A COMPARISON OF THE FRACTURE PROPERTIES OF SELF COMPACTING CONCRETE (SCC) AND CONVENTIONAL VIBRATED CEMENT CONCRETE (VCC)

Muralidhar. N., Muttana S. Balreddy., Shivaram Bagade* and S.V.Dinesh

Department of Civil Engineering, Siddaganga Institute of Technology, Tumkur
**BASF Construction Chemicals Pvt. Ltd., Shanghai, China*

ABSTRACT

The study focuses on the comparison of fresh and hardened properties of self compacting concrete with special reference to fracture characteristics. Self compacting concrete mixes consisting of two grades of concrete viz., M20 and M35 and conventional concrete mixes of the same grade were prepared using binder combination of cement-fly ash (25% by mass of binder). The fracture characteristics evaluated for the different mixes included the LEFM parameters K_{1c}, G_{1c} and parameters related to Bazant's size effect law viz., fracture energy G_f and size of fracture process zone C_f. The test results show that both G_f and C_f increase with increase in compressive strength and are higher for SCC compared to VCC. The study demonstrates the strong size effect in both SCC and VCC and also shows that even the size effect model parameters are not really independent of size.

Keywords: *Fracture, concrete and vibrated cement concrete.*

INTRODUCTION

The use of Self compacting concrete is growing at an exponential rate. The SCC mix has to meet the requirement of compressive strength and other desirable properties such as flowability, passing ability. SCC generally incorporates large quantity of cement replacement materials such as ground granulated blast furnace slag(GGBS) and Portland cement and fly ash to make concrete dense and economical compared to traditional vibratory compacted concrete(VCC) . In high strength concretes the high cement content can lead to higher shrinkage and greater emission of heat of hydration. A partial substitute of mineral admixtures using flyash, GGBS, silica fume, metakaolin etc along with the admixtures eliminates the drawbacks besides enhancing durability characteristics (Palaniswamy *et al*., 2008). The use of hyper plasticizer in SCC as high range water reducing admixture helps to achieve high degree of fluidity and segregation resistance. However, such admixtures entrain more air and also have a tendency to increase shrinkage. The use of blended cements leads to better densification and improved pore structure, higher compressive strength and tensile strength is compared to VCC. However, the use of mineral and chemical admixtures may produce micro cracks due to high plastic shrinkage in the fresh concrete compared to VCC. SCCs have generally higher content of fines (cement and fine aggregate) and chemical admixtures so that enhanced cohesiveness with no tendency for segregation is achieved (Annie Peter *et al,* 2004). The use of super fine and highly reactive silica fume and the ball bearing action of flyash as basic ingredients for concrete imparts high strength and very high fluidity. The fracture characteristics of SCC are likely to be better compared to VCC as it has improved pore structure due use of high volumes of cement replacement materials. However, the coarse aggregate content being relatively less, the SCC's are more prone to rapid crack propagation and brittle fracture. In SCC there is increased plastic shrinkage due to high fluidity of the mix and cracks develop in fresh concrete between cement paste and aggregate and propagate in the hardened concrete, this results in less resistance across the crack surface. In the present study, both the conventional LEFM parameters and the parameters characterizing the size effect of SCC and VCC are determined by conducting three point bend tests on notched beam specimens of notch to depth of ratio of 0.15. The theoretical background of the fracture parameters are discussed in the following paragraphs (Manu Santhanam and Subramanian, 2004 and Mattur *et al.,* 2009).

Evaluation of K_{1c} and G_{1c} Based On LEFM Approach: The fracture parameter critical stress intensity factor k_{1c} for different specimen geometries and loading configuration is proportional to the applied failure load P_{max}. For the determination of k_{1c}, notched beam specimens are commonly used and they are tested under three or four point bending.

$$k_{1c} = (3Pl\ /\ 2td^2)(\sqrt{\pi a_o})F(a) \qquad (2.1)$$

Where

$$F(A) = (1/\sqrt{\pi})(1.99 - A(1-A)(2.15 - 3.93A + 2.7A^2))/((1+2A)(1-A^2)) \qquad (2.2)$$

$$A = (a_0 / d) \qquad (2.3)$$

P is the maximum load, t is the width of the beam, d is the depth of the beam and a_0 is the initial notch depth.

The critical strain energy release rate G_{Ic} is related to k_{1c} as $G_{Ic} = (k_{IC})^2 / E$ (2.4)

Where E is the young's modulus.

Determination of Fracture Energy (G_F) from the Work of Fracture: Fracture energy or the specific fracture energy G_F is the energy required to create a crack of unit area and is expressed by the (RILEM committee TC-89 (1985) as

$$G_F = (W_F + W_S\delta_0)/A_{lig} \quad (2.5)$$

Where W_F is the work of fracture (equal to area under load deflection plot). W_S is the sum of the self weight of the specimen and fixtures. A_{lig} is the area of the ligament that was intact before the test.

Size Effect Law for Maximum Nominal Stress: Size effect is defined through comparison of geometrically similar structures of different sizes and is conveniently characterized in terms of the nominal stress σ_N at maximum load (P_{max}) [Bazant (1984)]. When σ_N values for geometrically similar structures of different sizes are the same, we can say that there is no size effect. A dependence of σ_N on the size of the structure is called size effect. The nominal stress need not represent any actual stress in the structure but may be defined simply as

When the similarity is two-dimensional

$$\sigma_N = P_{\max}/td \quad (2.6) \quad \text{or} \quad \sigma_N = P_{\max}/td^2 \quad (2.7)$$

When the similarity is three-dimensional. According to classical theories, such as elastic analysis, plastic limit analysis, elasto-plastic analysis, as well as other failure theories, which use limits or failure criterion in terms of stresses, σ_N is constant and it is taken to be independent of the structural size. Bazant (1984) proposed the size effect law where LEFM and limit analysis concepts were clubbed together. He assumed that the total potential energy released at fracture is proportional to the square of the crack length 'a', which scales proportionally to the specimen size (a_o/d = constant), while the energy dissipation is proportional to 'a', the crack band being assumed constant and proportional to the maximum aggregate size g. the nominal stress as per size effect law is $\sigma_N = Bf_t/(1+d/\lambda_0 g)^{1/2}$ (2.8) or

$$\sigma_N = A/(1+d/B)^{-1/2} \quad (2.16)$$

Fracture energy (G_f) and Fracture process zone (c_f) from Size-effect law: The RILEM recommendation for the size effect method for the determination of fracture energy of concrete is adopted in the study. The maximum loads of geometrically similar notched concrete specimens of different sizes are measured. Size-effect law model is given by (RILEM committee TC-89 FMT test methods, 1991)

$$\sigma_N = Bf_t/(1+d/d_0)^{1/2} \quad (2.9)$$

Where $\sigma_N = c_n p/td$ is the nominal stress at maximum load

p = maximum load, c_n = arbitrary constant (here it is equal to 1), *t* = the width of the beam and *d* = the depth of the beam. B and d_0 are the material parameters related to fracture energy (G_f) and size of fracture process zone (c_f) for the infinitely large specimen as (Bazant, 1984).

$$G_f = (Bf_t/c_n)^2(d_0 g(\alpha)/E) \quad (2.10)$$

$$c_f = d_0 g(\alpha)/g'(\alpha) \quad (2.11)$$

Where $g(\alpha) = c_n \pi\alpha f(\alpha)^2$, $g'(\alpha) = dg(\alpha)/d\alpha$, G_f is the fracture energy and c_f is the size of fracture process zone. Substituting in the above equation

$$\sigma_N = c_n[EG_f/g'(\alpha)c_f + g(\alpha)d]^{1/2} \quad (2.12)$$

Size Effect in Geometrically Similar Specimens: Since g (α) and g'(α) are constant for geometrically similar specimens and when depth is varying, Eq 2.9 can be rearranged as $Y = A_1 X + C_1$ (2.13)

Where $Y = c_n/\sigma_N)^2, X = d$

$$G_{f1} = g(\alpha)/EA_1 \quad (2.14)$$

$$c_{f1} = (g(\alpha)/g'(\alpha))(C_1/A_1) \quad (2.15)$$

The constants A_1 and C_1 can be evaluated from the measured maximum loads of geometrically similar specimens, from which one can calculate G_{f1} and c_{f1} (the subscript 1 indicates that the fracture parameters G_f and c_f are evaluated from the test results of geometrically similar specimens)

RILEM (1990 b) recommends that specimens of at least three different sizes, characterized by depths d = d_1, d_2 . d_n and loaded spans l = l_1, l2...l_n should be tested. The smallest depth d_1 should not be larger than 5 times the maximum aggregate size and the largest depth d_n must not be less than 10 times the maximum aggregate size. The ratio of d_n / d_1 should be at least 4. The ratio of adjacent size d_2 / d_1, d_3 / d_2...... should be approximately constant. Optimally, the size range should be as broad as possible. The specimens of all sizes should be as far as practicable geometrically similar in two dimensions, with the third dimension (width t) the same for all specimens. In other words, the ratios l/d, a_o/d, L/d, where a_o is the initial notch depth, L is the length of the specimen should be same for all depths. The value of l/d should be in the range of 2.5-8. The value of a_o/d should be in the range of 0.15-0.5. Where *A* and *B* are empirical constants, *B* and λ_0 are the material constants related to G_f and c_f.

EXPERIMENTAL INVESTIGATIONS

Materials Used: Ordinary Portland cement (OPC) of 53 grade conforming to IS 12269: 2009 was used in all grades of concrete mixtures. Natural river sand conforming to zone II of IS 383: 1970 was used as fine aggregate for VCC while crushed sand was used as fine aggregate in SCC. Graded crushed granite of 16mm down size with 50 percent of the quantity in the size range of 10mm size, was used as coarse aggregate. GLENIUM 6100 a modified polycarboxylic ether type of hyper plasticiser was used to achieve rheodynamic properties. The fly ash of specific gravity 2.2 and belonging to F Class was used as Cement Replacement Material (CRM) at

25% by mass of cement. Table 1 shows the type and properties of the materials used in the study.

Mix Design: Two grades of concrete M20 and M35 were considered for the study. In each grade, conventional VCC and SCC mixes were produced using the Fly ash as CRM at 25% by mass of cement. The mixes were designed using EFNARC specifications and guidelines for SCC [2005]. The mix composition for the different types and grades of concrete is shown in Table 2.

Specimen Preparation: Three sets flexural prisms of thickness 80mm and notch depth(a_o = 0.5d and with depth of 75mm, 150mm, 300mm were prepared for each mix. The corresponding lengths of beams were 245mm, 470mm, 900mm. All the beam specimens were cured under water up to 28 days before taking up for testing**.** The load deflection and crack mouth displacement were measured at regular intervals till failure.

Tests Carried Out

Workability tests: The workability of VCC was measured by conventional slump test while the workability of SCC was measured by slump flow test [EFNARC: 2005]

Compressive strength: The 28 day compressive strength of the mixes was determined by testing 150mm cube samples as per IS: 516:1999.

Fracture characteristics: The notched beam specimens were subjected to three point bend loading in a displacement controlled loading machine under a constant displacement rate of 0.02mm/min. The loads are applied through one hinge and two rollers with minimum possible rolling friction. Fig. 1 shows the schematic diagram of the test set up while Photo 1 presents a photographic view of the test in progress. For each variable, three specimens were tested and the average result was used in the computation.

TEST RESULTS AND DISCUSSIONS

Workability and Compressive Strength: The VCC mixes showed good slump of the order of 90-100 mm while SCC mixes had slump flow in the range of 635-650 mm and conformed to EFNARC specifications. There was no bleeding or segregation observed. This shows that the EFNARC procedure for mix design can give satisfactory SCC mixes. Although the SCC mixtures were prepared using 100% crushed sand as fine aggregate and inspite of the rough texture of crushed sand, self compacting concrete mixes could be produced. As seen from Table 2, all the mixes exceeded the target strength for the corresponding grade. The SCC mixes showed slightly higher compressive strength compared to (VCC) due to better compactabilty, reduced porosity and higher paste content. The use of crushed sand in lieu of natural sand has facilitated development of higher strength due to the higher particle size of the grains compared to natural sand. Table 3 shows fracture characteristics in terms of critical stress intensity factors (k_{1c}) and strain energy rate (G_c) based on LEFM principles, fracture energy (G_f) and length of fracture process zone (c_f) based on the size effect law for all the concrete specimens.

Figures 2, 3, 4 and 5 show load versus CMOD for the control mixes M1, M2, and SCC mixes S1 and S2 respectively. It is observed that CMOD increases with increase in peak load for depth of the specimen. It is observed that the load-CMOD curves are nearly linear and the slope of the plots increases with increase in beam depth in most of the cases. Although the curves do not show any post peak data due to the use of displacement controlled machine based on machine strain, advantage is taken of Bazant's size effect model which necessitates the determination of only the peak load for the computation of C_f and G_f. Figures 6 show the variation of LEFM parameters critical stress intensity factor (K_{IC}) for Vibrated Cement Concrete and Self compacting concreter corresponding to a_0/d=0.5. It is observed that there is an increase in stress intensity factor for a particular depth with increase in compressive strength concrete. The stress intensity factor increases with increasing in beam depth clearly pointing to the existence of size effect. It is observed from Table 3.3 that both K_{1c} and G_{1c} increase with increase in compressive strength and also with increase in beam depth. However, the latter shows less increase than the former. It is also observed that the fracture parameters are higher for SCC in contrast to the common expectation that they decrease with increaser in strength due to brittleness of the beams in case of high strength concrete

Figures 7 shows the energy release rate Vs beam depth for VCC and SCC mixes. It is observed that with increase in specimen depth, there is an increase in strain energy release rate but it becomes almost constant beyond 150 mm depth indicating the increase in brittleness and lower rate of strain energy for deep specimens. It is observed that GIC shows a steeper increase with increase in depth compared to VCC for lower depths up to 150 mm, which indicate that the conventional approach of taking lower energy absorption for HSC may not be always correct. Similar results have been reported by Bharat Kumar *et al.,* [2005] in respect of high performance concrete with slag and fly ash as cement replacement materials. However, Dinesh *et al*., (2004) have reported contrary results indicating that G_f is almost independent of beam depth unlike work of fracture G_F, which shows increase with increase in depth and remains constant with increase in compressive strength.

Figure 8 shows the results of fracture energy (G_f) Vs compressive strength for Vibrated cement concrete and Self compacting concrete for 28 day. Though the results are scattered, the results indicate a clear cut trend with the G_f increasing with increase in compressive strength as already discussed in the previous paragraph.

The size effect is illustrated by the plot of log (σ/Bf_t) verses log (d/d_0) for Vibrated Cement Concrete and Self compacting concrete (with fly ash as SCM) beams in figures 13 to 16 at 28 days. Both VCC and SCC concrete show size effect in tensile fracture. The experimental data is in close agreement with Bazant's size effect law (1984). It is also observed that the data points on the size effect law plot shift towards left for SCC compared to VCC indicating that the shift to the brittle region of LEFM. This corroborates the observation made by earlier investigators like Eskandari *et al*., (2010).

CONCLUSIONS

The method based on Bazant's size effect law enables the determination of fracture parameters for any type of concrete by determining the peak load for notched flexural specimens without taking recourse to determining the post peak behavior using costly and sophisticated equipments. The results show that as the beam depth increases the LEFM critical stress intensity factor and energy release rate also increases demonstrating the existence of size effect. Self Compacting Concrete shows increased stress intensity factor, critical energy release rate, and fracture toughness than Vibrated Cement Concrete contrary to expectations that HSC may show reduction in fracture parameters due to increased brittleness. Therefore there is no need for apprehensions about fracture behavior of SCC. The size of fracture process zone indicated by parameter also increases with increase in compressive strength and is higher for SCCs compared to VCC. However, the order of increase is substantially less compared to that of G_f. Both VCC and SCC mixes show a strong dependence on size effect law and show close agreement with Bazant's size effect law.

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Figure 1. Schematic diagram of three point bend test specimen

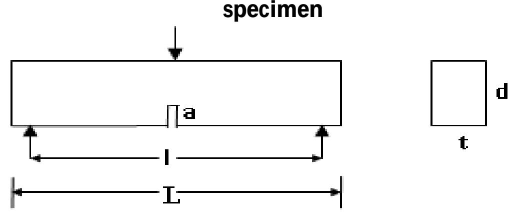

Photo 1. Photographic View Of The Test In Progress

Figure 2 Load versus CMOD for M1 (M20-VCC

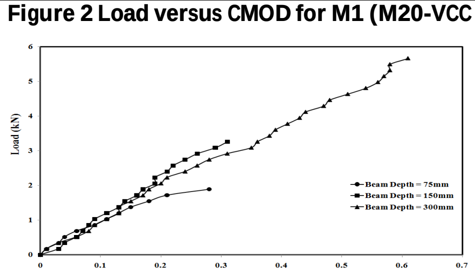

Figure 3 Load versus CMOD for S1 (M20-SCC)

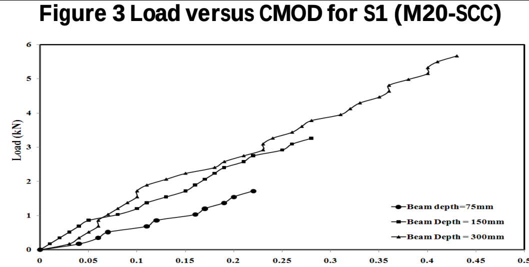

Figure 4 Load versus CMOD for M2 (M35-VCC)

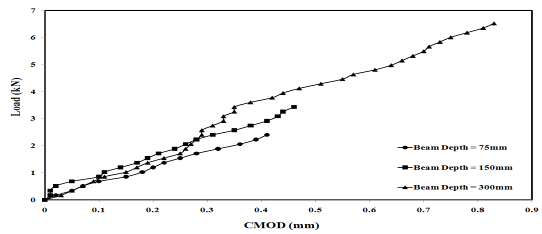

Figure 5 Load versus CMOD for S2 (M35-SCC)

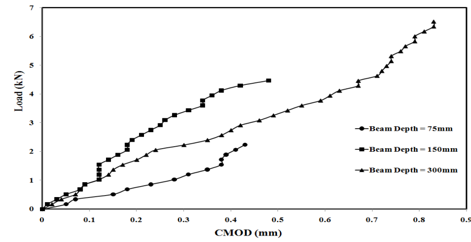

Fig 6 Variation of critical stress intensity factor with beam depth.

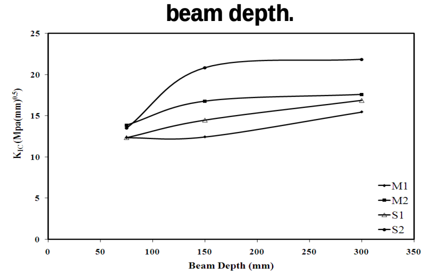

Fig 7 Variation of energy release rate Vs beam depth for a_0/d=0.5 at 28 days.

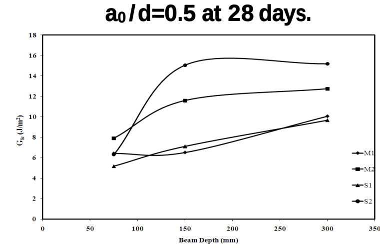

Fig 8 Fracture energy (G_f) Vs compressive strength at 28 days

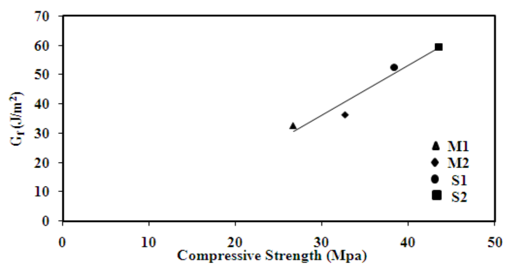

Fig 9 Size effect plot for VCC (M20) (a_0/d=0.5, Mix M1, 28 days)

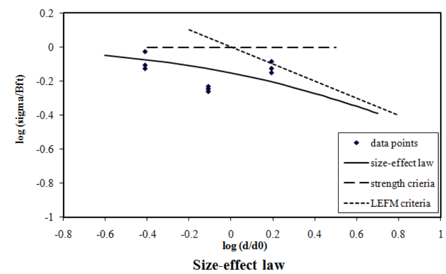

Fig 10 Size effect plot for SCC (M20) (a_0/d=0.5, Mix S1, 28 days)

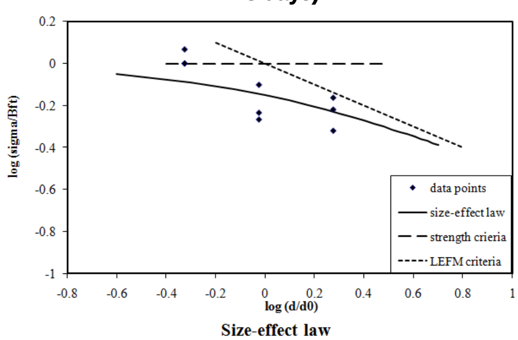

Fig 11 Size effect plot for VCC (M35) (a_0/d=0.5, Mix M2, 28 days)

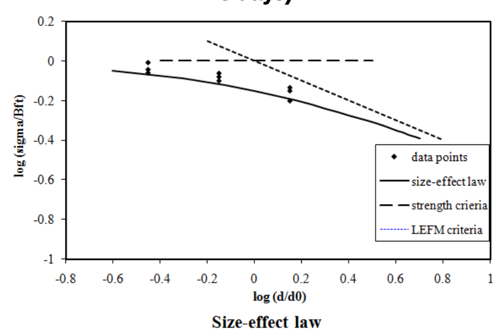

Fig 12 Size effect plot for SCC (M35) (a_0/d=0.5, Mix S2, 28 days)

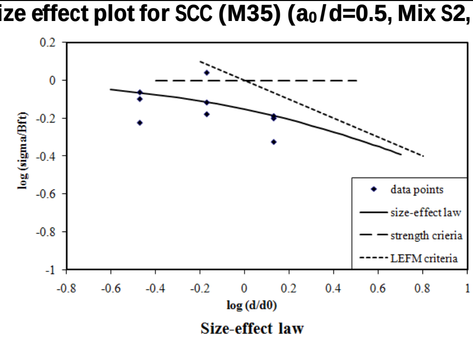

Table 1. Properties of the materials

Sl. No	Ingredients	Properties	Values
1	**Cement**	Specific gravity	3.15
		Standard consistency	31
		Initial setting time (min)	30
		Final setting time (min)	240
2	**Fine aggregate**		
	Natural Sand	Specific gravity	2.62
		Fineness modulus	3.22
		Bulk density (kN/m^3)	15.25
		Gradation	Zone II
	Manufactured Sand	Specific gravity	2.65
		Fineness modulus	2.81
		Bulk density (kN/m^3)	17.88
		Gradation	Zone II
3	**Coarse aggregate**	Specific gravity	2.67
		Bulk density (kN/m^3)	16.80
		Flakiness particles (%)	12.2
		Grain size distribution	Well graded
4	**Fly ash**	Specific gravity	2.2

Table 2. Mix Composition of VCC and SCC

MIX ID		M1	M2	S1	S2
Water binder ratio		0.52	0.4	0.48	0.4
Binders	Portland Cement (kg/m^3)	240	300	270	300
	Fly Ash (kg/m^3)	80	100	90	100
Fine aggregate (kg/m^3)	Natural Sand	807	784		
	Manufactured Sand			920	882.09
Coarse Aggregate (kg/m^3)	10mm	523	508	668	693
	16mm	523	508	223	231
Water(kg/m^3)		170	164	200	197
Glenium 600SCC (kg/m^3) % by Weight of the binder				2.88	3.2
Wet Density(kg/m^3)		2346	2367	2374	2407
Slump mm		90	100		
Slump Flow(mm)				631	630

Table 3. Experimental results

Mix Designation	Concrete grade	Compressive strength	Depth Of Beam (mm)	K_{IC} (MPa.mm$^{0.5}$)	G_{Ic} (J/m^2)	a_o/d	G_f (J/m^2)	c_f (mm)
M1	M20(N)	26.67	75	12.359	6.417	0.5	32.719	24.323
			150	12.450	6.511			
			300	15.474	10.058			
M2	M35(N)	38.36	75	13.858	7.915	0.5	52.337	32.462
			150	16.770	11.600			
			300	17.585	12.744			
S1	M20(SCC)	32.66	75	12.354	5.185	0.5	36.204	29.515
			150	14.481	7.124			
			300	16.880	9.680			
S2	M35(SCC)	43.53	75	13.485	6.311	0.5	59.315	34.019
			150	20.834	15.064			
			300	21.853	15.193			

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