible to use a relatively large scale up to the I_{10} criterion and switch to a smaller scale at higher deflections without interrupting the test. This keeps the size of the plot reasonable without adversely affecting the ability to accurately determine the area up to first crack and the areas up to the I_5 and I_{10} deflection criteria. For test specimens that exhibit a very rapid decrease in load and increase in deflection immediately after first crack, the shape of the portion of the load-deflection curve immediately following first crack may be affected by the response rate of the data recording and plotting system.

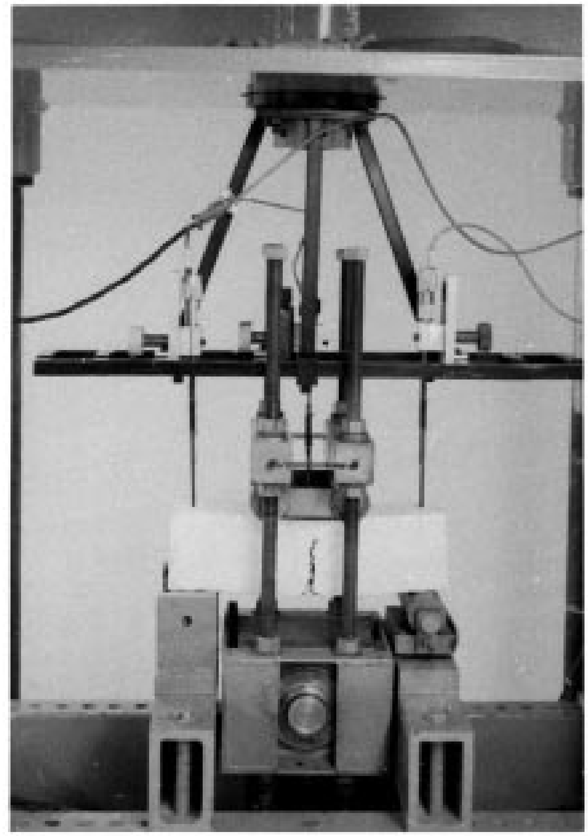


FIG. 1 Arrangement Using 3 Transducers

7. Sampling, Test Specimens, and Test Units

7.1 *General Requirements*—The nominal maximum size of aggregate and cross-sectional dimensions of test specimens shall be in accordance with Practice C 31 or Practice C 192 when using molded specimens, or in accordance with Test Method C 42 when using sawn specimens, except when the following specific requirements are contravened:

7.1.1 The length of test specimens shall be at least 2 in. (50 mm) greater than three times the depth, and in any case not less than 14 in. (350 mm).

7.1.2 The width of test specimens shall be at least three times the maximum fiber length. The three times maximum fiber length requirement for width and depth may be waived at the option of the purchaser to permit specimen width or depth of 6 in. (150 mm) when using fibers of length 2 to 3 in. (50 to 75 mm).

7.1.3 The depth and size of test specimens shall conform to either of the following two sets of requirements:

7.1.3.1 *Thick Sections*—The depth of test specimens shall be at least three times the maximum fiber length. Subject to meeting this requirement and the requirements of 7.1, 7.1.1, and 7.1.2, the preferred specimen size is 14 by 4 by 4 in. (350 by 100 by 100 mm). When the preferred size is not large

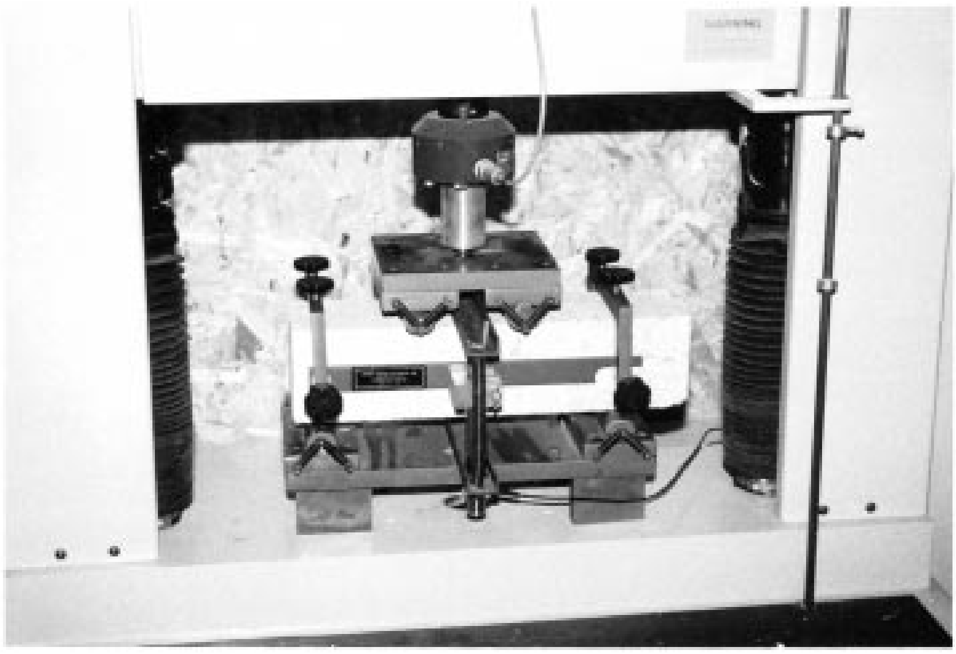


FIG. 2 Arrangement Using Rectangular Jig

enough to meet all of these requirements, specimens of square cross-section large enough to meet the requirements shall be tested. The three times maximum fiber length requirement for width and depth may be waived at the option of the purchaser to permit specimen width or depth of 6 in. (150 mm) when using fibers of length 2 to 3 in. (50 to 75 mm).

7.1.3.2 *Thin Sections*—When the requirements of 7.1 and 7.1.3.1 are not met in the application in which the concrete is to be used, as for example in overlays or shotcrete linings, specimens of depth equal to the section thickness actually used shall be tested.

NOTE 9—When testing freshly mixed fiber-reinforced concrete, it may be desirable to prepare additional specimens of the preferred standard size in order to make proper comparisons of their performance with results obtained on other jobs or reported in the literature. The results of tests of beams with steel fibers longer than one-third the width or depth of the beam may not be comparable to test results of similar-sized beams with fibers shorter than one-third the width or depth because of possible preferential fiber alignment, and different size beams may not be comparable because of size effects.

7.2 *Freshly Mixed Concrete*—Samples of freshly mixed fiber-reinforced concrete for the preparation of test specimens shall be obtained in accordance with Practice C 172.

7.2.1 Specimens shall be molded in accordance with Practice C 31 or Practice C 192, except that compaction shall be by external vibration, as internal vibration or rodding may produce nonuniform fiber distribution. Make sure that the time of vibration is sufficient to ensure adequate consolidation, as fiber-reinforced concrete requires a longer vibration time than concrete not containing fibers, especially when the fiber concentration is relatively high. Take care to avoid placing the concrete in a manner which produces lack of fiber continuity between successive placements by using a wide shovel or scoop and placing each lift of concrete uniformly along the length of the mold. Use a single layer for specimens of depth 3 in. (75 mm) or less and two layers for specimens of depth greater than 3 in. (75 mm).

7.2.2 In placing the final layer, attempt to add an amount of concrete that will exactly fill the mold after compaction. When trowelling the top surface, continue vibration in order to ensure that fibers do not protrude from the finished surface.

7.2.3 Curing shall be in accordance with Practice C 31 or Practice C 192.

7.3 *Hardened Concrete*—Samples of hardened fiber-reinforced concrete from structures shall be selected in accordance with Practice C 823.

7.3.1 Sawn specimens shall be prepared and cured in accordance with Test Method C 42.

7.4 *Test Unit*—At least three specimens from each sample of fresh or hardened concrete shall be prepared for testing.

8. Conditioning

8.1 When the time between removal of test specimens from their curing environment and the start of testing is likely to exceed 15 min, drying shall be minimized by applying a curing compound or by other appropriate techniques.

9. Procedure

9.1 Molded or sawn specimens representing thick sections, as defined in 7.1.3.1, shall be turned on their side with respect to the position as cast before placing on the support system. Molded or sawn specimens representing thin sections, as defined in 7.1.3.2, shall be tested as cast without turning. Specimens representing shotcrete panels of any thickness shall be tested as placed without turning.

9.2 Arrange the specimen and the loading system so that the specimen is loaded at the third points in accordance with Test Method C 78. The span length shall be three times the specimen depth or 12 in. (300 mm), whichever is greater. If before loading, full contact is not obtained between the specimen, the load-applying devices, and the supports, grind or cap the contact surfaces of the specimen in accordance with Test Method C 78.

9.3 Operate the testing machine so that the deflection of the specimen at the mid-span increases at a constant rate. For 14 by 4 by 4 in. (350 by 100 by 100 mm) specimen size, the rate of increase of Net Mid-Span deflection shall be within the range 0.002 to 0.004 in./min (0.05 to 0.10 mm/min) until the specified end-point deflection is reached. The corresponding rate for other sizes and shapes of specimens shall be based on reaching the first-crack deflection 30 to 60 s after the start of the test. First-crack deflection for third-point loading is estimated assuming elastic behavior up to first crack from the equation:

$$\delta = 23\,PL^3\,/1296\,EI\left[1 + \frac{216\,D^2(1+\mu)}{115\,L^2}\right]$$

where P is the first-crack load, L is the span, E is the estimated modulus of elasticity of the concrete, I is the cross-sectional moment of inertia, D is the specimen depth, and μ is Poisson's ratio.

NOTE 10—Testing machines capable of automatically controlling the rate of movement of the loading heads are well suited but not essential to this procedure.

9.4 Exercise care to ensure that the measured deflections are the net values exclusive of any extraneous effects due to seating or twisting of the specimen on its supports or deformation of the support system. At regular intervals or when using test equipment for the first time, or after major alterations or maintenance, confirm the reliability of net mid-span deflection values by comparing the value of first-crack deflection determined experimentally with the value derived from the formula given in 9.3.

NOTE 11—Location of deflection-measuring devices at the mid-width of the specimen minimizes the effect of twisting and reduces the number of devices needed to determine the net deflection at the mid-span. When deflection is measured on the sides of the specimen, deflection-measuring devices are needed on both sides of the specimen to eliminate the possible effects of twisting of the specimen on deflection values.

9.5 Unless otherwise specified by the purchaser, terminate the test at a deflection large enough to ensure that the area up to the end-point deflection of 5.5 times the first-crack deflection specified for the I_{10} index can be determined.

9.6 When the level of serviceability appropriate to the particular application in terms of permissible deflection and cracking indicates that the specified end-point deflection should be higher, further testing to an appropriate deflection criterion shall be specified at the option of the purchaser. In general, the end-point deflection for an index I_n is $(n + 1)/2$ times the first-crack deflection. Rationale for selection of end-point deflection is given in X1.3 of Appendix X1.

9.7 Make two measurements of the specimen depth and width adjacent to the fracture (one at each face) to the nearest 0.05 in. (1.0 mm) to determine the average depth and width.

9.8 Determine the position of the fracture by measuring the distance along the middle of the tension face from the fracture to the nearest end of the specimen.

9.9 When the fracture occurs outside the middle third of the span by more than 5 % of the span length, discard the results.

10. Calculation

10.1 If the load-deflection curve is slightly concave upwards throughout its initial portion, determine first crack by placing a straightedge coincident with that portion of the load-deflection curve which is essentially linear, and identifying the point at which the curvature first increases sharply and the slope of the curve exhibits a definite change, as at point *A* in Fig. 3(a). To correct for the extraneous effects identified in 9.4, extend the straight line, *AT*, representing the linear portion of the load-deflection curve from the point, *T*, at which it departs from the experimental curve to a new origin at point *O′*, as shown in Fig. 3(a). The line *O′TA* in Fig. 3(a) is used in subsequent area computations rather than the curve *OTA*.

10.2 If the load-deflection curve is slightly convex upwards throughout its initial portion, that is like the stress-strain curve for plain concrete in tension or compression, first crack is the point at which the curvature first increases sharply and the slope of the curve exhibits a definite change, as at A in Fig. 3(b). The straight line O′A in Fig. 3(b) is used in subsequent area computations rather than the O′A portion of the curve.

NOTE 12—Small ripples or fluctuations in the load-deflection curve due to electronic noise or mechanical vibration should not be confused with a definite change in overall slope and curvature, particularly when the portion of the curve in question is artificially magnified.

10.3 Calculate the first-crack strength using the load corresponding to first crack on the load-deflection curve and the formula for modulus of rupture given in Test Method C 78.

NOTE 13—When the flexural strength is required, it may be determined using the maximum load attained on the load-deflection curve and the formula for modulus of rupture given in Test Method C 78. The value thus obtained may differ from the flexural strength obtained using the constant-rate-of-loading procedure specified in Test Method C 78.

10.4 Determine the first-crack deflection as the deflection corresponding to the length *O′B* in Fig. 3.

10.5 Determine the area under the load-deflection curve up to the first-crack deflection. This is the triangular area corresponding to *O′AB* in Fig. 3. If required, calculate the corresponding first-crack toughness in inch-pound or SI units.

10.6 Determine the area under the load-deflection curve up to a deflection of 3.0 times the first-crack deflection. This corresponds to the area *O′ACD* in Fig. 3 where *O′D* equals 3.0 times the first-crack deflection. Divide this area by the area up to first crack, obtained in accordance with 10.4, and report the number rounded to the nearest 0.1 as the toughness index I_5.

NOTE 14—Determination of the irregularly shaped areas needed to implement the instructions of this and subsequent sections 10.6-10.9 requires a planimeter, or application of Simpson's rule, or the counting of squares or other suitable elements of known area. When different deflection scales are used on the same plot, care must be taken to ensure that this is taken into account when converting physical area measurements to toughness indices.

10.7 Determine the area under the load-deflection curve up to a deflection of 5.5 times the first-crack deflection (area *O′* AEFin Fig. 3). Divide it by the area up to first crack, and report the number rounded to the nearest 0.1 as the toughness index I_{10}.

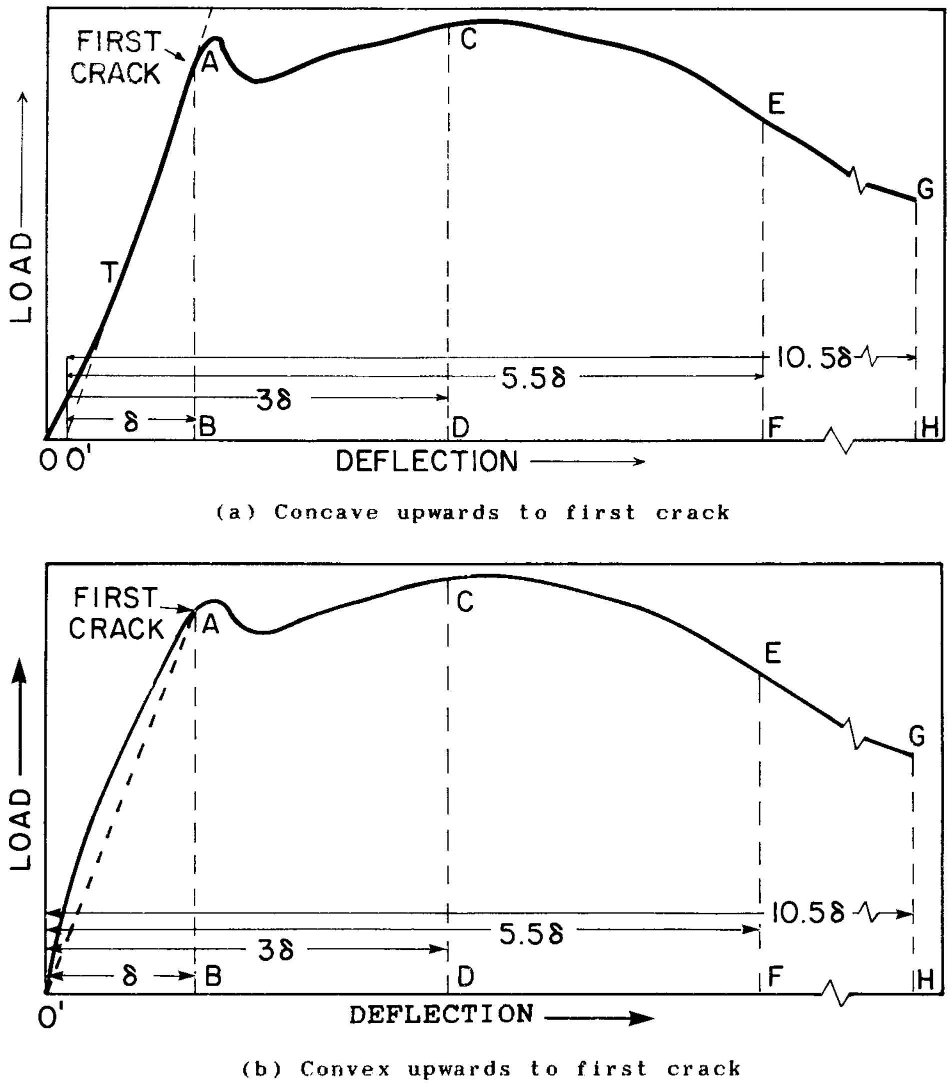


FIG. 3 Important Characteristics of the Load-Deflection Curve

10.8 When required, determine the area under the load-deflection curve up to a deflection of 10.5 times the first-crack deflection (area *O′ AGH* in Fig. 3). Divide it by the area up to first crack, and report the number rounded to the nearest 0.1 as the toughness index I_{20}.

10.9 Determine the residual strength factor $R_{5,10}$ as $20(I_{10} - I_5)$, and, when required, the residual strength factor $R_{10,20}$ as $10(I_{20} - I_{10})$.

NOTE 15—While the foregoing calculations presume that the load-deflection curve is determined in graphical form, it is not inconceivable that electronic equipment capable of digitally recording load and deflection may be developed, and that the recorded data may be analyzed by computer to determine relevant areas and toughness indices.

11. Report

11.1 Report the following information:

11.1.1 Type of specimen (molded or sawn) and specimen identification numbers or symbols,

11.1.2 Average width of specimen to the nearest 0.05 in. (1.0 mm),

11.1.3 Average depth of specimen to the nearest 0.05 in. (1.0 mm),

11.1.4 Span length to the nearest 0.1 in. (2.0 mm),

11.1.5 First-crack load and, when required, the maximum load, lbf(N),

11.1.6 First-crack deflection, in. (mm) to the nearest 0.0001 in. (0.002 mm), and the location where deflection was measured (mid-span or loading points),

11.1.7 First-crack strength and, when required, flexural strength to the nearest 5 psi (0.05 MPa),

11.1.8 First-crack toughness, lbf·in. (N·m), to the nearest 0.1 lbf·in. (0.01 N·m), when required,

11.1.9 Toughness indices I_5 and I_{10}, and the residual strength factor $R_{5,10}$,

11.1.10 Toughness index I_{20} and the residual strength factor $R_{10,20}$ when required,

11.1.11 Age of specimens at test,

11.1.12 Curing history and moisture condition of specimens at test,

11.1.13 Whether specimen was capped, or ground, and

11.1.14 Defects in specimen prior to test and abnormalities in specimen behavior during test.

12. Precision and Bias

12.1 *Within-Laboratory Precision*—Single-operator values of the one-sigma limit in percent (1s %), defined in accordance with Practice C 670, have been determined for concretes containing steel fibers as follows:

Parameter	Within-Batch 1s %	Overall 1s %[A]
First-crack strength	5	7
First-crack toughness	10	12
Toughness index I_5	12	13
Toughness index I_{10}	14	16
Toughness index I_{20}	16	20
Flexural strength	5 to 8[B]	8 to 10[B]

[A] Inclusive of batch-to-batch variability, but not variability due to changes in specimen geometry, test span, and mode of loading.

[B] Upper limit appears applicable to relatively high fiber concentrations, 200 lb/yd^3 (120 kg/m^3) or more of straight uniform fibers, or 70 lb/yd^3 (42 kg/m^3) or more of deformed fibers.

NOTE 16—These levels of precision are based on data from a small number of investigations[3,4] conducted by experienced operators using good, but not necessarily the best possible equipment. The levels of precision achievable probably depend on the nature of the equipment used to produce the load-deflection curve, and the care exercised in computing the areas under this curve. As more sophisticated deflection-measuring and plotting devices become available, it may be possible to achieve 1s % values lower than those indicated.

12.2 No data are yet available to indicate whether the levels of precision for concretes containing other types of fibers, such as glass or polypropylene, differ from those quoted in 12.1.

12.3 *Multilaboratory Precision*—No data suitable for the evaluation of multilaboratory precision are yet available.

12.4 *Bias*—This test method has no bias since the properties determined can only be defined in terms of this test method.

[3] Johnston, C. D., "Effects of Testing Rate and Age on ASTM C 1018 Toughness Parameters and Their Precision for Steel Fiber-Reinforced Concrete," *Cement Concrete and Aggregates*, CCAGDP, Vol 15, No. 1, Summer 1993, pp 50-58.

[4] Johnston, C. D. and Skarendahl, A., "Comparative Flexural Performance Evaluation of Steel Fibre-Reinforced Concretes According to ASTM C1018 Shows Importance of Fibre Parameters," *RILEM Materials and Structures*, Vol 25, May 1992, pp 191–200.

APPENDIX

(Nonmandatory Information)

X1. RATIONALE FOR THE METHOD

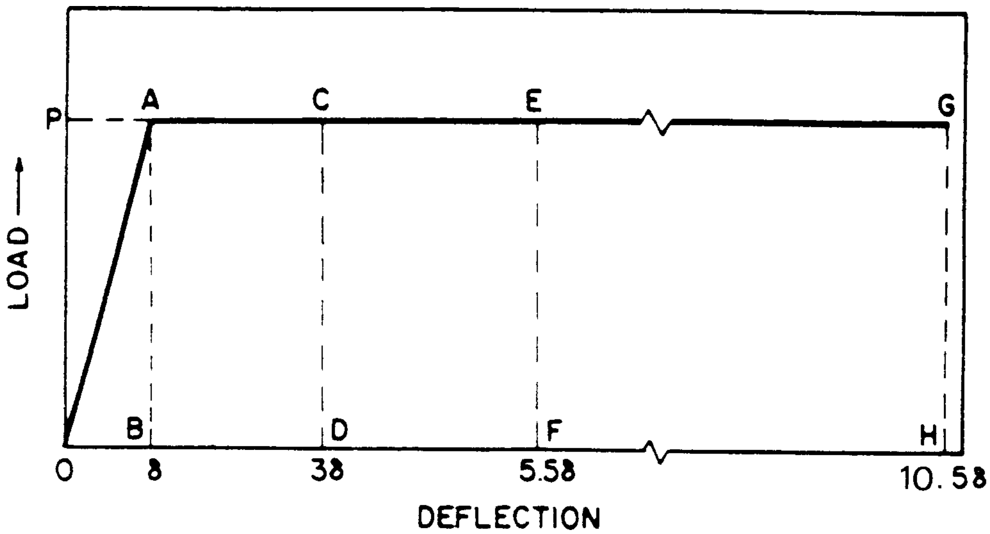
X1.1 Absolute values of toughness up to the first-crack or other specified deflections depend entirely on geometrical variables associated with the specimen and the testing arrangement, and bear no direct relationship to the energy absorption capability of a structural element made with a fibrous concrete identical to that used to prepare specimens for testing according to this test method.

X1.2 Toughness indices I_5, I_{10}, and I_{20} enable actual performance to be compared with a readily understood reference level of performance. In this regard, values of 5.0, 10.0 and 20.0 for I_5, I_{10}, and I_{20} correspond to linear elastic material behavior up to first crack and perfectly plastic behavior thereafter[5] (Fig. X1.1). Such behavior is desirable for many applications requiring high toughness, and can be reached or exceeded only by careful selection of fiber type, fiber concentration, and concrete matrix parameters. The indices have the same meaning regardless of the cross-sectional size and span of the test specimen.

X1.3 When the conditions of serviceability or the purchaser's needs require a specified end-point deflection higher than that identified in 9.5, it is recommended that the end-point deflection be specified as a multiple of the first-crack deflection and that it be consistent with the rationale in X1.2. For example, an end-point deflection of 10.5 times the first-crack deflection permits calculation of the I_{20} index.

X1.4 The residual strength factors $R_{5,10}$ and $R_{10,20}$ represent the average level of strength retained after first crack as a percentage of the first-crack strength for the deflection intervals *CE* and *EG*respectively in Fig. 3 (a). Values of 100 correspond to perfectly plastic behavior (Fig. X1.1). Lower values indicate inferior performance. Plain concrete has residual strength factors of zero.

[5] Johnston, C. D., "Definition and Measurement of Toughness Parameters for Fiber-Reinforced Concrete," *Cement, Concrete, and Aggregates*, CCAGDP, Vol 4, No. 2, Winter 1982, pp 53–60.



Area Basis[A]	Index Designation	Deflection Criterion	Values of Toughness Indices		
			Plain Concrete	Elastic-Plastic Material	Observed Range for Fibrous Concrete
OACD	I_5	3δ	1.0	5.0	1 to 6
OAEF	I_{10}	5.5δ	1.0	10.0	1 to 12
OAGH	I_{20}	10.5δ	1.0	20.0	1 to 25

[A] Indices calculated by dividing this area by the area to the first crack OAB.

FIG. X1.1 Definition of Toughness Indices in Terms of Multiples of First-Crack Deflection and Elastic-Plastic Material Behavior