# Thirty years of fibre reinforced concrete research at the University of British Columbia

S. Mindess
*Department of Civil Engineering, University of British Columbia, Vancouver, B.C., Canada*



ABSTRACT: Fibre reinforced concrete (FRC) research has been carried out at the University of British Columbia for about the past thirty years. The emphasis in this paper is on three of the major areas of research: better ways of characterizing the effects of fibres on the toughness of concrete; the properties of FRC under impact loading; and the use of hybrid fibre systems. These research areas are discussed largely in terms of the work carried out by our many graduate students over this period of time. The paper concludes with a discussion of possible future developments of this technology.

## 1 INTRODUCTION

Fibres have been used to reinforce materials that are weaker in tension than in compression since ancient times. Straw reinforced mud bricks were used in the Middle East as long as 10,000 years ago, and sun-dried adobe bricks (a mixture of sand, clay and straw) were long used in the Americas by the indigenous inhabitants, particularly in the American Southwest and inparts of South America. The first modern FRC was asbestos cement, which was introduced in about 1900 with the development of the Hatschek process. However, serious theoretical studies of FRC began only in the early 1960's, with the work of Romualdi and his colleagues [*e.g.* Romualdi & Batson 1963; Romualdi & Mandel 1964].

Today, FRC is very widely used, with annual production now approaching about 100 m$^3$. The principal applications are slabs on grade, shotcrete, and precast members, as well as a number of specialty applications. Until now, most of the production of FRC has been for "non-structural" applications, with the fibres added primarily for control of cracking due to plastic or drying shrinkage. However, there is now increasing use of fibres as the primary reinforcement in truly structural applications, even though most building codes, particularly in North America, do not really recognize the contribution of the fibres to the mechanical properties of the concrete.

While FRC can now be considered to be a mature technology, there are still some areas in which further research is required. This paper deals with three such areas, all of which are being studied extensively at the University of British Columbia (UBC): better ways of characterizing the effects of fibres on the *toughness* of concrete; the properties of FRC under *impact* loading; and the use of *hybrid fibre* systems.

## 2 CHARACTERIZING TOUGHNESS

While fibres can improve the pre-peak mechanical properties of concrete, particularly when used at high fibre volumes (>2% by volume), their principal role is to control the cracking of the FRC, and then to modify the behaviour of the composite once the concrete matrix has cracked. By bridging across cracks as they begin to open, the fibres can provide some post-cracking ductility to the FRC. Unfortunately, while we know *qualitatively* what the fibres can do to modify the post-peak behaviour of the concrete, it has been very difficult to get general agreement on an unambiguous method to *quantify* this behaviour. Over the years, a number of such tests have been proposed.

For instance, the Japan Concrete Institute has published a method for determining the *compressive* toughness of FRC, JSCE SF5: *Method of Test for Compressive Strength and Compressive Toughness of Steel Fibre-Reinforced Concrete.* In this method, the complete load vs. deflection curve is analyzed, through the calculation of a compressive toughness factor, $T$, defined as:

$$T = 4T_c/(\pi d^2 \delta_{tc}) \qquad (N/mm^2) \qquad (1)$$

where $T_c$, the compressive toughness, is the area under the load vs. deformation curve out to a strain of 0.75% (J); $d$ is the specimen diameter (mm); and $\delta_{tc}$ is the deformation corresponding to 0.75% converted to strain (mm). According to JSCE SF5, the test may be carried out in an open-loop testing machine, but it has been found [Zhang & Mindess 2005] that this works only for compressive strengths below about 60 MPa; for higher strengths, a catastrophic brittle failure occurs unless a closed-loop machine is used. However, since fibres have little effect on the compressive strength of concrete, this test is rarely, if ever, used.

The static mechanical tests most commonly used to characterize FRC are flexural tests, since FRC is most commonly used in flexural applications. A number of such tests have been proposed over the years, and several have been adopted as standards in various jurisdictions. According to Mindess *et al.* [2003], any toughness or residual strength parameter used for the specification or quality control of FRC should, ideally, satisfy the following criteria:

- It should have a physical meaning that is readily understandable.
- The 'end-point' used in the calculation of toughness parameters should represent the most severe serviceability conditions anticipated for any particular application.
- The variability inherent in any measurement of concrete properties should be acceptably low.
- It should be able to quantify some important aspect of FRC behaviour (strength, toughness, crack resistance) and should reflect some characteristics of the load vs. deflection curve.
- It should be largely independent of specimen size and geometry.

Unfortunately, none of the test methods that have so far been standardized meet these criteria, in large part because neither strength nor the shape of the load vs. deflection curve are themselves fundamental concrete properties. However, it is important to understand the difficulties involved in using the methods to be described below, particularly since the tests often give conflicting results when compared with each other.

For many years, by far the most common test, at least in North America, was ASTM C1018: *Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading).* A small beam specimen (100mm x 100mm x 350mm) is tested in flexure under third-point loading, and 'toughness indices' are defined in terms of the ratio of the load under the load vs. deflection curve out to some specified deflection to the area under the curve out to the point of 'first crack', as shown in Figure 1. In addition, 'residual strengths' are usually calculated from the toughness indices; they represent the average post-cracking load that the specimen may carry over a specific deflection interval.

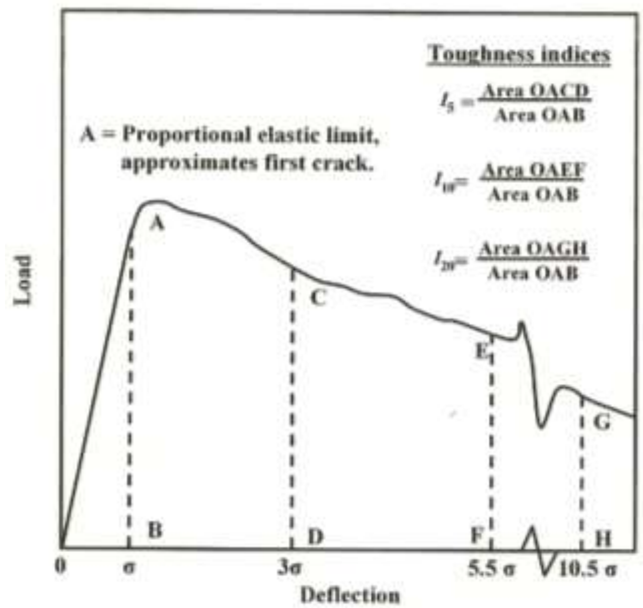


Figure 1. Schematic of load vs. deflection curve and definition of toughness parameters according to ASTM C1018.

However, this test was found to suffer from a number of shortcomings:

- Since the deflections out to first crack are very small, it is necessary to measure the first part of the load vs. deflection curve accurately, but this is often difficult, due to various "extraneous" deflections that may occur due to machine deformations and seating of the specimen on the supports. As was shown by Chen *et al.* [1995], different laboratories correct for these effects differently, and thus may obtain quite different results. Different testing machines may also lead to different results. Figure 2 [Chen *et al.* 1995] shows the very different load vs. deflection curves, particularly in the post-peak region, that were obtained by different laboratories on identical specimens.

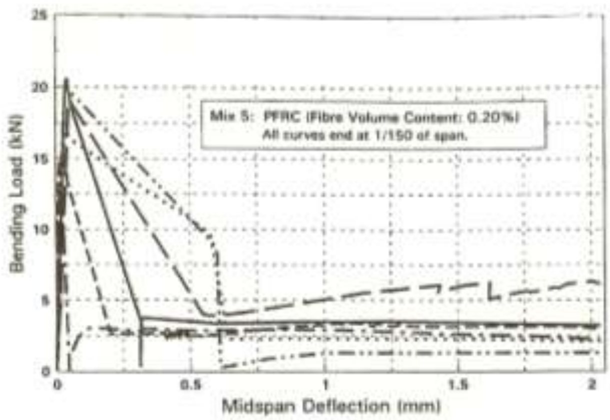


Figure 2. Effect of different impact machines on the load vs. deflection curves of identical FRC beams [Chen *et al.* 1995].

- The calculated toughness parameters depend on precisely how the point of ‘first crack’ is defined. However, since microcracking begins almost as soon as the specimen is loaded, this point cannot be defined in an unambiguous manner.
- The toughness parameters are not independent of specimen size.
- An *instability* often occurs in the measured load vs. deflection curves immediately after the first major crack, particularly for low fibre volume materials, as shown in Figure 3 [Chen *et al.* 1995]. Again, different testing machines can lead to quite different calculated toughness parameters.

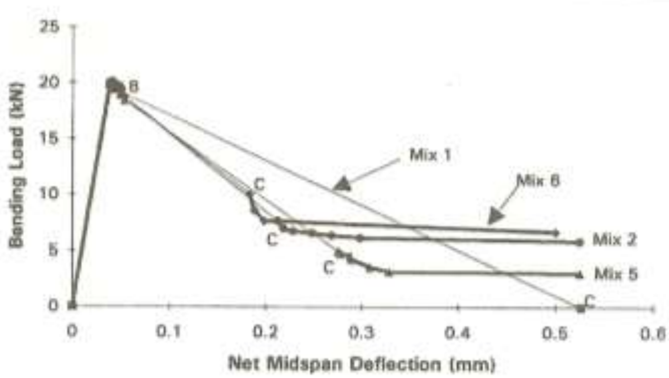


Figure 3. Region of instability for low fibre volume beams; mix 1 represents plain concrete [Chen *et al.* 1995].

As a result of these problems, ASTM C1018 was withdrawn in 2006. It has been replaced with ASTM C1609: *Standard Test Method for Flexural Performance of Fibre-Reinforced Concrete (Using Beam with Third-Point Loading)*. This test uses the same procedures as ASTM C1018 for obtaining the load vs. deflection curve, but the resulting curve is analyzed in a totally different way. Instead of the toughness parameters of ASTM C1018, the residual strengths are determined directly from the load vs. deflection curves. In addition, a toughness parameter may be calculated as the area under the load vs. deflection curve out to any specified deflection. This test appears to be more sensitive to different fibre types and volumes than was ASTM C1018.

There are two other ASTM standard tests for FRC. ASTM C1399: *Test Method for Obtaining Average Residual Strength of Fiber-Reinforced Concrete* employs a small beam cracked in a standard manner by loading it in combination with a steel plate; the purpose of the plate is to prevent total failure when the beam starts to crack. The plate is then removed, and the cracked FRC specimen is reloaded in order to obtain a reload vs. deflection curve. The average residual strength of the FRC over the deflection range of 0.5 – 1.25 mm is then determined. It was found by Banthia and Dubey [1999; 2000] that the load vs. deflection curves obtained in this way were very similar to those obtained using a closed-loop testing machine with good displacement control. This test appears to be most useful for relatively low fibre volumes. However, it too has some serious problems:

- The effect of the fibres on the behaviour just after first cracking is ignored.
- The length of the pre-crack obtained is not known, and is variable for different FRC systems. This makes comparison between different FRC beams difficult.
- Simple beam theory (as required in this test method) cannot be used to calculate the “strength” of a cracked system, so it is far from clear what the calculated residual strengths actually represent.

ASTM C1550: *Standard Test Method for Flexural Toughness of Fiber Reinforced Concrete (Using Centrally Loaded Round Panel)* involves the centre-point loading of a large circular plate, 800mm in diameter and 75mm thick, supported on three points. The specimen toughness is assessed in terms of the energy absorbed in loading the plate to some selected values of central deflection. This test has become popular with producers of fibre reinforced shotcrete, and is often used in the mining industry. It provides similar results to other toughness test, though with lower variability. As will be seen below, it is also very useful as an impact test specimen. Its chief disadvantage is that the specimen itself is too large and heavy (~90 kg) to be handled easily, and does not fit into many common testing machines.

Another test that is gaining popularity in the shotcrete industry is the *South African Water Bed* test [Trottier *et al.* 2002]. A large plate specimen 91600mm x 1600mm x 75mm) is fastened in place over a water bladder, which is then filled with water to apply pressure over the entire specimen. The energy absorbed (*i.e.* the toughness) is the area under the load vs. deflection curve out to a series of given deflections ranging from 25mm to 150mm.

*EFNARC* (European Federation of Producers and Contractors of Special Products for Structures) has proposed a plate test [EFNARC, 1996] involving a 600mm square plate, 100mm thick, supported on all four sides and loaded at the centre. The toughness is determined from the load vs. deflection curve out to a deflection of 25mm. This test is sometimes used in Europe, but rarely in North America.

'*Template' approach*: The template approach, suggested by Morgan *et al.* [1995] utilizes a 100mm x 100mm x 350mm beam loaded in 4-point bending, as in ASTM C1609. It does not involve the calculation of a toughness parameter *per se.* Rather, *toughness performance levels* such as those shown in Figure 4, are used. The actual load vs. deflection curve is then compared to the template to see whether the FRC conforms to the specified toughness performance level. The real advantage of this method is that it is not sensitive to the precise location of the 'first crack', to extraneous deflections, or to any instability in the load vs. deflection curve, since the shape of the curve up to a deflection of 0.5mm is not taken into consideration. Similar approaches have been adopted in the Norwegian and Austrian codes.

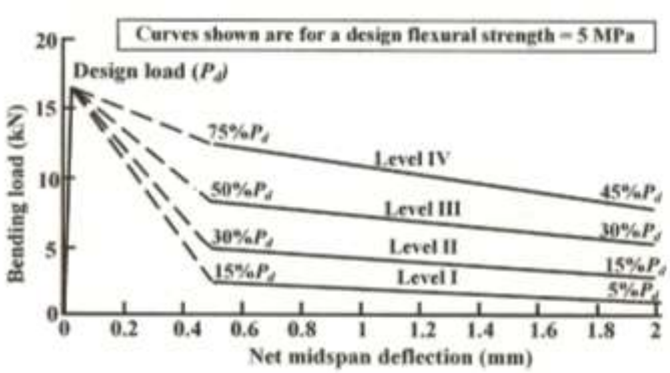


Figure 4. Template approach to specifying toughness in terms of residual strengths [Morgan *et al.* 1995].

The last (of many other) tests worth mentioning is that suggested by *RILEM TC162-TDF* [2002], as described in detail by Vandewalle [2004]. In this procedure, a *notched* beam (150mm x 150mm x 550mm) is tested in centre-point loading, and the crack mouth opening across the mouth of the notch is measured, using a closed-loop testing machine. The energy absorption capacities out to particular deflections are determined as a function of the area under the load vs. deflection curve. This method is intended to provide values that can be used directly in the structural design of FRC beams.

As should be apparent from the brief descriptions above, *all* of the proposed methods are empirical in nature, and are thus not directly comparable. They all violate one or more of the criteria outlined above [Mindess *et al.* 2003], and thus are of limited usefulness in providing design values for FRC. Indeed, it is this lack of a commonly agreed upon method for characterizing the performance of FRC that has inhibited the truly *structural* use of this composite material.

## 3 IMPACT RESISTANCE

It is well known that fibre additions can greatly improve the impact resistance of concrete. FRC is a strain rate sensitive material, but it has been found that it is not possible to predict the behaviour of FRC under high loading rates from static tests [*e.g.*, Banthia 1987]. The problem is complicated by the fact that, depending on the particular FRC system and the strain rate, the failure mechanisms may be quite different. Further, FRC systems may be subjected to very different strain rates ($\acute{\varepsilon}$), depending on the source of the dynamic event [Comité Euro-International du Béton 1988]:

| | |
|---|---|
| Traffic | $\acute{\varepsilon} = 10^{-6} - 10^{-4}\ s^{-1}$ |
| Gas explosion | $\acute{\varepsilon} = 5 \times 10^{-5} - 5 \times 10^{-4}\ s^{-1}$ |
| Earthquake | $\acute{\varepsilon} = 5 \times 10^{-3} - 5 \times 10^{-1}\ s^{-1}$ |
| Pile driving | $\acute{\varepsilon} = 10^{-2} - 10^{0}\ s^{-1}$ |
| Aircraft landing | $\acute{\varepsilon} = 5 \times 10^{-2} - 10^{0}\ s^{-1}$ |
| Hard impact | $\acute{\varepsilon} = 10^{0} - 5 \times 10^{1}\ s^{-1}$ |
| Hypervelocity impact | $\acute{\varepsilon} = 10^{2} - 10^{6}\ s^{-1}$ |

Because of this enormous range of possible strain rates, and the complexity of the FRC system itself, the high strain rate and impact properties of FRC are still poorly understood. There are a number of reasons for this [Jones and Mindess 1996; Banthia *et al.* 2003]:

- There are no standardized tests for either high strain rate or impact. While a number of test methods have been developed in various laboratories, the test arrangements and specimen geometries have been sufficiently different that the results from the many published studies are generally not comparable, and are often contradictory.

- There are no 'standard' cement-based materials that can be used to calibrate test techniques.
- All of the impact tests so far developed are extremely sensitive to the precise details of the procedures.
- There is no consensus on which parameters should be used to characterize the response of FRC to impact.

In what follows, some of the research carried out at the University of British Columbia over the last twenty-five years on the impact properties of FRC will be described.

Most of the work at UBC has been carried out using the instrumented drop weight impact machine shown schematically in Figure 5. This machine is capable of dropping a 575kg mass from heights of up to 2.5m. Two smaller machines of the same type, but with smaller drop hammers (about 60 kg and 10kg), have also been used. In recent years, the load cells, accelerometers, strain gauges and displacement transducers used to instrument the system have been supplemented by a high speed camera. This degree of instrumentation is essential, since the impact events studied usually have a duration of only a few milliseconds.

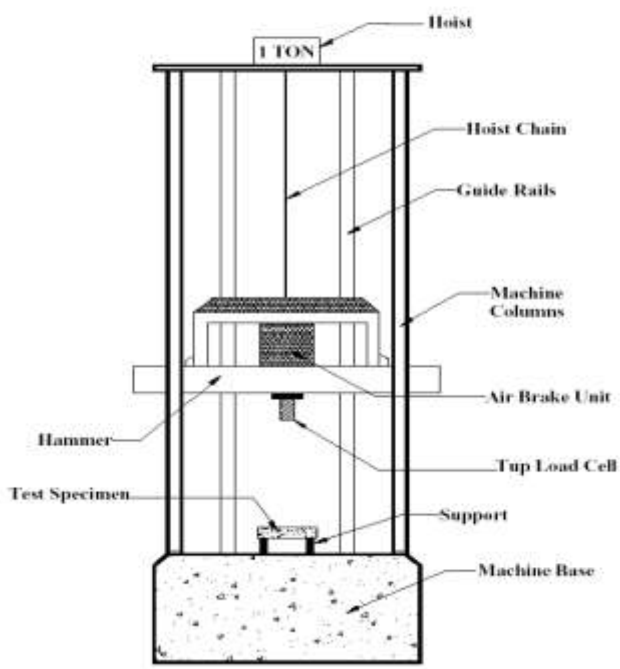


Figure 5. Schematic sketch of the instrumented impact machine at the University of British Columbia.

With the exception of the split Hopkinson pressure bar, all of the instrumented impact tests result in high specimen accelerations that manifest as inertial forces in the system. These inertial forces must somehow be accounted for, as they may represent a considerable portion of the recorded load. At the beginning of an impact event, a beam is accelerated and the inertial forces and the bending forces are both recorded by the load cell. Thus, during this time period, the recorded load is considerably greater than that actually involved in bending the beam. In order to overcome this difficulty, various techniques have been developed. The approach taken at UBC [Bentur *et al.* 1986; Banthia *et al.* 1987] is to account for the inertial load by recording the specimen acceleration during the impact event, using accelerometers attached to the specimen. From the accelerometer readings, the generalized inertial load canbe derived using the principle of virtual work. Then, the load actually involved in deflecting the specimen during the impact event, $P_b(t)$, can be calculated as the difference between the total load recorded by the striking tup, $P_t(t)$, and the inertial load, $P_i(t)$:

$$P_b(t) = P_t(t) - P_i(t) \tag{1}$$

The deflection at mid-span of the beam can then be calculated by integrating twice, with respect to time, the acceleration at mid-span (or by direct reading with a laser transducer). The bending load vs. time curve can then be established. This approach permits a differentiation amongst the three types of loads. As may be seen from Figure 6 [Bentur *et al.* 1986], the inertial load may be a large fraction indeed of the total load during the initial stages of the impact event, particularly for FRC.

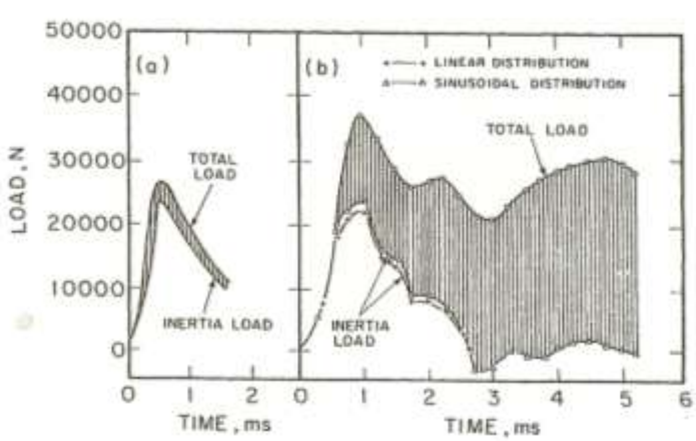


Figure 6. Total load and inertia load vs. time curves of beams subjected to impact (a) plain concrete; (b) reinforced concrete [Bentur *et al.* 1986].

### 3.1 *Effects of test parameters on impact data*

As stated above, the precise details of the impact test system can have a considerable effect upon the resulting data. Some of the principle test parameters are discussed below.

#### 3.1.1 *Rigidity of the impact machine*

There are no documented studies dealing with the effects of machine rigidity. While the rigidity probably has little effect upon the peak load, it will affect the post-peak behaviour, through its affect upon the energy absorbed by the impact machine itself.

#### 3.1.2 *Rigidity and geometry of specimen supports*

Ideally, the specimen supports should be as rigid as possible. However, if the supports are too rigid, such that the time required for the load to reach its maximum value is less than one-half of the natural frequency of the specimen, then the stress waves set up during the impact event must be taken into account, which enormously complicates the analysis.

Since there is inevitably some cracking or crushing at the specimen supports, the shape of the supports may have some effects on the measured values as well.

#### 3.1.3 *Size of the loading tup*

Sukontasukkul [2001] carried out impact tests on small FRC plates, using two different circular loading tups, with diameters of ¼ and ⅜ of the clear span of the simply supported plates. For the smaller tup, the failure mode was dominated by shear; for the larger one, mixed shear and flexure failure modes were found. This too changes the apparent resistance of the FRC to impact.

#### 3.1.4 *Specimen size*

Bindiganavile [2003] tested three different sizes of geometrically similar steel FRC beams. As may be seen in Figure 7, not only the strengths of the beams, but also the shapes of the load vs. deflection curves, depend on the specimen size. Other tests have shown that impact tests are also greatly affected by the relationship between the weight of the impact hammer, and the specimen size and strength. However, we cannot yet quantify these relationships.

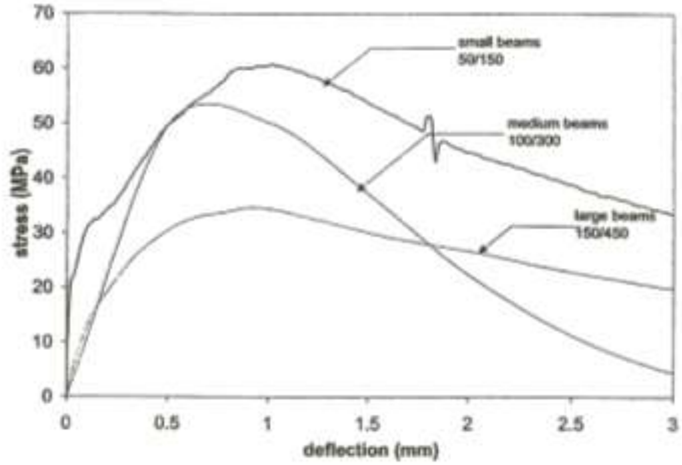


Figure 7. Stress vs. deflection responses of beams of different sizes, with beam depth:span ratios of 50:150, 100:300 and 150:450 [ Bindiganavile 2003].

#### 3.1.5 *Impact velocity and impact energy*

Both the impact velocity and the impact energy have significant effects on the behaviour of FRC. Table 1 shows the results of tests carried out at UBC with two similar (except for the hammer weight) drop weight impact machines. Tests 1 and 2 have different impact velocities, and hence different impact energies; tests 1 and 3 have the same impact energies but different impact velocities; and tests 2 and 3 have the same impact velocities but different impact energies. It may be seen that there are no clear relationships amongst the impact velocity, the impact energy, the hammer weight, the mid-span deflection and the fracture energy. It is therefore not clear which test parameters best characterize the material, or which test conditions should be "standardized" for impact tests.

Table 1. Impact test data for high strength concrete beams.

| Test | Hammer weight (kg) | Drop height (mm) | Max load (kN) | Mid-span deflection at max load (mm) | Fracture energy (N·m) |
|---|---|---|---|---|---|
| 1 | 578 | 156 | 75.3 | 12.43 | 318 |
| 2 | 578 | 1500 | 253.6 | 2.57 | 373.1 |
| 3 | 60 | 1500 | 190.5 | 2.05 | 258.4 |

Similarly, Table 2 shows the results of tests on Steel FRC beams, using the same 60kg drop hammer. Here, the drop height (and hence the impact velocity and impact energy) was varied. With increasing drop height, the strength increased while the fracture energy decreased. Again, it is not clear how best to describe the material behaviour.

Table 2. Impact data for steel fibre reinforced concrete beams.

| Drop height (mm) | Static | 1000 | 1100 | 1200 | 1300 |
|---|---|---|---|---|---|
| Max load (kN) | 59.1 | 281.5 | 291.4 | 299.2 | 307.0 |
| Nominal flexural strength (MPa) | 17.2 | 81.8 | 84.7 | 87.0 | 89.2 |
| Fracture energy (N·m) | 263 | 489 | 450 | 386 | 353 |

Figure 8 shows the results of splitting tension tests carried out on steel FRC cubes [Mindess 1995]. The cubes all failed by vertical splitting. In general, the crack velocity increased with increasing impact velocity, as might be expected. However, it is again unclear as to which drop height should be used to characterize the material behaviour.

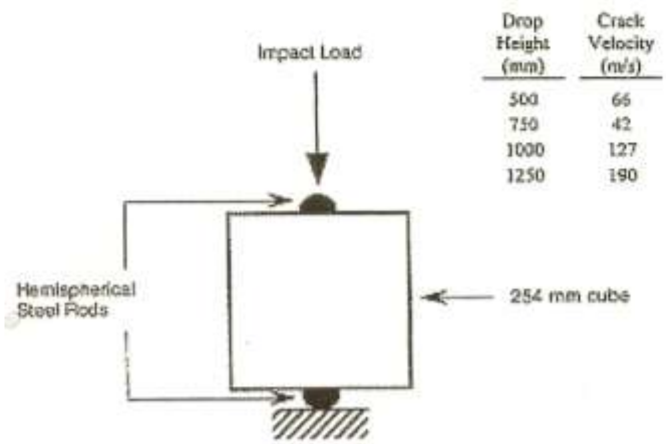


Figure 8. Impact of fibre reinforced concrete cubes in splitting tension [Mindess 1995].

Bindiganavile [2003] showed that maintaining a condition of identical impact energy is insufficient to standardize an impact test. He tested both steel FRC and polypropylene FRC using the same impact machines mentioned earlier. With a large drop mass, the steel FRC appeared to be tougher; the reverse was true when the small mass was used. Which, then, is tougher under impact loading?

Similarly, Bindiganavile and Banthia [2001]found that heavier hammers simulate longer pulses during impact, while greater drop heights simulate shorter pulses. Thus, quite different flexural toughness values can be obtained for the same FRC using machines of different capacities, as shown in Figure 9.

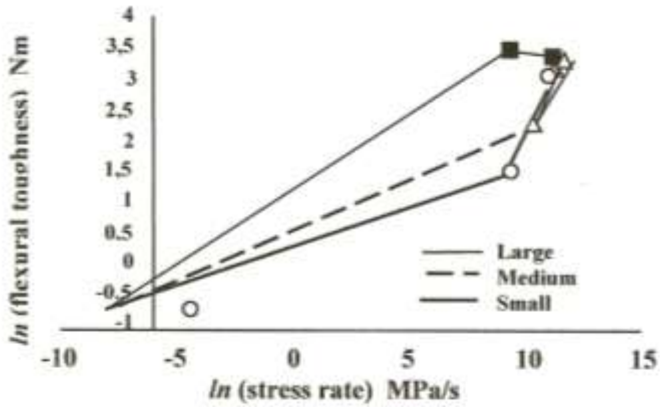


Figure 9. Influence of machine capacity on the impact response of FRC [Bindiganavile & Banthia 2001].

3.1.6 *How should we characterize impact of FRC?* From the above, it is clear that the behaviour under impact loading of FRC (or of plain concrete) depends largely on how the test is carried out. The variabilities in test results described above (for tests with geometrically similar drop-weight impact machines) are enormously magnified when tests by other researchers, using quite different test techniques, are also considered.

The peak load (or specimen strength) is commonly determined during impact tests. However, it is the *post-peak* behaviour which is the really important characteristic of FRC, and so it is not clear how useful the strength value is. In our view, it would be more useful to record the residual load-bearing capacity of the specimen at different deflections which represent the particular service conditions. In some cases, some arbitrary measures of damage may also be useful, although there is no agreement on how this damage is to be defined or quantified.

The fracture energy is probably the most commonly determined parameter measured in an impact test. However, as shown above, the fracture energy is strongly dependent on how it is measured, particularly with regard to the mass of the impacting hammer and the hammer velocity. The relative masses of the specimen and the impact hammer are also important. Thus, in the absence of any sort of "standard" test, it is now essentially impossible to compare the results of different investigations.

There have been some limited attempts to measure the crack velocity during impact tests of FRC, using high speed photography [*e.g.* Mindess & Bentur 1985; Mindess *et al.* 1986; Banthia 1987; Mindess 1995]. These measurements can provide invaluable information about the nature of the fracture process, and may even provide qualitative information about the relative effectiveness of different fibre types, they cannot provide any useful design information. And, like other measurements, crack velocities depend strongly on how the specimen was tested.

The degree of damage or fragmentation provides only a qualitative measure of fibre effectiveness. Again, this information cannot be used in design or analysis.

Thus, we remain in the situation that we are unable to agree on any way to characterize the behaviour of FRC under impact loading. This lack of standards inhibits the use of FRC in structural applications involving blast or impact, even though we know with certainty that fibres are effective in mitigating the effects of these types of loading. Regrettably, more than twenty years of research has not brought us much closer to solving this problem.

## 4 HYBRID FIBRE SYSTEMS

The combination of two or more different types of fibres (different fibre types and/or geometries) is becoming more common, with the aim of optimizing overall system behaviour. The intent is that the performance of these hybrid systems would exceed that induced by each fibre type alone. That is, there would be a *synergy*. Banthia and Gupta [2004] classified these synergies into three groups, depending on the mechanisms involved:

- Hybrids based on the fibre constitutive response, in which one fibre is stronger and stiffer and provides strength, while the other is more ductile and provides toughness at high strains [Banthia and Gupta 2004].
- Hybrids based on fibre dimensions, where one fibre is very small and provides microcrack control at early stages of loading; the other fibre is larger, to provide a bridging mechanism across macrocracks.
- Hybrids based on fibre function, where one type of fibre provides strength or toughness in the hardened composite, while the second type provides fresh mix properties suitable for processing.

These concepts have been applied both for thin sheet FRC (particularly for asbestos-cement replacement), and for high performance – high ductility systems, with fibre volumes of from 2-10%.

In composites with only one type of fibre, high modulus fibres tend to increase strength with only modest improvements in toughness, while low modulus fibres tend to increase the toughness, with little or no improvement in strength. However, it has been shown in many studies that a judicious combination of the two fibre types can lead to a composite in which the disadvantages of the two fibre types are offset, and only their advantages are displayed.

Another type of hybrid material is FRC made with a polymer-cement matrix. Adding a polymer to a concrete matrix has a large effect on the fibre-matrix bond, and hence on the properties of the resulting FRC composite. This technology is now being investigated, though it has still not been used much in practice.

Current research at UBC has shown that polymer-modified steel FRC has greatly enhanced flexural properties under both static [Xu *et al.* 2004] and impact loading [Xu & Mindess 2005a]. This was also true for both static and impact loading in compression [Xu *et al.* 2005]. It was also found that, with the appropriate polymer addition (styrene-butadiene rubber latex), a significant improvement in fibre-matrix bond properties could also be achieved [Xu & Mindess 2005b].

## 5 CONCLUDING REMARKS

From this brief summary of some of the research carried out at UBC over the past thirty years, it may be seen that we have made great strides in our understanding of behaviour of FRC. We know how to “tailor-make” FRC for a wide variety of applications, and FRC has become very much a mainstream construction material. However, its applications would still be considered to be primarily in non-structural applications (industrial floors, thin-sheet materials, fibre shotcrete tunnel linings, and so on). FRC is rarely mentioned in modern building codes, which of course greatly inhibits its use in structural applications.

A massive amount of research that has been carried out during this time, both at UBC and elsewhere worldwide, and countless papers and books have been published. (For instance, the recent edition of Bentur and Mindess, *Fibre Reinforced Cementitious Materials* [2007] contains over 1150 carefully selected references). Unfortunately, this has not resulted in the sort of information required for routine structural design. Part of the problem is that, in North America and in most other parts of the world, structural design in concrete is almost entirely strength based. However, at the fibre volumes generally used in practice (<1%), fibres have little effect on the concrete strength; their purpose is to make the material appear to be more 'ductile', by providing a degree of post-cracking load bearing capacity. Design codes such as ACI 318: *Building Code Requirements for Reinforced Concrete* simply do not recognize this post-peak behaviour. To take the real behaviour of FRC into account, it is probably necessary to adopt a fracture mechanics approach to analysis and design, rather than the current strength-based approach. However, this is highly unlikely, at least in North America, since we generally do not even teach the fundamentals of fracture mechanics in undergraduate Civil Engineering curricula.

On the other hand, one should not simply blame the structural engineers for this state of affairs. We in the concrete materials research community are equally remiss. While we have focused on the fundamental properties of FRC, the mechanisms underlying FRC behaviour, and how to produce ever more exotic FRC composites, we have not put sufficient effort into developing appropriate methods of characterizing the behaviour of FRC in a manner that can be quantified unambiguously and thus used in design. The relatively few current test methods, such as they are, are not suitable for this purpose. For properties such as impact resistance, which is becoming an increasingly important design consideration, we can neither characterize FRC behaviour nor test this behaviour in a consistent and theoretically sound manner. Until the materials engineers and the structural engineers begin to work ***together*** to solve these problems, FRC will be unable to take its rightful place as a useful, modern, high technology construction material.

## 6 ACKNOWLEDGMENTS

I would like to acknowledge the contributions of all of our many graduate students, both past and present, whose energy and ingenuity made much of this research possible. Most of the references in this paper reflect their contributions. As well, this work would not have been possible without the expert assistance of the staff of the Civil Engineering machine shop, who helped to design the impact equipment, and who then built, modified and maintained it for the last thirty years.

## REFERENCES

Banthia, N.P. 1987. *Impact Resistance of Concrete.* Ph.D. Thesis, Vancouver, B.C., Canada: University of British Columbia.

Banthia, N., Bindiganavile, V. & Mindess, S. 2003. Impact resistance of fibre reinforced concrete: a progress report, In A.E. Naaman & H.W. Reinhardt (eds.), *High Performance Fiber Reinforced Cement Composites (HPFRCC4)*. RILEM Proceedings PRO 30: 117-131. Bagneux, France: RILEM.

Banthia, N. & Dubey, A. 1999. Measurement of flexural toughness of fiber reinforced concrete using a novel technique, Part 1: assessment and calibration, *ACI Materials Journal* 89: 651-656.

Banthia, N. & Dubey, A. 2000. Measurement of flexural toughness of fiber reinforced concrete using a novel technique, Part 2: performance of various composites, *ACI Materials Journal* 97: 3-11.

Banthia, N. & Gupta, R. 2004. Hybrid fibre reinforced concrete (HyFRC): fiber synergy in high strength matrices, *Materials and Structures (RILEM)* 37: 707-716.

Banthia, N., Mindess, S. & Bentur, A. 1987. Impact behaviour of concrete beams, *Materials and Structures (RILEM)* 20: 293-302.

Bentur, A. & Mindess, S. 2007. *Fibre Reinforced Cementitious Composites.* London & New York: Taylor & Francis.

Bentur, A., Mindess, S. & Banthia, N. 1986. The behaviour of concrete under impact loading: experimental procedures and method of analysis, *Materials and Structures (RILEM)* 19: 371-378.

Bindiganavile, V.S. 2003. *Dynamic Fracture Toughness of Fiber Reinforced Concrete.* Ph.D. Thesis, Vancouver, B.C., Canada: University of British Columbia.

Bindiganavile, V.S. & Banthia, N. 2001. Machine effect in the drop-weight impact testing of plain concrete beams, In N. Banthia, K. Sakai & O.E. Gjorv (eds.), *Concrete under Severe Conditions*, (CONSEC'01), Vol. 1: 589-596. Vancouver, B.C., Canada: University of British Columbia.

Chen, L., Mindess, S., Morgan, D.R., Shah, S.P., Johnston, C.D. & Pigeon, M. 1995. Comparative toughness testing of fiber reinforced concrete, In D. Stevens, N. Banthia, V.S. Gopalaratnam & P.C. Tatnall (eds.), *Testing of Fiber reinforced Concrete.* Publication SP-155: 41-75. Farmington Hills, MI, USA: American Concrete Institute.

Comité Euro-International du Béton 1988. *Concrete Structures under Impact and Impulsive Loading – Synthesis Report*. Bulletin 187: §3.6. CEB.

EFNARC 1996. *European Specification for Sprayed Concrete*, European Federation of Producers and Contractors of Special Products for Structures.

Jones, N. & Mindess, S. 1996. Experience and capabilities in precision impact testing, In T. Krauthammer, A. Jenssen & M. Langseth (eds.), *Precision Testing in Support of Computer Code Validation and Verification.* Workshop Report, Fortifikatorisk Notat Nr 234/96: 35-51. Norwegian Defence Construction Service.

Mindess, S. 1995. Crack velocities in concrete subjected to impact loading, *Canadian Journal of Physics* 73: 310-314.

Mindess, S., Banthia, N., Skalny, J.P. & Ritter, A. 1986. Crack development in cementitious materials under impact loading, In S. Mindess & S.P. Shah (eds.), *Cement-Based Composites: Strain Rate Effects on Fracture*, Materials Research Society Symposia Vol. 64: 217-224. Pittsburgh, PA, USA: Materials Research Society.

Mindess, S. & Bentur, A. 1985. A preliminary study of the fracture of concrete beams under impact loading using high speed photography, *Cement and Concrete Research* 15: 474-484.

Mindess, S., Young, J.F. & Darwin, D. 2003. *Concrete*, 2nd ed. Upper Saddle River, NJ: Prentice Hall.

Morgan, D.R., Mindess, S. & Chen, L. 1995. Testing and specifying toughness for fibre reinforced concrete and shotcrete, In N. Banthia & S. Mindess (eds.), *Fiber Reinforced Concrete: Modern Developments*: 29-50. Vancouver, Canada: University of British Columbia.

RILEM TC 162-TDF 2002. Test and design methods for steel fibre reinforced concrete – bending test, *Materials and Structures (RILEM)* 35: 579-582.

Romualdi, J.P. & Batson, G.B. 1963. Mechanics of crack arrest in concrete, *Journal of Engineering Mechanics* 89: 147-168.

Romualdi, J.P. & Mandel, J.A. 1964. Tensile strength of concrete affected by uniformly dispersed and closely spaced short lengths of wire reinforcement, *Journal of the American Concrete Institute* 61: 657-672.

Sukontasukkul, P. 2001. *Impact Behaviour of Concrete under Multiaxial Loading.* Ph.D. Thesis, Vancouver, B.C., Canada: University of British Columbia.

Trottier, J.-F., Forgeron, D. & Mahoney, M. 2002. Influence of construction joints in wet-mix shotcrete panels, *Shotcrete* Fall: 26-30.

Vandewalle, L. 2004. Test and design method for steel fibre reinforced concrete based on the $\sigma$-$\varepsilon$ relation, In A.M. Brandt (ed.), *Some Aspects of Design and Application of High Performance Cement Based Materials*. Lecture Notes 18 135-190. Warsaw, Poland: Institute of Fundamental Technological Research.

Xu, H. & Mindess, S. 2005a. Effect of polymers on steel fibre reinforced round concrete panels under impact loading, In V. Bilek & Z. Kersner (eds.), *Non-Traditional Cement and ConcreteII; Proc. 2nd International Symposium on Non-Traditional Cement and Concrete, Brno, Czech Republic 14-16 June 2005*: 604-612. Brno, Czech Republic: Brno University of Technology.

Xu, H. & Mindess, S. 2005b. Dynamic pullout performance of steel fibers in polymer modified mortar, In N. Banthia, T.Uomoto, A. Bentur & S.P.Shah (eds.), *Construction Materials; Proc. ConMat '05 and Mindess Symposium, Vancouver, British Columbia, Canada 22-24 August 2005.* CD-ROM. Vancouver, Canada: University of British Columbia.

Xu, H., Mindess, S. & Fujikake, K. 2004. Post crack flexural performance of high strength fiber-reinforced concrete with latex modification, In M.Maultzsch (ed.), *Proceedings, 11th International Congress on Polymers in Concrete, ICPIC'04*: 445-460. Berlin, Germany: BAM.

Xu, H., Mindess, S. & Fujikake, K. 2005. Impact performance of latex-modified high strength FRC under uniaxial compressive loading, In N. Banthia, T.Uomoto, A. Bentur & S.P.Shah (eds.), *Construction Materials; Proc. ConMat '05 and Mindess Symposium, Vancouver, British Columbia, Canada 22-24 August 2005.* CD-ROM. Vancouver, Canada: University of British Columbia.

Zhang, L. & Mindess, S. 2005. The compressive toughness of high strength fiber reinforced concrete, In N. Banthia, T.Uomoto, A. Bentur & S.P.Shah (eds.), *Construction Materials; Proc. ConMat '05 and Mindess Symposium, Vancouver, British Columbia, Canada 22-24 August 2005.* CD-ROM. Vancouver, Canada: University of British Columbia.