Congrès de la Société canadienne de génie civil
Annual Conference of the Canadian Society for Civil Engineering

Montréal, Québec, Canada
5-8 juin 2002 / June 5-8, 2002

IMPACT RESPONSE OF AN ULTRA-HIGH STRENGTH CEMENT COMPOSITE

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ABSTRACT: Structures of military and strategic importance are required to withstand severe loading conditions, especially those induced by impact and shock. Such high stress rates demand a very high strength material, which is equally capable of maintaining its integrity under impact loading. In this study, Compact Reinforced Composite (CRC), which is a high volume fraction, steel fiber reinforced, ultra-high strength cement composite was investigated for its response to impact loading.

The high fiber content did not pose any difficulty in workability. Quasi-static tests revealed that compared to normal strength steel fiber reinforced concrete (SFRC), CRC is about 4 times stronger in flexure and more importantly, it can dissipate 3 times more energy. Impact tests performed with the instrumented drop-weight set up showed that while CRC can withstand over 2.5 times the load taken by SFRC, it is over 4 times as tough. As expected for high strength materials, CRC was found to be less stress-rate sensitive than SFRC. This was accompanied by an increase in flexural toughness until very large drop heights (or stress rate). It is clear from this study that Compact Reinforced Composite is an ideal candidate for use in structures of military importance where resistance to impact loading is desired.

1. INTRODUCTION

Compact reinforced composite (CRC) is the designation for a special type of high fiber volume fraction, steel fiber reinforced, high-strength concrete. Developed by Aalborg Portland, it is characterized by a low water/binder ratio, high silica fume content and absence of any coarse aggregates (Bache 1981). As a result, CRC has a very high compressive strength (150-400 MPa) and is usually reinforced with very high volume fraction of steel fibers, typically 6 %.

Strictly speaking, in the absence of coarse aggregates, CRC is basically a mortar. It has been seen to undergo enormous autogenous shrinkage at very early ages, which however, practically stops around the 10^{th} day. This has been attributed to the large amount of unhydrated cement grains (~50 %), which reinforce the granular skeleton of the hydrating material and stiffen it (Loukili et al. 1999). The dense microstructure of CRC is reported to give it superior durability compared to conventional high-strength concrete (Andrade et al. 1996).

While CRC has been promoted primarily for pre-cast applications in slender structures, its high strength and high ductility make it potentially very resistant to explosive and high stress rate loading. Typically, structures of military and strategic importance must be resistant to impact loading that may arise from explosive blasts or missiles and projectiles. Few studies have been made on ultra-high strength concrete under impact. Lee *et al*. demonstrated the superior resistance of Reactive Powder Concrete (having f'_c~180-400 MPa) under projectile impact over normal and high strength concrete (Lee et al. 2001). While some tests were performed in Sweden to demonstrate its superior resistance to impact with a missile shot from a cannon, a detailed and systematic study of the high stress rate behaviour of CRC has never been made. In this light, the present study focuses on the impact behaviour of CRC using an instrumented drop-weight impact machine and compares the material with the more conventional forms of fiber reinforced concrete.

2. EXPERIMENTAL PROGRAM

The program involved the study of the flexural behaviour of CRC under both quasi-static and impact loading. Beams (100 mm x 100 mm x 350 mm) and cylinders (50 mm ƒ x 100 mm) were cast in order to test the material under flexure and splitting tension (quasi-static only) respectively. Three specimens were cast for each data point. The quasi-static flexural tests were performed in accordance with ASTM C-1018 (1998) and ASTM C–1399 (1998) on the Instron Materials Testing System (Figure 1). The broken halves of the tested beams were cored to yield four cylinders, which were tested in compression as per ASTM C 42 (1998). Splitting tensile tests were carried out on the Amsler Testing Machine as per ASTM C-496 (1998). For the impact tests, an instrumented drop-weight impact machine of capacity 1,500 J (developed at UBC) was employed (Figure 2). The instrumentation is described in detail by Banthia (Banthia 1987). Briefly, the striking 'tup' is mounted with strain gauges (as shown in Figure 3) and hence works as a load cell. The beams were fitted with an accelerometer on the underside at mid-span. The load recorded by the tup was corrected for the inertial effect (Banthia et al. 1989), to obtain the true bending loads. The accelerometer readings were integrated twice with respect to time to yield the deflection-time response. Thus, the load-deflection response could now be evaluated.

Figure 1. ASTM C 1018 Flexural Toughness test

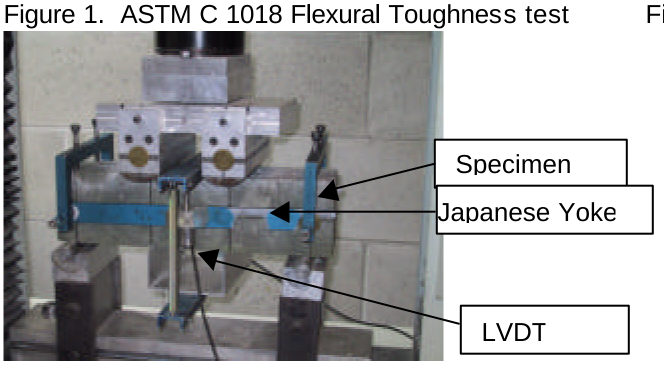


Figure 2. Impact Test Machine

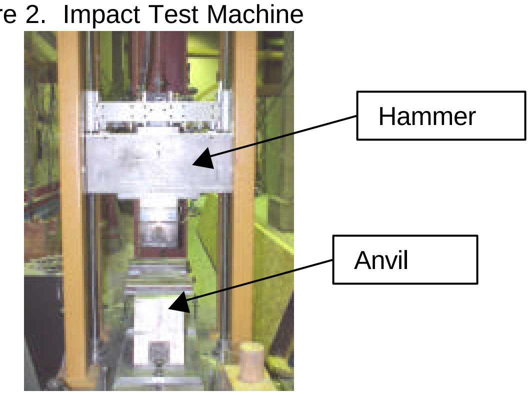
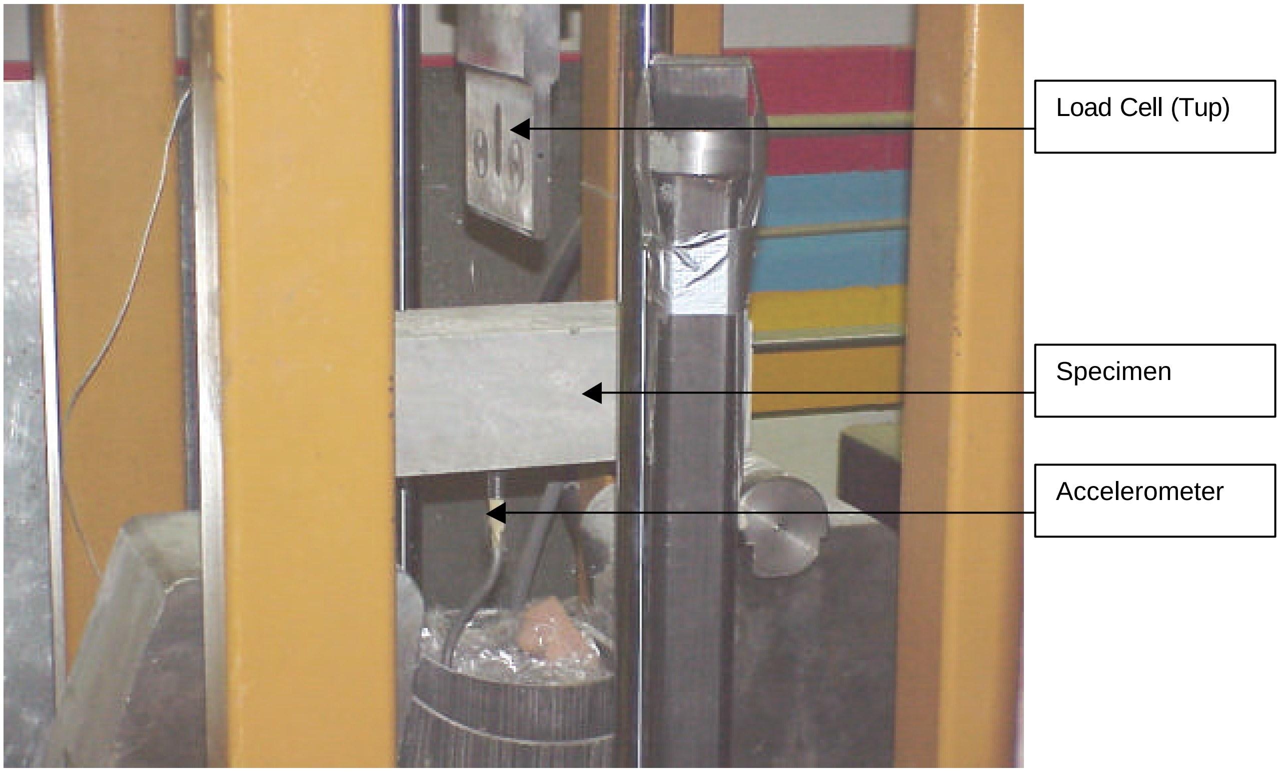


Figure 3. Instrumented Striker (‘*tup*’)



Four drop-heights (200 mm, 500 mm, 750 mm and 1000 mm) were investigated to help describe the impact behaviour under a range of stress rates.

Table 1 Mix Proportions in Compact Reinforced Composite (CRC)

Constituent	Cement	Silica fume	SP	Quartz Sand			Water	Fiber
				0-0.25 mm	0.25- 1 mm	1-4 mm		
Proportion (kg/m^3)	750	179	21	189	383	613	150	457

The mix proportion for CRC designed in this study is shown in Table 1. A white Portland cement containing 66.9 % C_3S, 19.2 % C_2S, 4.35 % C_3A and 1 % C_4AF was used along with silica fume (24 % of cement by weight). A dry superplasticizer of condensed naphthalene sulphonate was used to achieve workability. The aggregate was quartz sand of 4 mm maximum particle size and steel fibers, 12 mm long and 0.4 mm f were added at the rate of 6 % V_f as reinforcement. The mixing technique was as follows: Cement, silica fume, sand and the superplasticizer were mixed in a pan mixer for 2 minutes followed by the addition of the entire mix water (w/[c+sf] = 0.16). The material was allowed to mix for a further 6 minutes. This is required to allow the dry superplasticizer sufficient time to plasticize the mix. The fibers were introduced after this period, gradually to ensure maximum dispersion. Slump tests were carried out both before and after the fiber addition.

3. RESULTS AND DISCUSSION

3.1 Workability

Figures 4 and 5 show the slump of fresh CRC before and after the addition of 6 % steel fibers. While the slump for the former was 200 mm, the slump for the latter was 120 mm. Clearly, the material was quite workable even at such high fiber content. However, mixes with 9 and 12 % have been found to be very stiff (Tjiptobroto et al. 1991).

Figure 4. Slump test on CRC mix without fiber

Figure 5. Slump test on CRC mix with 6% fiber

3.2 Quasi-static tests

Compressive strength of CRC was found to be 192 MPa. Splitting tensile tests carried out on 50 mm f cylinders yielded values of 20 MPa. The flexural responses of CRC beams in accordance with ASTM C1018 and ASTM C 1399 are plotted in Figure 6. Note that the plot showing the post crack response in the figure corresponds to the deflection beyond that corresponding to first crack. However, due to the heavy reinforcement and absence of any instability, the instance of first crack could not be determined. The results of the quasi-static flexural tests are analysed and shown in Table-2.

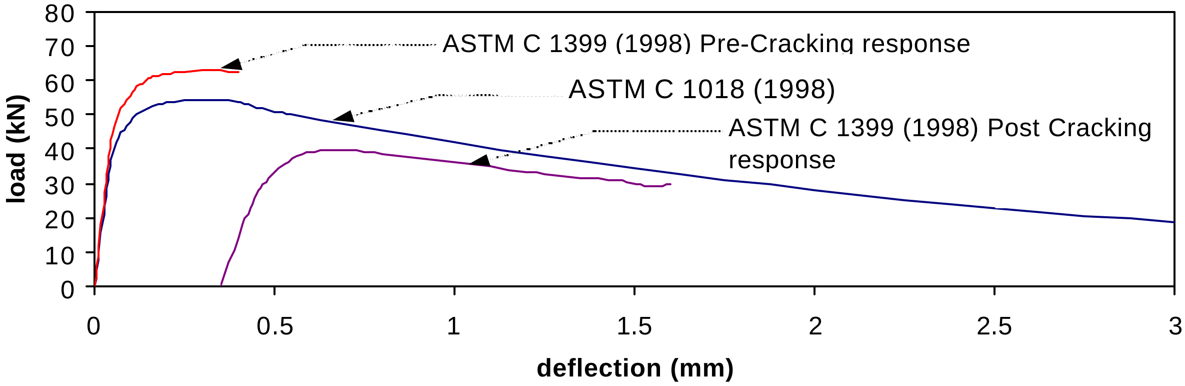
Table 2. Flexural response of CRC under quasi-static loading

<table>
<tr><td rowspan="2">ASTM C 78 &
JSCE SF4</td><td>Peak Load</td><td>Toughness</td><td>Toughness Factor</td></tr>
<tr><td>53 kN</td><td>69.2 J</td><td>10.38 MPa</td></tr>
<tr><td colspan="4"></td></tr>
<tr><td rowspan="2">ASTM C 1399</td><td>MOR</td><td>RS</td><td>RSI</td></tr>
<tr><td>16 MPa</td><td>10.07 MPa</td><td>63 %</td></tr>
</table>

Compact reinforced composite is a high-strength, high volume fraction steel fiber reinforced cement composite. The low water/binder ratio coupled with significant quantities of silica fume and superplasticizer impart a very high strength to the material, as seen by the quasi-static behaviour of CRC, shown in Figure 6. A measure of the post peak residual strength capacity is obtained from the Residual Strength Index (RSI), which is defined as the percentage of the residual strength to the moment of rupture

(MOR). The value of 63 % is high and reflects the presence of the large volume fraction of steel fibers in the mix.

Figure 6. Flexural response of CRC beams under quasi-static loading



ASTM C 1399 test is recommended for low modulus-low volume fraction fiber reinforced mixes. CRC, with its very high steel fiber content is clearly suited for tests with the ASTM C 1018 or the JSCE SF 4 methods, given that it is practically impossible to replace the steel plate upon first crack (as is required by the ASTM C 1399 method). Consequently, considerable damage occurs to the beam prior to the reloading.

3.3 **Impact tests**

The response of CRC to impact loading is plotted in Figure 7. The plots are analysed as per JSCE SF 4 and are compared with the quasi-static response in Table 3.

Figure 7. Comparison of impact load deflection plots for compact reinforced composite

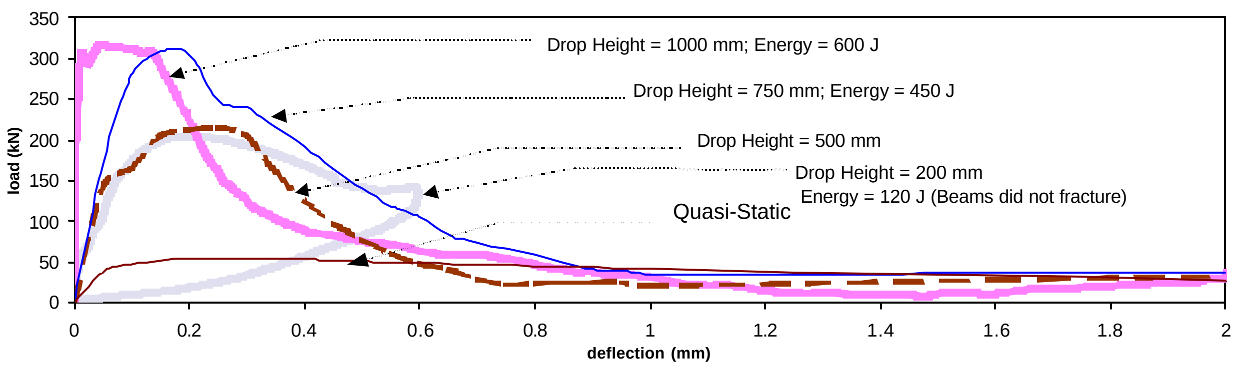
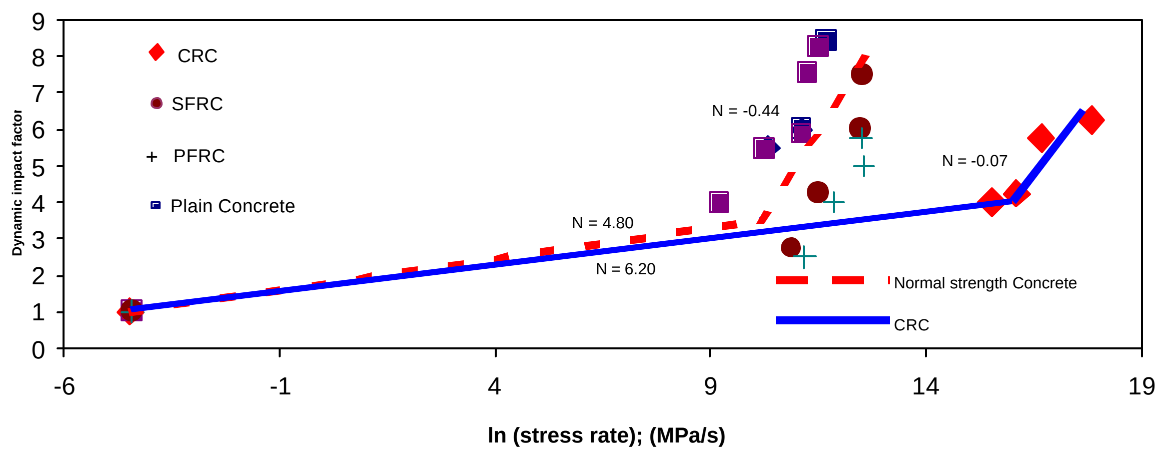


Table 3. Flexural response of CRC under impact loading

Loading type	Drop Height	Peak Load (kN)	Toughness (J)	Toughness factor (MPa)	Impact factor	
					Peak load	Toughness factor
Quasi-Static	-	53	69.2	10.38		
Impact	200 mm	205	97.7	14.66	3.87	1.41
	500 mm	215	122.8	18.38	4.06	1.77
	750 mm	308	181.9	27.27	5.81	2.63
	1000 mm	317	137.0	20.55	5.98	1.98

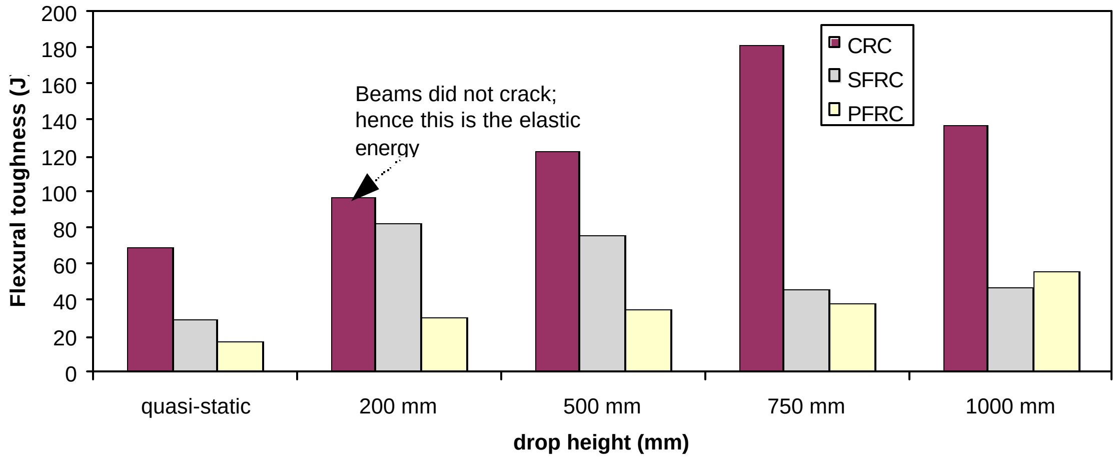
Stress rate sensitivity may be obtained from the formulation proposed by Nadeau *et al*. (Nadeau et al. 1982). This is shown in Figure 8 where in the stress rate sensitivity of flexural strength for CRC is compared with that of plain and fiber reinforced normal-strength concrete. Note that CRC is less sensitive than normal strength concrete and that the high stress rate behaviour is triggered at larger stress rates than for normal strength concrete. This phenomenon is characteristic of high strength materials as indicated by Bentur *et al*. (Bentur et al. 1987) and Ross (Ross 1997). Bischoff and Perry (Bishoff et al. 1995) on the other hand have reported results to the contrary where by higher strength concrete has a higher sensitivity when loaded under impact in compression. It may however be merely a function of the scatter in their results, which one should expect when experimenting with concrete. Ross (Ross 1997) explains that lower strength (and modulus) materials have lower limiting crack velocities. So, the *facture process zone* (fpz) ahead of the crack is smaller than for higher strength (and modulus) materials. This results in an apparently higher strength for the same strain rate. Since this is the limiting velocity, at any strain rate, the same trend is witnessed leading to the impact factor for the lower strength material being always higher than that for the high strength counterpart.

Figure 8. Stress-Rate Sensitivity Plots for CRC and Conventional Fiber Reinforced Concrete



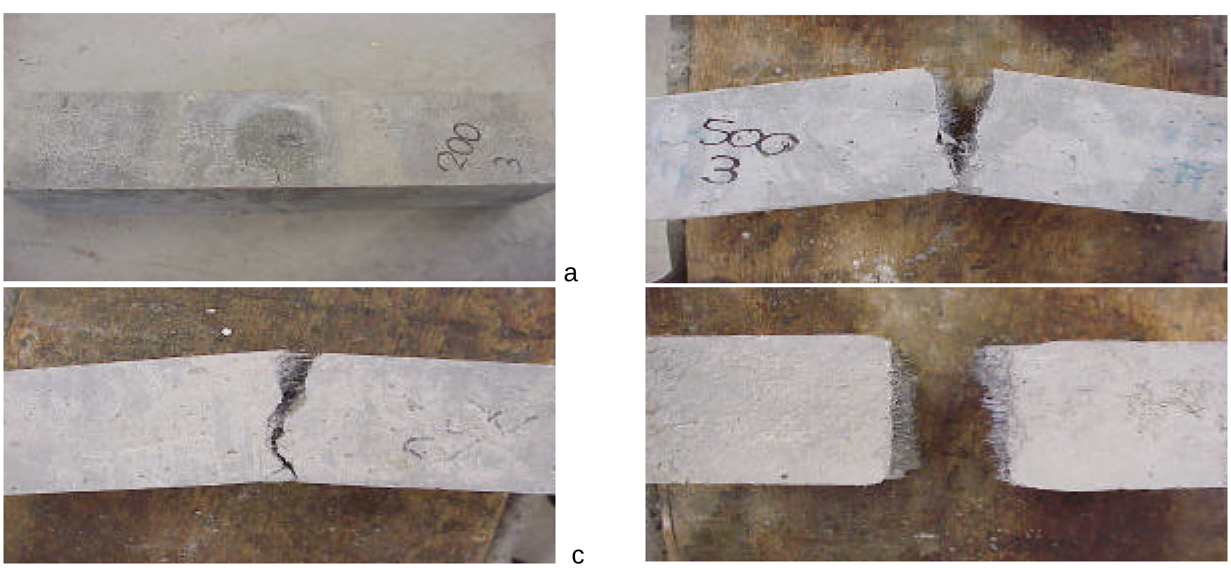
The impact behaviour of CRC highlights several interesting features. As expected from high strength concrete, CRC exhibits a less sensitive behaviour to high stress rate. However, because of its high strength and high fiber content, the material is capable of dissipating greater amounts of energy up to very large stress rates as witnessed in Figure 9. Normal strength SFRC and PFRC (polymeric fiber reinforced concrete) are also shown for comparison. One notes that while SFRC is increasingly brittle under impact loading, CRC initially improves with impact loading and becomes brittle only at a very large drop height (or stress rate).

Figure 9. Toughness (as per JSCE SF-4; Total Energy Absorbed to Span/150) of CRC, Conventional Steel Fiber Reinforced Concrete and Conventional Macro-Polypropylene Fiber Reinforced Concrete under Quasi-Static and Impact Loading



Figures 10 a-d show the representative specimens after impact. All the beams experienced the fiber pull-out mode of failure. Notice that the beams do not fracture completely at lower drop heights and break apart only at a drop height of 1000 mm. There is a corresponding decrease in flexural toughness at this drop height. This implies that brittle behaviour, a characteristic of high stress rate response, manifests itself only at larger stress rates for ultra-high strength systems such as CRC.

Figure 10. Photographs of CRC Failure in Impact under Various Drop Heights, a) 200 mm, b) 500 mm, c) 750 mm & d) 1000 mm



a b c d

In Figure 7, note that a gradual reduction in the flexural toughness was noticed for steel fiber concrete. The CRC specimens on the other hand exhibit an increase in toughness with higher drop height (or stress rate) indicating that the material is not immediately brittle at higher stress rates as one might expect. Impact of projectiles on to high strength concrete reinforced with steel fibers by Dancygier and Yankelevsky (Dancygier et al. 1996) reveals that while the higher strength by itself results in brittle fracture, the presence of random discrete reinforcement renders both the compression and the tension face (with respect to the impactor) more resistant to damage. A similar trend is reported by Luo *et al*. (Luo et al. 2000).

A possible explanation for the increase in toughness under impact for high strength fiber reinforced mixes is as follows: Under impact, the high strength matrix achieves higher peak loads. However, while this is accompanied by lower strain-at-peak resulting in brittleness for a plain matrix, in the presence of fibers, post-peak energy dissipation becomes possible. Toughness, which is a measure of both load and deformation sustained by the specimen, is thus improved in a high strength-high fiber reinforced material up to larger rates of stress. Accordingly, CRC emerges as an ideal building material suitable for use in structures of military and strategic importance that are susceptible to impact loads.

4. CONCLUSION

The following conclusions were drawn from the present study: -

1. Under quasi-static flexure, the Residual Strength Test Method (ASTM C1399) indicates that for high fiber content mixes, the Residual Strength Factor is lower than what one could obtain by directly evaluating the load sustained beyond peak from the ASTM C 1018 method. This may be explained by the difficulty in identifying the instance of first crack as is required by the ASTM C 1399 method. Where upon, considerable damage is allowed to occur to the beam prior to the reloading thereby, under-estimating the residual strength of such a highly reinforced material

2. CRC is less stress rate sensitive than normal strength SFRC. This is in keeping with the expected behaviour for high strength materials.

3. CRC is capable of dissipating higher energy compared with conventional SFRC. This may largely be attributed to the combination of high strength and the high volume fraction of steel fibers in the mix. Hence, it may be promoted as a material suitable for impact resistant structures.

5. REFERENCES

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