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Measurement of Properties of Fiber Reinforced Concrete

Reported by ACI Committee 544

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This report outlines existing procedures for specimen preparation in general and discusses testing, workability, flexural strength, toughness, and energy absorption. Newly developed test methods are presented for the first time for impact strength and flexural toughness. The applicability of the following tests to fiber reinforced concrete (FRC) are reviewed: air content, yield, unit weight, compressive strength, splitting tensile strength, freeze-thaw resistance, shrinkage, creep, modulus of elasticity, cavitation, erosion, and abrasion resistance.

Keywords: abrasion tests; cavitation; compression tests; cracking (fracturing); creep properties; energy absorption; erosion; fatigue (materials); **fiber reinforced concretes;** flexural strength: freeze-thaw durability; impact tests; modulus of elasticity; shrinkage; splitting tensile strength; **tests;** toughness; workability.

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INTRODUCTION

This report applies to conventionally mixed and placed fiber reinforced concrete (FRC) or fiber reinforced shotcrete (FRS) using steel, glass, polymeric, and natural fibers. It does not relate to thin glass fiber reinforced cement or mortar products produced by the spray-up process. The Prestressed Concrete Institute,[1]

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This report supercedes ACI 544.2R-78 (Revised 1983). The revision was extensive. Existing sections were expanded and new sections were added. The order of presentation has been rearranged and references were provided.

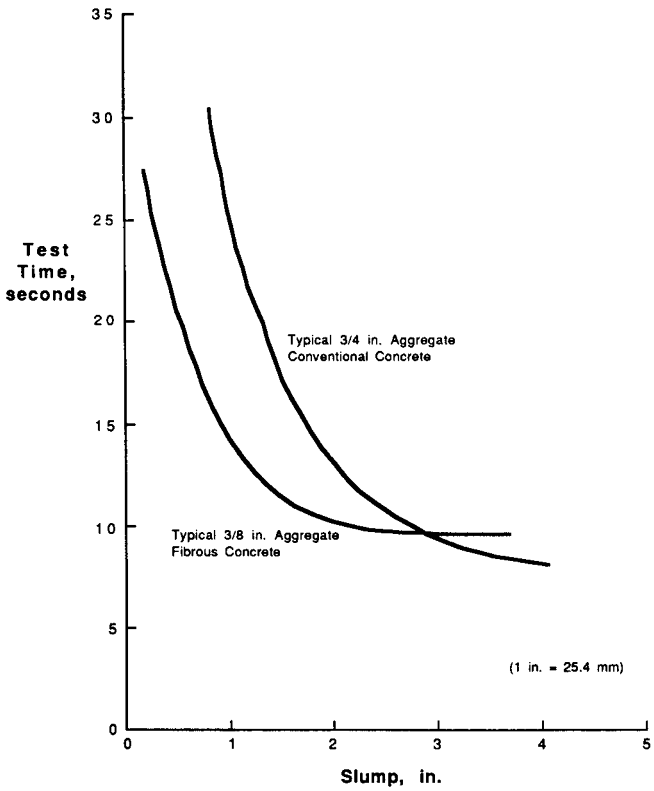

Fig. 1-Slump versus inverted cone time[10]

Glassfibre Reinforced Cement Association,[2] and ASTM have prepared recommendations for test methods for these spray-up materials.

The use of fiber reinforced concrete (FRC) has passed from experimental small-scale applications to routine factory and field applications involving the placement of many hundreds of thousands of cubic yards annually throughout the world. This has created a need to review existing test methods and develop new methods, where necessary, for determining the properties of FRC. These methods are presented in an effort to standardize procedures and equipment so that test results from different sources can be compared effectively. While it is recognized that the use of procedures and equipment other than those discussed in this report may be employed because of past practices, availability of equipment, etc., use of nonstandard tests does not promote the development or broadening of the data base needed to quantify consistently properties of the various forms of FRC. To date, some progress on standardization of test methods has been made in North America by ASTM and similar organizations outside North America, but greater efforts are needed, as is indicated in this report.

Although most of the test methods described in this report were developed initially for steel fiber reinforced concrete, they are applicable to concretes reinforced with glass, polymeric, and natural fibers, except when otherwise noted.

The test methods described in this report may in some cases lead to difficulties or problems in obtaining meaningful results. In these instances, Committee 544 welcomes information on the problems and any modification of equipment or procedures that provides more meaningful results. This is of particular interest where tests developed initially for steel FRC are used to measure properties of concretes containing other fibers, such as glass, polymeric, or natural fibers.

WORKABILITY

The workability of freshly mixed concrete is a measure of its ability to be mixed, handled, transported, and, most importantly, placed and consolidated with a minimal loss of homogeneity and minimal entrapped air. Several tests are available to assess one or more of these characteristics.

Slump test (ASTM C 143)

The slump test is a common, convenient, and inexpensive test, but it may not be a good indicator of workability for FRC. However, once it has been established that a particular FRC mixture has satisfactory handling and placing characteristics at a given slump, the slump test may be used as a quality control test to monitor the FRC consistency from batch to batch.

Time of flow through inverted slump cone test (ASTM C 995)

This test has been developed specifically to measure the workability of FRC.[3] It effectively measures the mobility or fluidity of the concrete under internal vibration. The test is not suitable for flowable mixtures of FRC, such as produced using high-range water-reducing admixtures, because the concrete tends to run through the cone without vibration. The slump test is used for monitoring the consistency of these concretes.

Fig. 1 shows typical results of this test for conventional and FRC mixtures in relation to slump. Even at very low slump, FRC mixtures respond well to vibration. The flattening of the FRC curve above 2 or 3 in. (50 or 75 mm) slump indicates that for these mixtures there is no improvement in workability as slumps increase beyond about 2 in. (50 mm). Fig. 2 shows a similar curvilinear relationship between the slump obtained under static test conditions and the time of flow obtained with vibration. It also shows a linear relationship illustrating direct proportionality between inverted cone time and Vebe time. This suggests that both of these vibration-type tests measure essentially the same characteristic of the freshly mixed concrete. The exact nature of the relationships of Fig. 1 and 2 will vary from one concrete to another depending on aggregate maximum size and gradation, fiber concentration, type and aspect ratio, and air content.

The inverted cone test can be used to compare FRC to conventional mixtures with similar slump values. For example, at a 2 in. (50 mm) slump, a $^{3}/_{8}$ in. (10 mm) aggregate FRC mixture has substantially less flow time than a $^{3}/_{4}$ in. (19 mm) aggegate mixture at the same slump (Fig. 1). This demonstrates that although the slumps of these two mixtures are similar, the workability of the FRC mixture was much better. The advantage of the inverted slump cone test over the slump test is that it takes into account the mobility of concrete, which comes about because of vibration.

Vebe test

The Vebe consistometer described in the British Standards Institution standard BS 1881, "Methods of Testing Concrete, Part 2," measures the behavior of concrete subjected to external vibration and is acceptable for determining the workability of concrete placed using vibration, including FRC. It effectively evaluates the mobility of FRC, that is, its ability to flow under vibration, and helps to assess the ease with which entrapped air can be expelled. The Vebe test is not as convenient for field use as either the slump or inverted cone test because of the size and weight of the equipment.

AIR CONTENT, YIELD, AND UNIT WEIGHT

Standard ASTM air content test equipment and procedures for conventional concrete can be used for determining the air content, yield, and unit weight of FRC (ASTM C 138, C 173, and C 231). The concrete samples should be consolidated using external or internal vibration as permited by ASTM C 31 and C 192, and not by rodding. Rodding may be used when a high flow consistency has been produced by the use of high-range water-reducing admixtures.

SPECIMEN PREPARATION

In general, procedures outlined in ASTM C 31, C 42, C 192, and C 1018 should be followed for specimen preparation. Additional guidance for preparing fiber reinforced shotcrete specimens is available in ACI 506.2-77 (Revised 1983). Test specimens should be prepared using external vibration whenever possible. Internal vibration is not desirable and rodding is not acceptable, as these methods of consolidation may produce preferential fiber alignment and nonuniform distribution of fibers. Although external vibration may produce some alignment of fibers, the amount of alignment produced in the short duration vibration required for consolidation of test specimens is of negligible influence.

The method, frequency, amplitude, and time of vibration should be recorded. Test specimens having a depth of 3 in. (75 mm) or less should be cast in a single layer to avoid fiber orientation and fiber-free planes. Two layers should be used for specimens of depth greater than 3 in. (75 mm) with each layer being vibrated. Care should be taken to avoid placing the concrete in a manner that produces a lack of fiber continuity between successive placements. The preferred placement method is to use a wide shovel or scoop and place each layer of concrete uniformly along the length of the mold. Any preferential fiber alignment by the mold surfaces can influence test results, particularly for small cross sections with long fibers. Generally, the smallest specimen dimension should be at least three

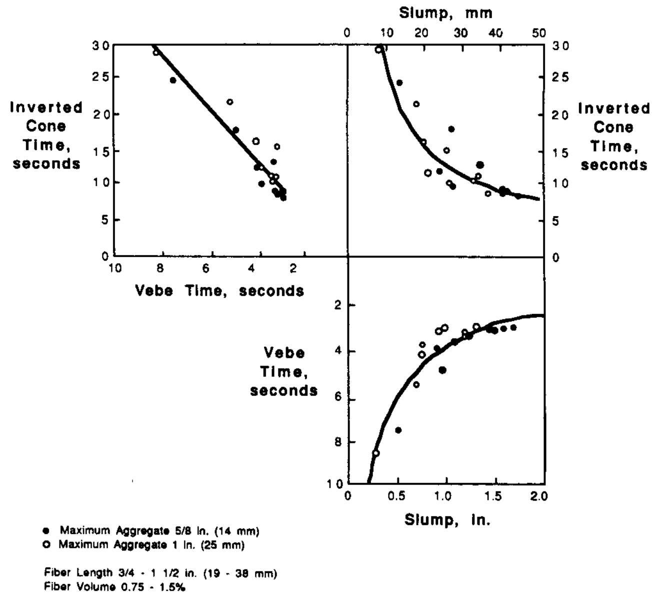

Fig. 2-Relationship between slump, Vebe time, and inverted cone time[3]

times the larger of the fiber length and the maximum aggregate size. Recommendations for selecting specimen size and preparing test specimens for flexural toughness tests are given in ASTM C 1018.

COMPRESSIVE STRENGTH

ASTM compressive strength equipment and procedures (ASTM C 31, C 39, and C 192) used for conventional concrete can be used for FRC. The cylinders should be 6 x 12 in. (150 x 300 mm) in size and should be made using external vibration or a 1 in. (25 mm) nominal width internal vibrator. External vibration is preferred since an internal vibrator may adversely influence random fiber distribution and alignment.

The presence of fibers alters the mode of failure of cylinders by making the concrete less brittle. Significant post-peak strength is retained with increasing deformation beyond the maximum load. Fibers usually have only a minor effect on compressive strength, slightly increasing or decreasing the test result. Since smaller cylinders give higher strengths for conventional concrete and promote preferential fiber alignment in FRC, small cylinders with long fibers may give unrealistically high strengths. Cubes may also be used for compressive strength tests, but few reference data are available for such specimens and the relationship between cube strength and cylinder strength has not been determined for FRC.

FLEXURAL STRENGTH

The flexural strength of FRC may be determined under third-point loading using ASTM C 78 or C 1018, or by center-point loading using ASTM C 293. Third-point loading is the preferred technique. If only maximum flexural strength is of interest, ASTM C 78 or C 293 can be used. Maximum flexural strength is calculated at the section of maximum moment corre-

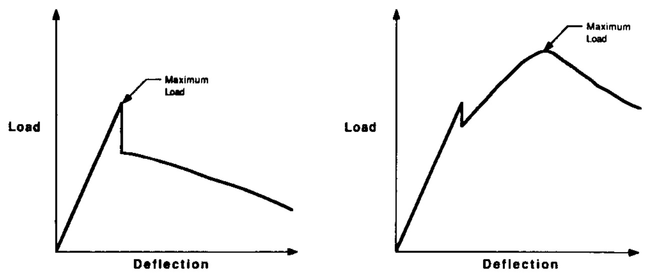

Fig. 3-Flexural strength-Calculated in accordance with ASTM C 78 or C 293 using the maximum load

sponding to the peak fiber stress in tension based on the assumption of elastic behavior, as shown in Fig. 3. If toughness or load-deflection behavior is also of interest, ASTM C 1018 can be used. However, results obtained in load-controlled testing according to ASTM C 78 may differ from those obtained using the deflection-controlled procedures of ASTM C 1018.[4]

At least three specimens should be made for each test according to the "Specimen Preparation" section of this report and ASTM C 1018. For thick sections, specimen width and depth should equal or exceed three times both the fiber length and the nominal dimension of the maximum size aggregate. When the application for the FRC involves a thickness less than this, e.g., overlays, specimens with a depth equal to the actual section thickness should be prepared. These should be tested as cast, rather than turned 90 deg as is required for standard-size beams, to evaluate the effects of preferential fiber alignment to be representative of the FRC in practice.

When it is possible to meet the width and depth requirements of three times the fiber length and aggregate size, a set of specimens with a preferred size of 4 x 4 x 14 in. (100 x 100 x 350 mm) should be made and tested with third-point loading to allow comparison of results with a large base of available data from other projects that have used this as the standard test specimen. Otherwise, the size of specimens for thick sections should conform to the requirements of ASTM C 1018. If the width or depth of a specimen is less than three times the fiber length, preferential fiber alignment tends to increase the measured flexural strength. This increase is representative only when a similar preferential fiber alignment increase can be expected for the FRC in use.

The relationship between flexural strength and direct tensile strength has not been determined for FRC.

TOUGHNESS

Toughness is a measure of the energy absorption capacity of a material and is used to characterize the material's ability to resist fracture when subjected to static strains or to dynamic or impact loads. The difficulties of conducting direct tension tests on FRC prevent their use in evaluating toughness. Hence, the simpler flexural test is recommended for determining the toughness of FRC. In addition to being simpler, the flexural test simulates the loading conditions for many practical applications of FRC.

The flexural toughness and first-crack strength can be evaluated under third-point loading using specimens meeting the requirements for thick sections or for thin sections outlined in ASTM C 1018. Specimens should be prepared and tested according to ASTM C 1018 to establish the load-deflection curve. The flexural strength may also be determined from the maximum load reading in this test as an alternative to evaluation in accordance with ASTM C 78.

Energy absorbed by the specimen is represented by the area under the complete load-deflection *(P-d)* curve. The *P-d* curve has been observed to depend on (a) the specimen size (depth, span, and width); (b) the loading configuration (midpoint versus third-point loading); (c) type of control (load, load-point deflection, cross-head displacement, etc.); and (d) the loading rate.[5,6]

To minimize at least some of these effects, normalization of the energy absorption capacity is necessary. This can be accomplished by dividing the energy absorbed by the FRC beam by that absorbed by an unreinforced beam of identical size and matrix composition, tested under similar conditions. The resultant nondimensional index I_t (Fig. 4) represents the relative improvement in the energy absorption capacity due to the inclusion of the fibers.[7] It is an index for comparing the relative energy absorption of different fiber mixes.

Several useful methods for evaluating toughness that do not require determining I_t, e.g., ASTM C 1018 and JCI SF4,[8] have been adopted. These methods are based on the facts that: (a) it may not always be practical to obtain the complete *P-d* characteristics of FRC (time constraints in slow tests or rate-dependent behavior in rapid tests); (b) a stable fracture test of the unreinforced beam requires a stiff testing machine, or closed-loop testing;[9] (c) each toughness test using the I_t measure would require both FRC and unreinforced beams of identical matrix to be cast, cured, and tested; and (d) I_t does not reflect the relative toughness estimates at specified levels of serviceability appropriate to specific applications.

ASTM C 1018 provides a means for evaluating serviceability-based toughness indexes and the first-crack strength of fiber reinforced concretes. The procedure involves determining the amount of energy required to deflect the FRC beam a selected multiple of the first-crack deflection based on serviceability considerations. This amount of energy is represented by the area under the load-deflection curve up to the specified multiple of the first-crack deflection. The toughness index is calculated as the area under the *P-d* diagram up to the prescribed deflection, divided by the area under the *P-d* diagram up to the first-crack deflection (first-crack toughness).

Indexes I_5, I_{10}, and I_{30} at deflections of 3, 5.5, and 15.5 times the first-crack deflection, respectively, are illustrated in Fig. 4. These indexes provide an indication of (a) the relative toughness at these deflections,

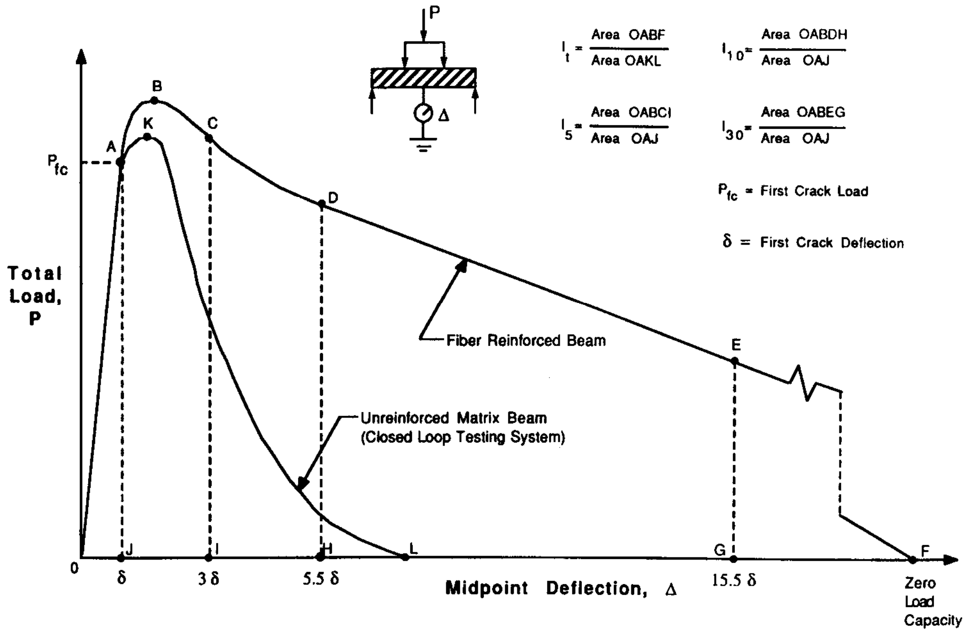

Fig. 4-Toughness indexes from flexural load-deflection diagram

and (b) the approximate shape of the post-cracking *P-d* response. The indexes I_5, I_{10}, and I_{30} have a minimum value of 1 (elastic-brittle material behavior) and values of 5, 10, and 30, respectively, for perfectly elastic-plastic behavior (elastic up to first crack, perfectly plastic thereafter). The unreinforced matrix is assumed to be elastic-brittle. It is possible for the indexes thus defined to have values larger than their respective elastic-plastic values, depending on fiber type, volume fraction, and aspect ratio.

ASTM C 1018 requires that the first-crack strength and the corresponding deflection and toughness be reported in addition to indexes I_5, I_{10}, and I_{30}. In addition, ASTM C 1018 allows extension of the toughness index rationale for calculation of greater indexes, such as I_{50} and I_{100}, to accomodate tougher fiber reinforced composites such as slurry-infiltrated fiber reinforced composites. However, as previously mentioned, I_t is a measure of the improvement in toughness relative to the unreinforced matrix, while I_5, I_{10}, and I_{30} provide measures relative to a particular fiber mixture's first-crack strength.

Some general observations listed in the following paragraphs are pertinent to the recommendations just mentioned and may be found useful. Additional information is available in the references.[5-7,9-11]

a. ASTM C 1018 toughness indexes are intended for fiber reinforced concretes with substantial ductility.

b. Deflection measurements, especially of small values such as the first-crack deflection, are subject to significant experimental error due to deflection of the beam supports and specimen rocking (initially large). As a result, caution should be exercised when using and interpreting these values to calculate toughness using areas under the load-deflection curve.[11]

c. The energy absorption capacity recorded in the third-point loading test (toughness, modulus of rupture tests) will overestimate the true fracture energy of the composite, particularly if nonlinear deformations occur at more than one cross section (occurrence of multiple cracking in the middle third of the specimen).

FLEXURAL FATIGUE ENDURANCE

The endurance in dynamic cyclic flexural loading is an important property of FRC, particularly in applications involving repeated loadings, such as pavements and industrial floor slabs. Although there is no current standard for flexural fatigue performance, testing similar to that employed for conventional concrete has been conducted using reversing and nonreversing loading, with applied loads normally corresponding to 10 to 90 percent of the static flexural strength.[12] Short beam specimens with small required deflection movements have been successfully tested at 20 cycles per second (cps) when hydraulic testing machines with adequate pump capacity were available.[12] However, verification that the full load and specimen response has been achieved at these high frequencies is desirable. Specimens with large deflections may need to be tested at reduced rates of 1 to 3 cps, to minimize inertia effects. Strain rates of 6000 to 10,000 microstrain per second (microstrain/sec) may result from testing at 20 cps versus a strain rate of 600 to 1000 microstrain/sec at 2 cps.

Loadings are selected so that testing can continue to at least two million cycles, and applications to 10 million cycles are not uncommon. The user should be aware that 10 million cycles at 2 cps will require over 57 days of continuous testing, and the influence of strength gain with time must be considered in addition to the influence of strain rates. Specimen testing at later ages may reduce the influence of aging when testing at the lower strain rates.

Test results in the range of 60 to 90 percent of the static flexural strength for up to 10 million cycles have been reported for nonreversed loading to steel fiber reinforced concrete with 0.5 to 1.0 volume percent fiber content.[13] Data on reversed loading cyclic testing and the influence of strain rate and load versus time parameters are not available.

SPLITTING TENSILE STRENGTH

Results from the split cylinder tensile strength test (ASTM C 496) for FRC specimens are difficult to interpret after the first matrix cracking and should not be used beyond first crack because of unknown stress distributions after first crack.[14] The precise identification of the first crack in the split cylinder test can be difficult without strain gages or other sophisticated means of crack detection, such as accoustic emission or laser holography.[15,16] The relationship between splitting tensile strength and direct tensile strength or modulus of rupture has not been determined.

The split cylinder tensile test has been used in production applications as a quality control test, after relationships have been developed with other properties when using a constant mixture.

IMPACT RESISTANCE

Improved impact resistance (dynamic energy absorption as well as strength) is one of the important attributes of FRC. Several types of tests have been used to measure the impact resistance of FRC. These can be classified broadly, depending upon the impacting mechanism and parameters monitored during impact, into the following types of tests:[17] (a) weighted pendulum Charpy-type impact test; (b) drop-weight test (single or repeated impact); (c) constant strain-rate test; (d) projectile impact test; (e) split-Hopkinson bar test; (f) explosive test; and (g) instrumented pendulum impact test.

Conventionally, impact resistance has been characterized by a measure of (a) the energy consumed to fracture a notched beam specimen (computed from the residual energy stored in the pendulum after impact); (b) the number of blows in a "repeated impact" test to achieve a prescribed level of distress; and (c) the size of the damage (crater/perforation/scab) or the size and velocity of the spall after the specimen is struck with a projectile or after the specimen is subjected to a surface blast loading.

Results from such tests are useful for ascertaining the relative merits of the different mixtures as well as for providing answers to specific practical problems. However, they depend on the specimen geometry, test system compliance, loading configuration, loading rate, and the prescribed failure criterion.[17] The simplest of the conventional tests is the "repeated impact," drop-weight test described in the next subsection.

More recently, instrumented impact tests have been developed that provide reliable and continuous time histories of the various parameters of interest during the impact-load, deflection, and strain.[18] These provide basic material properties at the various strain rates for the calculation of flexural/tensile strength, energy

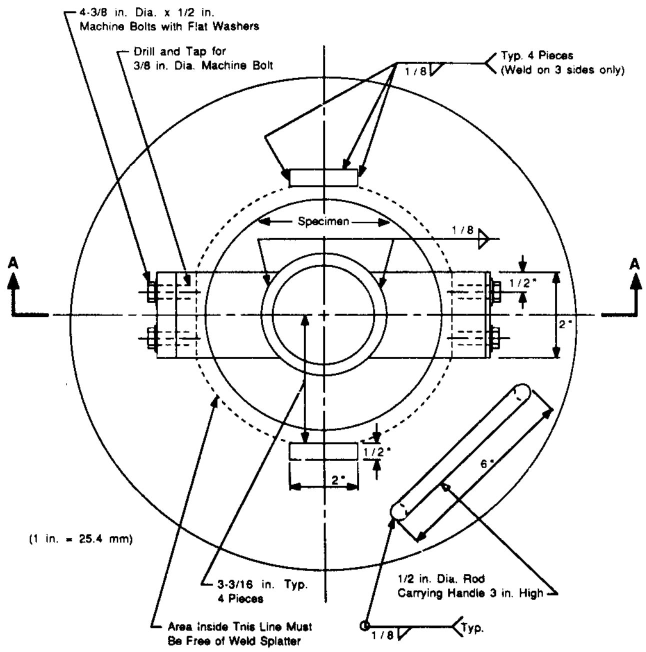

Fig. 5-Plan view of test equipment for impact strength.[13] Section A-A is shown in Fig. 6

absorption capacity, stiffness, and load-deformation characteristics. These types of tests are described in the instrumented impact test subsection.

More information on the merits and drawbacks of all the types of impact tests with particular emphasis on their usefulness for measuring the impact resistance of FRC is also available.[17,18]

Drop-weight test

The simplest of the impact tests is the "repeated impact," drop-weight test. This test yields the number of blows necessary to cause prescribed levels of distress in the test specimen. This number serves as a qualitative estimate of the energy absorbed by the specimen at the levels of distress specified. The test can be used to compare the relative merits of different fiber-concrete mixtures and to demonstrate the improved performance of FRC compared to conventional concrete. It can also be adapted to show the relative impact resistance of different material thicknesses.[19]

Equipment - Referring to Fig. 5 and 6, the equipment for the drop-weight impact test consists of: (1) a standard, manually operated 10 lb (4.54 kg) compaction hammer with an 18-in. (457-mm) drop (ASTM D 1557), (2) a $2\frac{1}{2}$ in. (63.5 mm) diameter hardened steel ball, and (3) a flat baseplate with positioning bracket similar to that shown in Fig. 5 and 6. In addition to this equipment, a mold to cast 6 in. (152 mm) diameter by $2\frac{1}{2}$ in. (63.5 mm) thick [$\pm\frac{1}{8}$ in., ± (3 mm)] concrete specimens is needed. This can be accomplished by using standard ASTM C 31 or C 470 molds.

Procedure - The $2\frac{1}{2}$ in. (63.5 mm) thick by 6 in. (152 mm) diameter concrete samples are made in molds according to procedures recommended for compressive cylinders but using only one layer. The molds can be filled partially to the $2\frac{1}{2}$ in. (63.5 mm) depth and float-

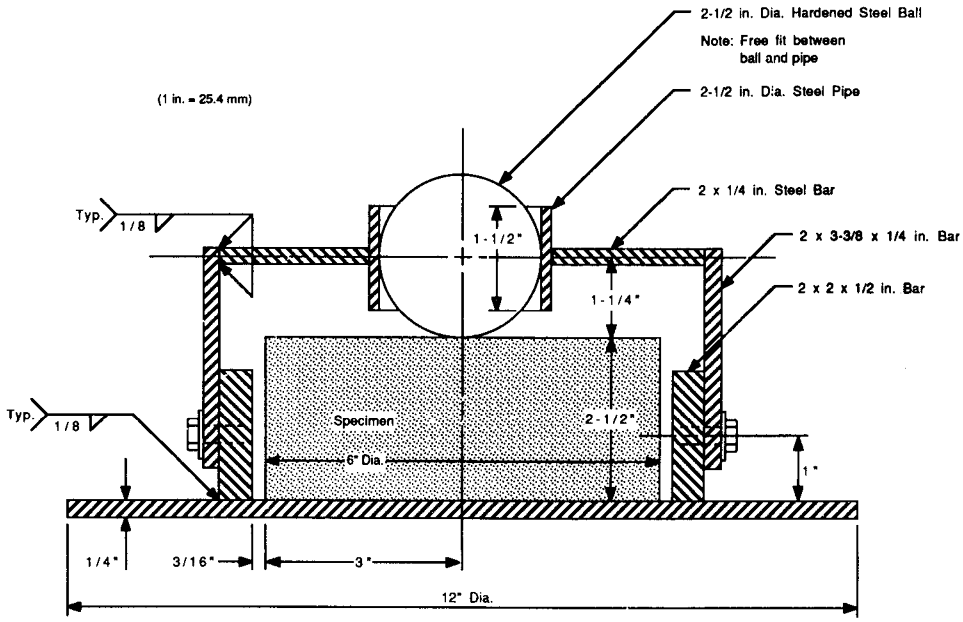

Fig. 6-Section through test equipment for impact strength shown in Fig. 5[19]

finished, or they can be sawn from full-size cylinders to yield a specimen size of the proper thickness. Specimens cut from full-size cylinders are preferred. If fibers longer than 0.80 in. (20 mm) are used, the test specimen should be cut from a full-size cylinder to minimize preferential fiber alignment.

Specimens should be tested at 7, 28, and (if desired) 90 days of age. Curing and handling of the specimens should be similar to that used for compressive cylinders. Accelerated curing is not desirable. The thickness of the specimens should be recorded to the nearest $^1/_{16}$ in. (1.5 mm). The reported thickness should be determined by averaging the measured thickness at the center and each edge of the specimen along any diameter across the top surface. The samples are coated on the bottom with a thin layer of petroleum jelly or a heavy grease and placed on the baseplate within the positioning lugs with the finished face up (if appropriate). The positioning bracket is then bolted in place, and the hardened steel ball is placed on top of the specimen within the bracket. Foamed elastomer pieces are placed between the specimen and positioning lugs to restrict movement of the specimen during testing to the first visible crack.

The drop hammer is placed with its base upon the steel ball and held there with just enough down pressure to keep it from bouncing off the ball during the test. The baseplate should be bolted to a rigid base, such as a concrete floor or cast concrete block. An automated system with a counter may also be used. The hammer is dropped repeatedly, and the number of blows required to cause the first visible crack on the top and to cause ultimate failure are both recorded. The foamed elastomer is removed after the first visible crack is observed. Ultimate failure is defined as the opening of cracks in the specimen sufficiently so that the pieces of concrete are touching three of the four positioning lugs on the baseplate.

Results of these tests exhibit a high variability and may vary considerably with the different types of mixtures, fiber contents, etc.[17]

Instrumented impact test

While retaining the conventional mechanisms to apply impact loads, instrumented impact tests permit the monitoring of load, deflection, strain, and energy histories during the impact event, manifested by a single blow fracture. This allows the computation of basic material properties such as fracture toughness, energy dissipation, ultimate strength, and corresponding strain or deformation at different strain rates of loading.

Instrumented impact testing has been applied successfully to fiber reinforced concrete. Two types of systems are commonly used: a drop-weight-type system and a pendulum-type system (Charpy impact system). Instrumentation of these systems is quite complex and implies instrumentation of the striker as well as the anvil supports that act as load cells.[20-22]

In the instrumented drop weight system [Fig. 7(a)], a weight equipped with a striker is dropped by gravity on the specimen while guided by two columns. The Charpy system [Fig. 7(b)] uses a free-falling pendulum weight equipped with a striker as the impacting mechanism. The weight of the impacter and the drop height in both systems provide a range of impact velocities and energy capacities for the impact test. In comparing Fig. 7(a) and 7(b), it can be observed that the electronic instrumentation is the same for both systems even though the mechanical configurations of the drop weight and the Charpy systems are different.

Instrumentation for instrumented impact testing includes dynamic load cells, foil-type resistance gages for

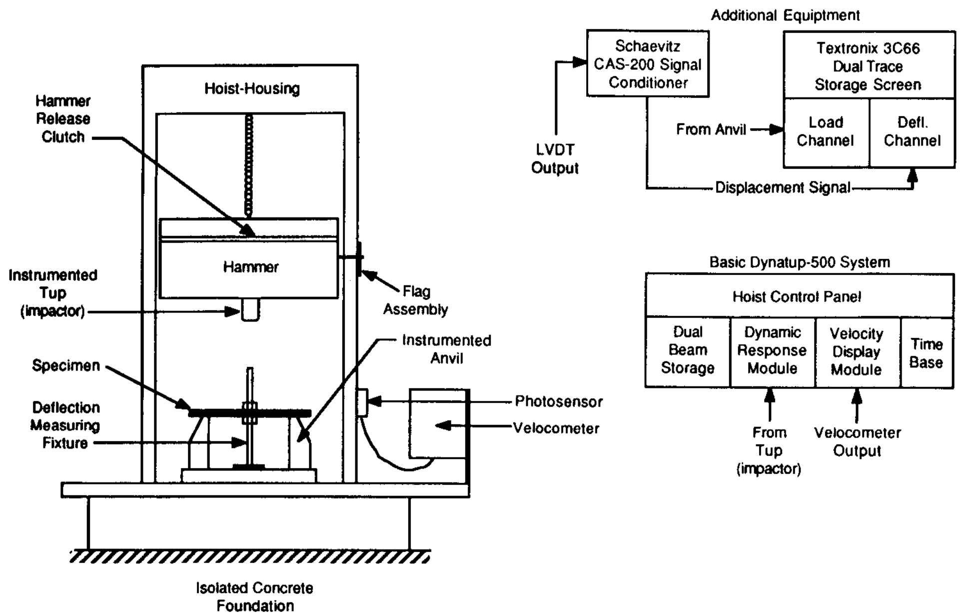

Fig. 7(a)-Block diagram of the general layout of the instrumented drop weight system[22]

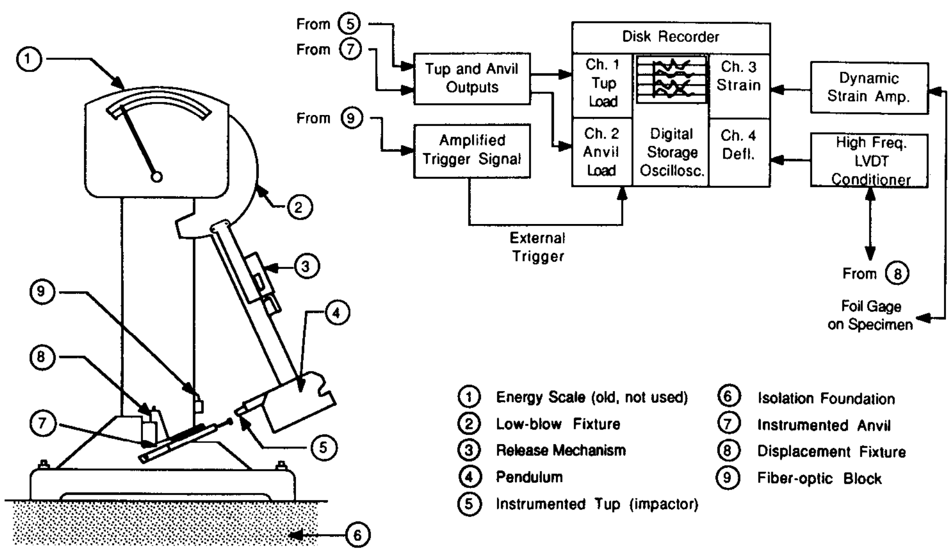

Fig. 7(b)-Block diagram of the general layout of the modified instrumented Charpy system[20]

strain measurements, and associated signal conditioning amplifiers and storage oscilloscope (preferably digital). All electronic equipment must have adequate high-frequency response to monitor and record all transducer outputs without distortions during the short impact event (< 1 millisecond).

Simultaneous electronic recording of the anvil and striker loads is essential for the proper interpretation of inertial loads and to assess the influence on the results of parameters such as test system compliance, specimen size, and impact velocity. The anvils and the striker should be designed to serve as dynamic load cells and to insure elastic behavior even under high loads. They should be sufficiently rounded at the specimen contact points to avoid local compression damage to the specimen on impact and to facilitate specimen rotation during bending. The load cells are instrumented using semiconductor strain gages mounted in full bridge configuration within protective recesses provided on either side of each cell (anvil and striker). The full bridge configuration is recommended for high signal-to-noise ratio and to allow for temperature compensation. Output signals from the two anvils should be connected in series to monitor the total load at the supports.

Problems of parasitic inertial loads in the responses recorded from instrumented impact tests and recommendations to overcome them are detailed in Reference 22. As a general guideline, test parameters should be selected so that the difference between the striker and anvil loads recorded during the test does not exceed 5 percent.

FREEZE-THAW RESISTANCE

ASTM C 666 is applicable to FRC. Weight loss is not a recommended method for determining the freeze-thaw resistance of FRC because material that becomes dislodged from the specimen mass remains loosely bonded by the fibers. The relative dynamic modulus of elasticity method is appropriate for FRC.

Inclusion of fibers should not be considered as a substitute for proper air entrainment to obtain freeze-thaw resistance.

LENGTH CHANGE (SHRINKAGE)

Unrestrained shrinkage

For length change of concrete, ASTM C 157 and C 341 are applicable to FRC. ASTM C 341 is the preferred test method since the test specimens are cut from larger cast concrete samples; thus, the influence on fiber orientation from casting specimens in smaller molds is minimized. However, these tests do not reflect the performance of FRC in early age shrinkage and crack control.

Restrained shrinkage

ASTM C 827 for early volume change of cementitious mixtures is also applicable to FRC. The degree of restraint to which the specimen is subjected varies with the viscosity and degree of hardening of the mixture so that measurements are useful primarily for comparative purposes rather than as absolute values.

RESISTANCE TO PLASTIC SHRINKAGE CRACKING

The lack of a standard test for plastic shrinkage cracking resistance of concrete at an early age has prompted the proposal of several methods. These involve measurement of the length and width of concrete cracks. Ring, rectangular, square, and combinations of these shapes (shown in Fig. 8) have been used to characterize the crack resistance characteristics of FRC compared to nonfiber reinforced concrete.[23-25] The thickness of the specimens varies from $^1/_4$ to 6 in. (6 to 152 mm), depending on the maximum size aggregate, fiber length, and application.

The specimens form cracks at the top surface and restraint is necessary for the cracks to occur. Bond breakers are employed on the horizontal surfaces of the specimen form to minimize surface restraint at the base. External restraint may be provided by casting in welded wire fabric attached to the form or an internal restraining ring, as shown by dashed lines in Fig. 8.

Measurements of cracking resistance are quantified by summing the product of the length and width of the cracks and expressing the results as a percentage in comparison to nonfibrous concrete at a 24-hr age. Most microcracks occur in the mortar fraction of the concrete within the first few hours when subjected to evaporation rates in excess of 0.15 lb of moisture loss per ft^2 per hr (0.732 kg/m^2/hr). A wind tunnel has been used to control the evaporation rate of the test specimens. More details regarding these proposed test methods can be found in References 23 through 25. The relationship between these test results and field applications has not been determined.

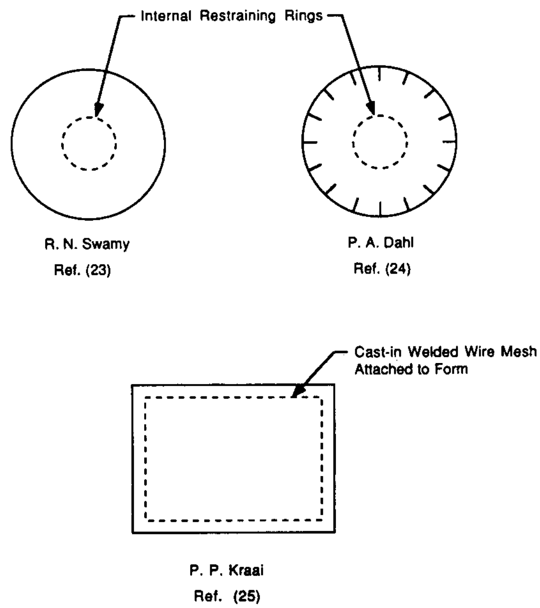

Fig. 8-Comparison of crack resistance characteristics of FRC to nonfiber reinforced concrete

CREEP

ASTM C 512 test for creep in concrete is applicable to FRC.

MODULUS OF ELASTICITY AND POISSON'S RATIO

ASTM C 469 test for modulus of elasticity and Poisson's ratio is applicable to FRC.

CAVITATION, EROSION, AND ABRASION RESISTANCE

As with conventional concrete, testing FRC for cavitation, erosion, and/or abrasion resistance according to ASTM C 418 and C 779 is extremely difficult if realistic and practical results are to be obtained. Any of these special tests should be evaluated carefully, and their specific applicability to a job should be considered. Whenever possible, large-size specimens should be cast and tested for these types of evaluations. Every effort should be made to include tests under conditions expected to be experienced in service.

An example of full-scale testing is the U.S. Army Corps of Engineers' hydraulic test flume for cavitation/erosion at Detroit Dam.[26] Erosion with small debris and low fluid velocity can be investigated by the Corps of Engineers' method CRD-C 63.

REFERENCES

Recommended references

The documents of the various standards-producing organizations referred to in this report follow with their serial designation, including year of adoption or revision. The documents listed were the latest revision at the time this report was published. Since some of these documents are revised frequently, generally in minor detail only, the user of this report should check directly with the sponsoring group if it is desired to refer to the latest revision.

American Concrete Institute

506.1R-84	State-of-the-Art Report on Fiber Reinforced Shotcrete
506.2-77 (Revised 1983)	Specification for Materials, Proportioning, and Application of Shotcrete
544.1R-82 (Reapproved 1986)	State-of-the-Art Report on Fiber Reinforced Concrete
544.3R-84	Guide for Specifying, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete
SP-44	Fiber Reinforced Concrete
SP-81	Fiber Reinforced Concrete-International Symposium
SP-109	Fiber Reinforced Concrete Properties and Applications

ASTM

A 820-85	Standard Specification for Steel Fibers for Fiber Reinforced Concrete
C 31-87a	Standard Practice for Making and Curing Concrete Test Specimens in the Field
C 39-86	Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens
C 42-85	Standard Method of Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
C 78-84	Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)
C 138-81	Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete
C 157-86	Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete
C 173-78	Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method
C 192-81	Standard Method of Making and Curing Concrete Test Specimens in the Laboratory
C 231-82	Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method
C 293-79	Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading)
C 341-84	Standard Test Method for Length Change of Drilled or Sawed Specimens of Cement Mortar and Concrete
C 418-81	Standard Test Method of Abrasion Resistance of Concrete by Sandblasting
C 469-87	Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression
C 470-87	Standard Specification for Molds for Forming Concrete Test Cylinders Vertically
C 496-86	Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
C 512-87	Standard Test Method for Creep of Concrete in Compression
C 666-84	Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C 779-82	Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces
C 827-87	Standard Test Method for Change in Height at Early Ages of Cylindrical Specimens from Cementitious Mixtures
C 995-86	Standard Test Method for Time of Flow of Fiber-Reinforced Concrete Through Inverted Slump Cone
C 1018-85	Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading)
D 1557-78	Standard Test Methods for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 10-lb (4.54-kg) Rammer and 18-in. (475-mm) Drop

British Standards Institution

BS 1881:Part 2	Methods of Testing Concrete

U.S. Army Corps of Engineers

CRD-C 63-80	Test Method for Abrasion-Erosion Resistance of Concrete (Underwater Method)

These publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 19150
Detroit, MI 48219-0150

ASTM
1916 Race Street
Philadelphia, PA 19103

British Standards Institution
Linford Wood
Milton Keynes MK14 6LE
England

U.S. Army Corps of Engineers
Waterways Experiment Station
P.O. Box 631
Vicksburg, MS 39180

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This report was submitted to letter ballot of the committee and was approved in accordance with ACI balloting procedures.

THE FOLLOWING DISCUSSIONS, WHICH WERE PUBLISHED IN THE JULY-AUGUST 1989 ACI Structural Journal (PP. 425-426), ARE NOT PART OF THE REPORT ACI 544.2R-89, BUT ARE PROVIDED AS ADDITIONAL INFORMATION TO THE READER.

Measurement of Properties of Fiber Reinforced Concrete. Report by ACI Committee 544

Discussion by Nemkumar Banthia and Committee

By NEMKUMAR BANTHIA

Member American Concrete Institute, Assistant Research Professor, Department of Civil Engineering, Laval University, Quebec

The committee is to be congratulated for developing a comprehensive report on testing fiber reinforced concrete that is timely, informative, and useful. However, I would like to raise a few points concerning the impact testing of concrete.

1. In any dynamic testing, a sudden change in the momentum of the system is bound to produce d'Alambert's forces or the inertial forces due to specimen accelerations. One way of dealing with the specimen inertia, as suggested in the report, is to vary the stiffness of the contact zone (by introducing a soft rubber pad) and/or by choosing the test parameters, such as the specimen dimensions, hammer/specimen mass ratio, etc., such that the peak load occurs only after the specimen has gained enough momentum and is no longer accelerating. This is indeed an ingenious method of dealing with the inertial forces; however, the introduction of the rubber pad leads to a considerable reduction in the applied stress-rate on the specimen,[27] and the restricted test parameters lead to a limited scope in testing. In my opinion, for dynamic testing, a proper dynamic analysis of the system is necessary. One way to do so is by actually measuring the specimen accelerations by piezo-electric accelerometers.[28,*,†] Once the accelerations are known, a proper dynamic analysis of the system is possible, and the load-versus-load point displacement plots may be obtained. Moreover, there are no restrictions in the choice of the test parameters and very high stress rates may be generated.

All the dynamic data-acquisition systems have a limited number of input channels. It may appear that to know the accelerations at every point, a large number of accelerometers are required with an equal number of input data channels. Fortunately, the specimen accelerations are often simple mathematical functions of the spatial coordinates,[27] and the experimental measurement of accelerations is necessary only at one or two selected points on the specimen.

2. In the case of the longer flexural specimens, a certain time-lag between the striker and the anvil load is possible with the anvil load peak lagging behind the striker load peak.† A comparison between the two, therefore, warrants caution. Furthermore, the total support load plotted against the measured load-point displacement, in a three-point bend test using time-based data, may yield an improper load-versus-displacement plot.

*Banthia, N.; Mindess, S.; Bentur, A.; and Pigeon, M., "Impact Testing of Concrete Using a Drop Weight Impact Machine," *Experimental Mechanics,* in press.

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COMMITTEE CLOSURE

The committee appreciates the discussion by Dr. Banthia. He suggests an alternate method of analyzing the results from the instrumented impact tests. It is certainly possible to measure the inertial forces that a specimen is subjected to during an impact event. These forces can then be subtracted from the measured tup load to evaluate the bending stresses experienced by the beam. This method can extend the range of the loading rate, which is possible with an instrumented testing system described in the committee report. Unfortunately there can be other problems with the method suggested by Dr. Banthia: 1) Flexural load experienced by the beam is the difference between two large numbers (measured tup load and calculated inertial forces). This reduces the accuracy of the result; 2) unless a large number of accelerometers are used, assumptions regarding the deflected shape of the beam have to be made; and 3) unless dynamic finite element analysis with singular elements is used, it is difficult to calculate fracture toughness for notched beams.

If the beam is unusually long and the rate of loading is unusually high, there may be a time lag between the tup load and the anvil load. Usually this is not a problem for fiber reinforced concrete beams.

In summary, the instrumented test method recommended by the committee is an accurate method to determine the rate effects on modulus of rupture values as well as fracture toughness values for concrete and fiber reinforced concrete.

For very high rates of loading, alternate methods of instrumentation and analysis are needed. A detailed discussion of different test methods for high-velocity impact loading can be found in Reference 29.

REFERENCE

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