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FRACTURE TOUGHNESS OF HIGH STRENGTH CONCRETE IN DIRECT TENSION

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Abstract: This paper discusses the strength and fracture properties of plain high strength concrete (HSC) under direct tensile loading. 500 mm x 500 mm x 80 mm plane elements with single edge notches (SEN) of 250mm were fabricated. Several concrete mixes producing varying levels of compressive strength have been designed to demonstrate the effect of size of coarse aggregate, various contents of cement and coarse aggregate on the strength and fracture energy. The crack mouth opening displacement (CMOD) decreases as the peak load on concrete tension increases. The CMOD decreases as the strength of concrete increases at failure, indicating that the concrete brittleness increases with increase in its compressive strength. However, the facture energy of concrete increases with an increase in the size of coarse aggregate. A large quantity of energy has been dissipated in the bulk of concrete at high coarse aggregate content. High strength concrete exhibits low fracture energy.

1 INTRODUCTION

Concrete with high strength and high performance are often required for special construction needs. Concrete with compressive strength greater than 60 MPa is classified as high strength concrete (HSC). According to ACI Committee 363 (1), compressive strength of 62 MPa the concrete is described as HSC. In the recent past, compressive strength of 150 MPa and more is producible without much difficulty due to improvement and addition of supplementary materials like fly ash, silica fume and high range water-reducing admixtures (HRWRA). High strength concrete (HSC) can be considered as high-performance concrete (HPC) if the required attributes are achievable with reasonably good agreement with its intended applications. The properties of concrete are influenced by the type of constituent materials, type of fine and coarse aggregate, chemical composition of cement, water-binder ratio, and the nature of interface developed between cement paste-aggregate. Fracture energy of concrete, G_F is an important property for design. The failure of concrete can be described through fracture energy, G_F, tensile strength, f_t, and stress-deformation response (2,3). RILEM-FMC 50 (4) recommends a simple method for the determination of fracture energy, G_F using simple three-point beams (TPB). The fracture energy increases with an increase in aggregate size (3,5-8). Contrary to this, (9) fracture energy does not change with the size of aggregate. Also reported that fracture energy decreases significantly with the addition of large size aggregate (10). Fracture toughness is not influenced by the specimen geometry (11). This study reports on the influence of size of coarse aggregate and compressive strength of concrete by varying mix proportions of concrete such as varying cement and coarse aggregate contents.

2. EXPERIMENTAL PROGRAM

2.1. Materials

An ordinary Portland cement conforming to IS: 8112-1989 was used. Natural river sand of 2.36 mm size with a specific gravity of 2.63 and fineness modulus of 3.2 was used. Crushed granite containing all aggregates sizes of 20mm down to 6.3mm size was adopted. To obtain this, aggregate was sieved through different sizes. For example, aggregate sieved through 20mm size and retained on 16mm could separate the 20mm maximum size. Aggregate passing through 16mm and retained on 12.5mm sieve obtains 16mm maximum size, while 10mm size aggregate sieved through 10mm size and collected on 6.3mm sieve obtains 10mm maximum size. Further, all three fractions of different aggregate sizes were mixed to achieve combined aggregate (M) in equal fractions. The coarse aggregate had uniform dimensions. The specific gravity of aggregate was 2.65 and its fineness modulus 6.8. Potable water was mixed for concreting and for curing as well. The p^H value of the water was 7.8. The water-binder ratio was 0.30. A water reducing agent of 5.0 lit/m^3 was mixed in the water to achieve the required workability.

2.2. Proportioning of concrete mixes

Very few standards specify standard procedure for mix proportioning to produce high strength concrete. In high strength concrete, aggregate strength, cement content and bond between cement paste and aggregate control the properties. High strength concrete always needs a low water-cement ratio to be maintained. In normal strength concrete, cement content varies between 250 and 350 kg/m^3. In high strength concrete, the content of cementitious material is normally high, varies from about 350 to 500 kg/m^3. A 0.30 water-cement ratio was used. To improve the workability of concrete a plasticizer was incorporated at 5.0 lit/m^3 of concrete.

Twenty-one concrete mixes were proportioned. They are grouped into two. Group-I contains twelve mixes, while Group II has nine mixes. In Group I, the maximum size of coarse aggregate and cement content of 10, 16 20mm and mixed, were adopted. Using a particular size of aggregate, three cement contents of 390, 425 and 459 kg/m^3 were used and three different coarse aggregate contents of 1169, 1134, and 1101 respectively were adopted at these cement contents. The sand contents were 779, 756, and 734 kg/m^3 respectively. In Group II, the three different contents of cement, sand and coarse aggregate contents were used; cement contents of 509, 487 and 469 kg/m^3; sand contents of 791, 758 and 730 kg/m^3 and coarse aggregate contents 961, 1029 and 1094 kg/m^3. For the coarse aggregate contents, three different aggregate sizes of 10, 16 and 20mm were used. Tables 1 and 2 show the material quantities in Groups I and II respectively.

2.3. Specimen geometry and dimensions

Concrete specimens of 500mm × 500mm × 80mm with a 250mm single edge notch at the mid height (notch-to-depth ratio of 0.5) were fabricated to test in tension. A uniform stress was applied using specially fabricated steel grips bonded at the boundaries, normal to the single edge notch to act as compact tension (CT) specimen. Two specimens were cast and tested for each concrete to determine fracture properties. Three standard cubes of 150mm × 150mm × 150mm and two standard cylindrical specimens of 150mm × 300mm were cast and tested to determine compressive and split tensile strengths of concrete at 28 days. Specially fabricated teak wood molds were fabricated to cast in concrete. Two specimens were made for every concrete mix. A plate vibrator compacts concrete in two layers, each layer was compacted well. The hardened concrete specimens were demolded after 24 hours and cured in water for 28 days.

A single edge notch was made using a diamond saw cutter just before testing, whose cross-section details are shown in Figure 1.

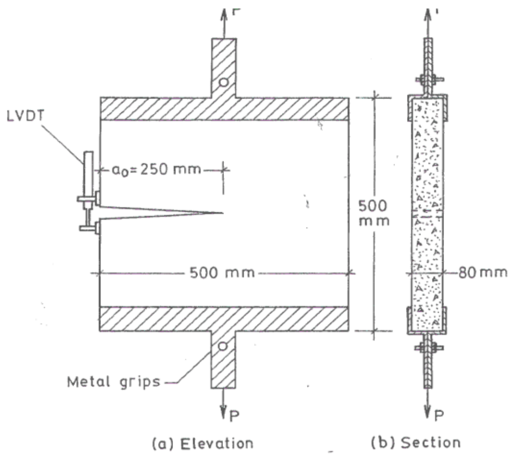

Figure 1: Typical SEN Specimen with Loading Arrangements And LVDT.

2.5. Testing procedure

The plane concrete CT specimens were tested in a 600 kN capacity hydraulic universal testing machine. The compact tension specimens subjected to uniform stress at the far ends, also induced with an eccentric force to the effective cross-section in the crack plane. Along with metal paste as a binding agent and mechanical gripping by specially fabricated steel grips, got through successfully transferring the tensile load. For gripping, a set of two MS equal angles welded with an MS flat to each angle were used. To improve friction between steel grips and the concrete, the angle section was provided with nuts-and-bolts system. Steel flats at the middle of the length were welded to the angles and projected to grip into the jaws of the machine. Additional G-clamps were also provided to improve the friction between steel grips and concrete during

Table 1: Quantities of Constituent Materials in Groups I Concrete Mixes (W/C= 0.30)

Mix Designation	Size of Coarse Aggregate (mm)	Cement Content, (kg/m^3)	Sand Content, (kg/m^3)	CA Content, (kg/m^3)
Mix-A1	10	390	779	1169
Mix-A2	16	390	779	1169
Mix-A3	20	390	779	1169
Mix-B1	10	425	756	1134
Mix-B2	16	425	756	1134
Mix-B3	20	425	756	1134
Mix-C1	10	459	734	1101
Mix-C2	16	459	734	1101
Mix-C3	20	459	734	1101
Mix-D1	M	390	779	1169
Mix-D2	M	425	756	1134
Mix-D3	M	459	734	1101

Table 2: Quantities of Constituent Materials in Groups II Concrete Mixes (W/C= 0.30)

Mix Designation	Size of Coarse Aggregate (mm)	Cement Content (kg/m^3)	Sand Content (kg/m^3)	CA Content (kg/m^3)
Mix-E1	10	509	791	961
Mix-E2	16	509	791	961
Mix-E3	20	509	791	961
Mix-F1	10	487	758	1029
Mix-F2	16	487	758	1029
Mix-F3	20	487	758	1029
Mix-G1	10	469	730	1094
Mix-G2	16	469	730	1094
Mix-G3	20	469	730	1094

testing. The load was increased gradually to attain a constant rate. At every load increment, crack mouth opening displacement (CMOD) was measured using linearly variable deformable transducer (LVDT).

3. FRACTURE ENERGY

The fracture energy is the energy needed to form a unit new crack surface. The fracture energy, G_F of concrete is determined using the work of fracture, W_F divided by area of uncracked ligament (A_{lig}).

$$G_F = \frac{W_F}{A_{lig}} = \frac{W_F}{b(d - a_0)} \qquad (1)$$

Where G_F = fracture energy, N-m/m^2, W_F = work of fracture, N-m, b = thickness, mm, and d = depth of the specimen, mm, a_0 = initial notch depth, mm, and A_{lig} = area of the uncracked ligament.

4. RESULT AND DISCUSSION

4.1. Fracture Energy vs. compressive strength

The fracture energy is calculated using Eq (1) as the total work done divided by the area of the uncracked ligament. In Figure 2, the fracture energy decreases with an increase in the concrete compressive strength in Groups I and II. High strength concrete behaves like a true composite in that the total energy absorption capacity is governed by the coarse aggregate content, strength, and cement-aggregate interface. Total energy absorption is the capacity of aggregate fraction and the cement paste on cracked surface.

In conventional concrete, crack propagation stops at the aggregate. The crack propagates (1) through aggregate, (2) around aggregate surface (compressive side), and (3) around aggregate surface (tension side). The tension cracking in conventional concrete consumes a large quantity of energy due to the large extent of damage to the region surrounding the crack tip. In HSC, a crack reaching the aggregate crosses through it due to a strong interface developed. In HSC, the energy absorbing capacity depends on the volume fractions of both coarse aggregate, and cement matrix. The combination of these influences the fracture energy of concrete.

From the experimental observations, the fracture energy, G_F decreases as the concrete strength increases. In Groups I and II concrete mixes, the variation of fracture energy of concrete with compressive strength is shown in Figure 2. Only less energy is consumed to form a unit crack length in brittle matrix composites.

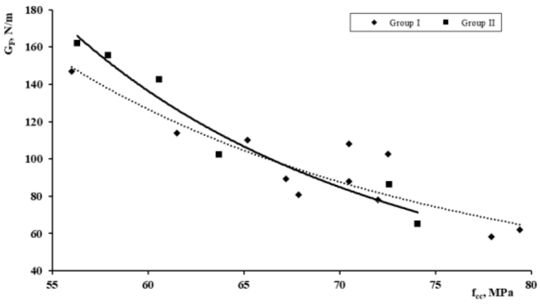

Figure 2: Fracture Energy vs. Compressive Strength of Concrete in Groups I and II.

There have been controversial reports (7, 8). In conventional concrete, a significant amount of energy is dissipated in the process zone because of micro-crack shielding, crack initiation, crack bridging, crack deviation and crack friction. All the mechanisms of fracture process observed in conventional concrete do not occur in HSC and can be justifiable that total energy dissipated in high strength concrete is reasonably low. Further, the micro-cracking forms in high strength concrete at a load of about 90 percent of the peak load. The fracture energy increases with concrete's compressive strength due mainly to the large quantity of surface energy needed to break strong interfaces in HSC.

Figure 3 shows the variation of fracture energy with compressive strength of HSC. The fracture energy of concrete is a function of compressive strength, with a correlation coefficient of 0.97. As per the proposed equation the fracture energy decreases with an increase in the concrete compressive strength. The expression for calculation of fracture energy, G_F of concrete is given below:

$$G_F = 5.2(f_{cc})^{0.70}, N/m \qquad (2)$$

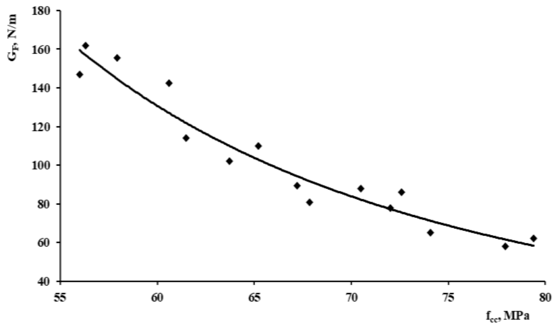

Figure 3: General fracture energy vs. compressive strength of concrete.

4.2. Fracture energy vs. coarse aggregate size

The size of coarse aggregate on the fracture energy, G_F is influenced by the heterogeneity and aggregate interlock, which increases the roughness of crack surface. The fracture energy of concrete strongly depends on the maximum size of coarse aggregate.

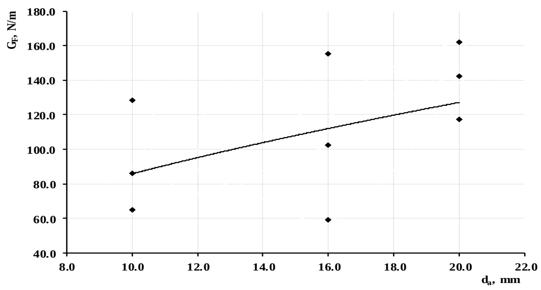

Figure 4: Fracture energy vs. aggregate size-Group I.

Figure 4 shows the variation of fracture energy with maximum size of coarse aggregate in Groups I concretes with different cement contents. Figure 5 shows the variation of fracture energy with size of coarse aggregate in Groups II concretes with different coarse aggregate contents. The fracture energy increases with increasing the size of coarse aggregate. The increase in fracture energy with the size of coarse aggregate is due to aggregate bridging and aggregate interlock, because of which the ductility of concrete increases, due to long descending portion of the load-CMOD response. The fracture surfaces of concrete incorporated with large size of aggregate exhibit aggregate pullout from the matrix.

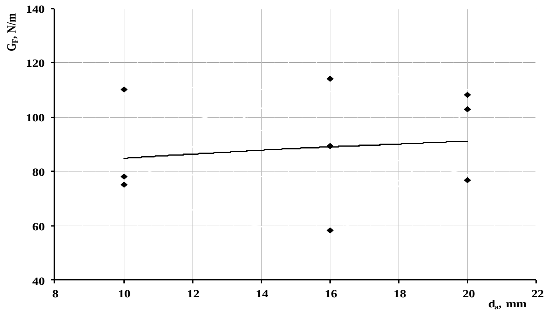

Figure 5: Fracture energy vs. aggregate size-Group II.

Table 3: Mean Fracture Energy-Groups I Concretes

Coarse Aggregate Size (mm)	Fracture Energy, G_F, (J-m/m^2)
10	87.68
16	87.15
20	95.80
M	105

Table 4: Mean Fracture Energy-Groups II Concretes

Fracture Parameter	Coarse Aggregate Size, (mm)			Coarse Aggregate Content, (kg/m^3)		
Fracture	10	16	20	961	1029	1094
Energy, (N/m)	76	129	152	116	103	120

The mean fracture energy in Groups I concretes ranges between 85 and 100 N/m, the higher value corresponds to the larger size coarse aggregate. In Groups II concretes the fracture energy varies between 70 and 150 N/m. At a cement content of 459 kg/m^3 the lowest fracture energy was observed since the crack propagates in a self-similar manner due to increase in the brittleness of concrete. The energy in HSC is utilized in overcoming the cohesion and adhesion between various phases of concrete, namely aggregate and mortar matrix. In addition to the size of coarse aggregate, mix proportioning of constituent materials, in general, also affects the fracture parameters. The mean values of fracture energy are shown in Tables 3 and 4 in Groups I and II concretes respectively.

Empirical equations have been proposed to estimate the fracture energy as a function of concrete's compressive strength and compared with the CEB - FIP expression in Tables 5 and 6. Figure 6 shows the comparison of fracture energy in the case of CEB-FIP equation and the proposed equation.

$$G_F = \alpha_n f'_c{}^{0.70}\ (CEB-FIP) \quad (3)$$

$$G_F = \alpha'_n f_{cc}{}^{0.70}\ (Present) \quad (4)$$

Where α_n and α'_n are constants and f'_c and f_{cc} are cylindrical and cube compressive strengths respectively.

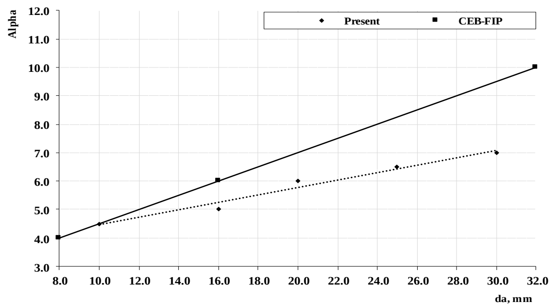

Figure 6: Coefficient (alfa) vs. size of aggregate.

4.3: Fracture energy vs. cement content

The higher cementitious material produces retrogression of concrete's compressive strength in the long run. The cement contents adopted for this study are 390, 425 and 459 kg/m^3. Figure 7 shows the variation of fracture energy with cement content in concrete cast with different sizes of coarse aggregate. For a given size of coarse aggregate, a few concrete mixes exhibited a decrease in fracture energy with cement content. This is due to the type of interface developed in concrete, which is influenced by size of coarse aggregate. For example, using 10 mm coarse aggregate, higher fracture energy has been observed at a cement content of 425 kg/m^3. At the cement content of 390 kg/m^3, the concrete with combined aggregate exhibited the highest fracture energy, while at a cement content of 459 kg/m^3, the highest fracture energy is absorbed with 20 mm size coarse aggregate.

As shown in Figure 7, the fracture energy decreases with an increase in the cement content. This is because concrete strength increases with high cement content. This leads the brittle concrete due to a strong interfacial bond, consuming less fracture energy. The fraction of cohesive fracture energy is less pronounced and hence less fracture energy.

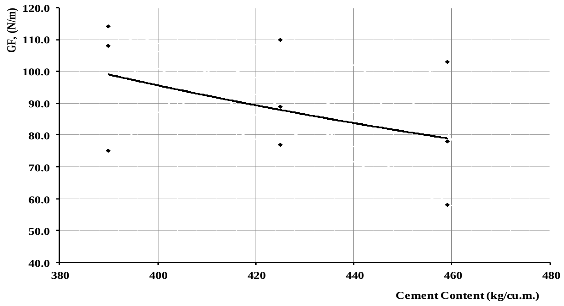

Figure 7: Fracture energy vs. cement content.

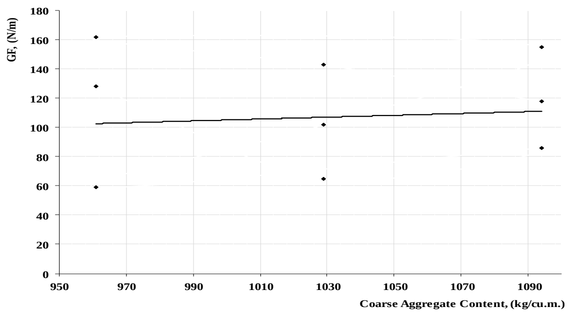

Figure 8: Fracture energy vs. coarse aggregate content.

4.4: Fracture energy vs. coarse aggregate content

Figure 8 shows the variation of fracture energy with the coarse aggregate content. It clearly demonstrates that concrete with different sizes of aggregate shows variation in fracture energy. It is too complex to predict a trend of fracture energy with the coarse aggregate content.

Table 5: Fracture energy using experimental data and CEB-FIP.

Aggregate Size (mm)	Fracture Energy (N/m)									
	10		16		20		25		30	
f_{cc} (MPa)	Exp	CEB	Exp	CEB	Exp	CEB	Exp	CEB	Exp	CEB
40	59.5	59.5	66	79	79	93	85	109	93	122
50	70	70	77	93	93	108	99	127	108	142
60	79	79	88	105	105	123	112	144	123	162
70	88	88	98	117	117	137	125	161	137	180
80	97	97	107	129	129	150	138	176	150	198
90	105	105	117	140	140	163	149	191	163	215
100	113	113	126	151	151	176	161	206	176	231

Table 6: Coefficients for evaluating fracture energy.

Approach		Maximum Size of Coarse Aggregate, mm		
		10	16	20
Present	cube	4.5	5.0	6.0
	cylinder	5.25	5.85	7.0
CEB-FIP		Maximum Size of Coarse Aggregate, mm		
		8	16	32
		4	6	10

Figure 8 shows that the concrete with larger size aggregate exhibits decreasing fracture energy. However, use of small size coarse aggregate increases fracture energy at higher aggregate content. Using large size coarse aggregate, the fracture energy reduces at high aggregate content. This is caused by the heterogeneity when larger size particles are added. When small size coarse aggregate is used, the heterogeneity decreases. At the aggregate content of 1094 kg/m^3, concrete with 16mm coarse aggregate exhibits high fracture energy. From Figure 10, the fracture energy increases as the coarse aggregate content increases up to 1094 kg/m^3, thereafter it decreases as the coarse aggregate content increases. The optimum coarse aggregate content ranges between 950 and 1100 kg/m^3.

5. CONCLUSIONS

The following conclusions may be drawn from the test results.

The $CMOD_c$ in single edge notched specimens decreases as the peak load increases. Also, the crack extension (CMOD) in concrete decreases as the compressive strength increases, which means that the higher concrete compressive strength, the more brittle in concrete's behaviour.

The fracture energy of concrete decreases with an increase in compressive strength of concrete. Also, it increases with increase in maximum size of coarse aggregate and aggregate content.

The addition of larger size coarse aggregate increases the heterogeneity of concrete. The fracture energy has been found to be low in concrete at a cement content of 425 kg/m^3. The fracture energy of concrete varies between 70 to 170 N/m.

REFERENCES

[1] ACI Committee 363, 1997. "State-of-the- art report on HSC (ACI 363R-92). *ACI Jl, Pro. 364R-1-364R-55.*

[2] Hillerborg, A., Modeer, M., and Petersson, P.E., 1976. Analysis of crack formation and crack growth in conc by means of fracture mech. and finite elements. *CCR. 6(6). 773-782.*

[3] Hillerborg, A., 1985. Results of three comparative test groups for determining the fracture energy G_f of concrete. *Mat. Strs.* 18(107). 33-39.

[4] RILEM, 1985. 50-FMC committee fracture mechanics of concrete. *Mat. Str*. 18(106). 285-290.

[5] Walsh, P.F., 1972. Fracture of plain concrete. *ICJ*. 46 (11). 469-476.

[6] Bazant, Z.P., and Oh, B.H., 1983. Crack Band Theory for Fracture of Concrete. *Mat. Str*. 16(93). 155-177.

[7] Giaccio, G., Rocco, C., and Zerbino, R., 1993. The fracture energy of HSCs. *Mat.Str*. 26.381-386.

[8] Zhou, F.P., Barr, B.I.G., and Lydon, F.D., 1995. Fracture properties of high strength concrete with varying silica fume content and aggregates. *CCR*. 25(3). 543-552.

[9] Petersson, P.E., 1980. Fracture energy of concrete : practical performance and expl results. *CCR*.10(1). 91-101.

[10] Tasdemir, C., Tasdemir, M.A., Lydon, F.D., and Barr, B.I.G., 1996. Effects of silica fume and aggregate size on brittleness of conc. *CCR*.26(1). 63-68.

[11] Barr, B.I.G., Hasso, E.B.D., and Weiss, V.J., 1986. Effect of spn and aggregate sizes upon the fracture characteristics of conc. *Jl. CCLWC. 8(2). 09-119.*

[12] Appa Rao, G., 2002. Nonlinear Fracture and Size Effect in high strength and High-performance Concrete - *An Experimental Approach", Ph.D. thesis* submitted at IISc, B'lore, India.