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FRACTURE TOUGHNESS OF STEEL FIBER REINFORCED SELF COMPACTING CONCRETE

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Abstract

The paper describes experimental results which have been obtained for Mode I (bending) fracture of steel fiber reinforced of self- compacting concrete and normal vibrating concrete. The mode I tested specimens are 100x100x400 mm prisms with a single notch introduced at the middle of the tension side of the specimen. The fracture toughness K_{Ic}

معامل الكسر للخرسانة ذاتية الرص المسلحة بالألياف الحديدية

الخلاصة:-

ان الهدف من هذا البحث هو لأيضاح نتائج التجارب التي حصل عليها من تحطم الخرسانة المسلحة بالألياف الحديدية تحت الأنحناء (Mode I) لكل من الخرسانة ذاتية الرص والخرسانة العادية التي تستعمل فيها أدوات الرص. أن أبعاد النماذج التي أجري عليها الفحص هي 100x100x400ملم لقسم منها أدخل قطع في منتصف الوجه الأسفل المعرض للشد بعمق 30ملم وسمك 3 ملم . أن معامل شدة الجهد klc ظهر بانة يتأثر بزيادة نسبة الألياف وكذلك أتجاهاتها الا أن معامل رايس Jlcأظهر أقل تأثرا لأضافة الألياف الحديدية لحدود ال 0.5% وأما CMOD فكان أقل تأثرا للحمل الأقصى المسلط.

Keywords: self- compacting concrete, normal vibrated concrete, steel fiber, stress intensity factor, J- Integral, crack mouth opening displacement.

INTRODUCTION

Several methods of determining fracture toughness of concrete and fiber reinforced concrete are well-established techniques in fracture mechanics. Many researchers observed that the increase in toughness, or ductility provided by including fiber reinforcement is probably the most important material property of fiber content especially when these fibers are deformed or provided with anchorage **(Jenq, Y.S. and Shah, S.P. 1985, Mindess, S. *et al* 1977**). Due to the qusi-brittle manner of concrete, various fracture models have been developed to study the crack propagation in concrete structures, such as fictitious crack model(**Zhimin, Wu *et al* 2006).**

Much effort is being devoted to develop fracture mechanics methods for the analysis of cracked concrete structures. Since **Kaplan F.1961** firstly introduced fracture mechanics into concrete beam to measure fracture toughness. Fracture mechanics deals of with the forces associated the rupture of a solid body and, in particular with the balance energies involved with propagation of cracks,(**Tada *et al* 2000).**The linear-elastic fracture mechanics has been applied to Portland cement pastes, mortars and concretes since the early 1970s (**Shah, s. p. and Mc Garry F. J. 1971**).However, these concepts cannot be successfully describe the behavior of mortars and concretes. **Rozie're, E *et al* 2007** studied the influence of the paste volume on the shrinkage and fracture properties, they concluded that the fracture parameters, K_{Ic} and G_{Ic} for self- compacting concrete are slightly decrease with an increase in paste content. However, (**Zheo *et al* 2005**) found that the self- compacting concrete and the normal vibrated concrete have similar fracture behavior in terms of fracture energy.

High strength concrete is defined as a concrete having a compressive strength above 55MPa according to ACI Committee 363. A self- compacting concrete with this limitation can be archived by using cement content greater than 400 kg/m³, well graded aggregates, low water/powder ratio, proper curing and addition of Superplasticizer to achieve workable concrete mix (**EFNARC,2002**). High strength concrete is a brittle material and brittleness can be reduced by the addition of short discrete fibers randomly distributed in concrete. The mechanical behavior such as compressive strength, tensile strength, flexural strength, impact strength, ductility and flexural toughness of high strength steel fiber concrete are effected by the size, type, fiber volume fraction(V_f), aspect ratio(L/d_f) of fibers, and bond between fibers and the cementitious matrix (**Marar *et al* 2001, Lin W.T. *et al* 2008**).

The objectives of this paper are to compare between the fracture parameters of the self-compacting concrete(SCC) and normal vibrated concrete(NVC) and to explain the effect of fiber inclusion and orientation.

Research Significance

The research presented here is intended to generate information on the behavior of the fracture parameters of SCC with respect to NVC.

Preparation of the Test Specimens

Two series of tests were carried out to determine the toughness of fiber reinforced concrete. In the first series, many trial mixes were done for fresh and hardened self-compacting concrete (SCC) to obtain the optimum mix as illustrated in Table 1. The V-funnel, L-box, slump flow tests were carried out on the SCC mix to find the fresh properties and the results are given in Table 2. To determine the mechanical properties of both self-compacting concrete and normal vibrating concrete mixes, compression test cubes of 150mm side length, indirect tension test on cylinders of 100mm diameter and 200mm height and flexure test on prisms 100x100 mm cross section and 400mm length loaded span were performed. The results of these tests are listed in Table 3. The addition of steel fibers influences all the results obtained in Table 2, by increasing the filling ability, slump flow time and reducing the passing ability.

In the second series, the normal vibrated concrete (NVC) mix proportions were 1: 1.745: 1.913 representing cement: fine aggregate: coarse aggregate. The cement used was ordinary Portland cement, the fine aggregate was river sand and the coarse aggregate was crushed gravel of 10 mm maximum size(for both mixes), which consisted of crushed limestone and siliceous river sand. The w/c ratio used in this mix was 0.50. Superplasticizer was added to the fiber concrete at a rate of 2% per weight of cement in the mix. The specimens were cast horizontally on a vibrating table and fiber orientation technique was similar to that used by (**Hannant and Spring,1974**).

The concrete was designed to give 28 day cube compressive strength of 55-60 MPa for both series. These compressive strengths were obtained after modifying the calculated mix by trail mixes(with and without plasticizer) until a plastic mix with adequate workability was obtained. In all mixes straight round steel fibers of aspect ratio equal 100 were used with a volume fraction varying between 0.25 – 1.5%.

All specimens (100x100x400 mm) were prepared to evaluate the (K_{Ic}) of the self-compacting fiber reinforced concrete materials. Fiber reinforced concrete (FRC) are not linearly elastic and show post-elastic deformation which encouraged the investigators to apply nonlinear elastic fracture mechanics concepts to fiber reinforced concrete. Since the initial loading response is linear, linear elastic fracture mechanics (LEFM) conditions may be assumed to apply in this region and K_{Ic} can be determined from the peak load. The nonlinear response of FRC beyond the point of first crack invalidates the application of LEFM in this region.

Evaluation of K_{Ic} and G_{Ic}

From standard notched beam specimens, the K_{Ic} and G_{Ic} results were calculated using ASTM-E399 expression as follows:

$$\mathrm{KIc} = \frac{3Pa^{½}(L1-L2)}{2B\,D^2} F\left(\frac{a}{D}\right) \qquad (1)$$

Where

$$F\left(\frac{a}{D}\right) = 1.99 - 2.47\left(\frac{a}{D}\right) + 12.9\left(\frac{a}{D}\right)^2 - 23.17\left(\frac{a}{D}\right)^3 + 24.80\left(\frac{a}{D}\right)^4$$

The criterion of strain energy release rate (which Irwin designated as G) is an equivalent criterion of crack propagation. The strain energy release rate at the onset of unstable crack propagation is referred to as the critical energy release rate, Gc, and can be calculated by the following general expression

$$G = \frac{1}{E}K^2 \qquad (2)$$

In a linear elastic situation the value of J = G the strain energy release rate. The J- integral is a measure of the fracture energy and calculated to the point of maximum load(i.e. at the start of the main crack growth); using the following expression

$$J = \frac{2A}{B(D-a)} \qquad (3)$$

Each of the SCC and NVC series comprised 48 specimens in which half were notched at the center of tension side, with 3 mm diamond saw, to give a notch depth of 30mm, a/D=0.3 . The specimens were tested in four point load. A digital gauge of accuracy 0.001 mm was used to measure the mid span deflection. The CMOD was also measured for notched specimens.

TEST RESULTS

The fracture toughness (K_{Ic}) results are summarized in Table 4, and illustrated in Fig.1. The K_{Ic} results for SCC concrete show higher values than NVC this may be referred to the well consolidated material resulted on less micro voids and defects in the matrix than NVC and to better distribution of steel fibers in the matrix of SCC . In general there was relatively little scatter in the values of K_{Ic} since the fracture toughness indicates the resistance of the concrete matrix. An increase in the fracture toughness can be observed with the increasing compressive strength of fiber concrete. This shows that K_{Ic} values increase with the increasing fiber content and orientation, which implies that the higher strength concrete is more tough. The J_{Ic} is much more sensitive to the fiber addition than the corresponding conventional stress intensity factor K_{Ic}. Fig.2 shows the relation between the fiber volume fraction(V_f%) and J_{Ic}.

From Table 3 the compressive strength of SCC and NVC improved significantly for both perpendicular and random distribution for the range of fiber content (0.25-1.5%) by volume. For perpendicular aligned fibers the compressive strength improved between 13%-33% while for normal vibrated concrete the improvement is 14%-29%. In random distribution fibers the compressive strength of self-compacting concrete increased about 17%-47%. The increase in compressive strength of SCC is 14% higher for random distribution than perpendicular.

The addition of steel fibers to concrete increases its tensile strength. For perpendicular aligned fibers, the increment is between 31% to 53% for SCC, whereas for NVC is between 21%-37%. The high increase in tensile strength of SCC probably due to the flowability which enable the fibers to rest on the required direction. These .
fibers play the role of bridges cutting discontinuities and defects resulting in a clear strengthening of that structure and making it more ductile.
which indicates that the fibers increase the resistance against crack growth. A substantial non-linearity prior to the peak load is observed. This non-linearity is due to stable, pre-critical crack growth (slow crack growth). Unless this stable crack extension is included in the calculation for K_{Ic}, one cannot obtain a correct value for the fracture toughness. The results in Table 5, show that the CMOD is independent of the maximum applied load required to fracture the beam. However, the effect of fibers on the CMOD appears to be more effective in perpendicularly aligned fibers for both self-compacting concrete and normal vibrating concrete than in randomly distributed fibers. In Figs. 1 and 3 both the critical stress intensity factor K_{Ic} and critical CMOD increase with the increase of the volume fraction of steel fibers, and tend to saturate at 1.5% of the volume fraction.

CONCLUSIONS

1- The critical intensity factor K_{Ic}, and the crack mouth opening displacement CMOD, increase with the increase of the volume fraction of steel fibers, and tend to saturate at 1.5% of the volume fraction for both concretes.

2- Self- compacting concrete exhibited higher resistance to crack propagation than normal vibrated concrete which is observed by increasing its tensile strength due to fiber inclusion and its orientation (for perpendicular aligned fibers the increment was between (31-53)%.and (21-37)% for SCC and NVC respectively.

3- The K_{Ic} results for SCC concrete show higher values than normal vibrated concrete this may be referred to the well consolidated material with less micro voids and defects in the matrix than the normal vibrated concrete..

4- At low fiber content, the J_{Ic} value for the SCC and normal vibrated concrete are nearly constant ,but rapidly increase at fiber content higher than 0.5% for both fiber orientation. This increase was more pronounced in NVC which shows more deformability than SCC .This concluded that SCC is more tough than normal vibrated concrete.

5- The results, show that the crack mouth opening displacement(CMOD) increases with increase of volume fraction . However, the effect of fibers on the CMOD appears to be more effective in perpendicularly aligned fibers for both SCC and normal vibrated concrete than in random distributed fibers. Both JIc and CMOD appear to be constant at low fiber content for both concretes and both orientations. The SCC fail in more brittle manner and the crack above the notch tip less tortuous than in normal vibrated concrete.

6- The J- integral was more sensitive to the fiber addition for both SCC and NVC than corresponding critical stress intensity factor K_{Ic} .

NOTATIONS

a= notch depth
A= area under load- displacement curve up to a particular load
B = beam width
CMOD= crack mouth opening displacement
D = beam depth mm
G= strain energy release rate
J_{Ic}= critical integral of Rice in Mode I
J = integral of Rice
K = stress intensity factor
K_{Ic}= critical stress intensity factor in Mode I
L_1= distance between supports
L_2= distance between load points
NVC= normal vibrating concrete
P= maximum applied load
SCC= self compacting concrete

Table 1 Proportion of mixes

Mix	Cement content (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	LSP* (kg/m^3)	SP** (l /m^3)
NVC	460	804	880	210	-----	-----
SCC	450	805	800	190	120	6.3

* Limestone powder , ** Supperplasticizer

Table 2- Fresh properties of SCC

Test designation		Lim its according to EFNARC
V-funnel	T=8.15 sec	(7-27) sec
L-box	0.899	≥0.70
Cone(slump flow)	Dave= 788 mm	(640-800)mm
Cone	T500= 3.12 sec	(2-5) sec

Table 3- Mechanical properties of SCC and NVC

V_f %	Compressive strength MPa		Tensile strength MPa		Flexural strength MPa		Orientation
	SCC	NVC	SCC	NVC	SCC	NVC	
0.0	60.0	50	5.80	4.8	6.4	4.95	------------
0.25	67.9	57	7.60	5.82	8.0	6.02	Perpendicular
0.25	70.0	53	7.20	6.17	7.8	6.45	Random
0.5	70.9	65.2	7.70	6.65	5.6	6.68	Perpendicular
0.5	77.20	68.3	8.26	7.2	9.52	5.64	Random
1.0	89.7	64.6	8.90	6.58	8.4	7.95	Perpendicular
1.0	88.6	68.6	8.36	6.99	7.92	7.82	Random
1.5	92.5	76.2	8.76	8.35	9.19	8.76	Perpendicular
1.5	88.5	67.3	8.80	8.07	8.15	8.95	Random

Table -4 Fracture toughness for SC and NV fiber concrete beams

V_f%	Fracture toughness K_{Ic} $MN/m^{3/2}$		Non-linear fracture toughness J_{Ic} kN/m		Orientation
	SCC	NVC	SCC	NVC	
0.0	0.88	0.90	0.035	0.033	---------------
0.25	0.95	0.85	0.172	0.12	Perpendicular
0.25	0.92	0.88	0.153	0.167	Random
0.5	1.25	1.02	0. 25	0.210	Perpendicular
0.5	1.28	1.05	0.198	0.188	Random
1.0	1.45	1.38	0.39	0.91	Perpendicular
1.0	1.53	1.47	0.35	0.62	Random
1.5	1.57	1.52	0.375	0.74	Perpendicular
1.5	1.48	1.50	0.42	0.77	Random

Table5- Load versus crack mouth opening displacement

V_f%	Max. load kN	CMOD mm	Max. load kN	CMOD mm	Orientation
	SCC		NVC		
0.00	6.12	0.20	6.18	0.21	------------
0.25	6.50	0.19	5.74	0.25	Perpendicular
0.25	6.21	0.18	5.84	0.21	Random
0.50	7.40	0.29	6.50	0.29	Perpendicular
0.50	8.05	0.29	6.57	0.26	Random
1.0	7.84	0.51	9.93	0.56	Perpendicular
1.0	8.66	0.39	11.33	0.46	Random
1.5	10.53	0.53	10.52	0.62	Perpendicular
1.5	9.12	0.38	10.70	0.41	Random

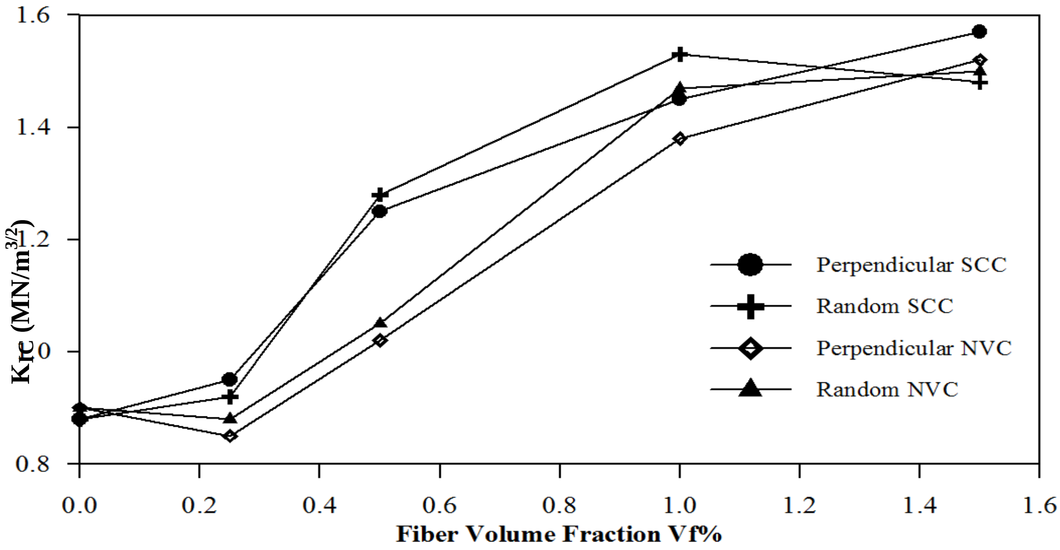

Fig. 1- Relation between KIc and fiber content and fiber orientation For SCC and NVC

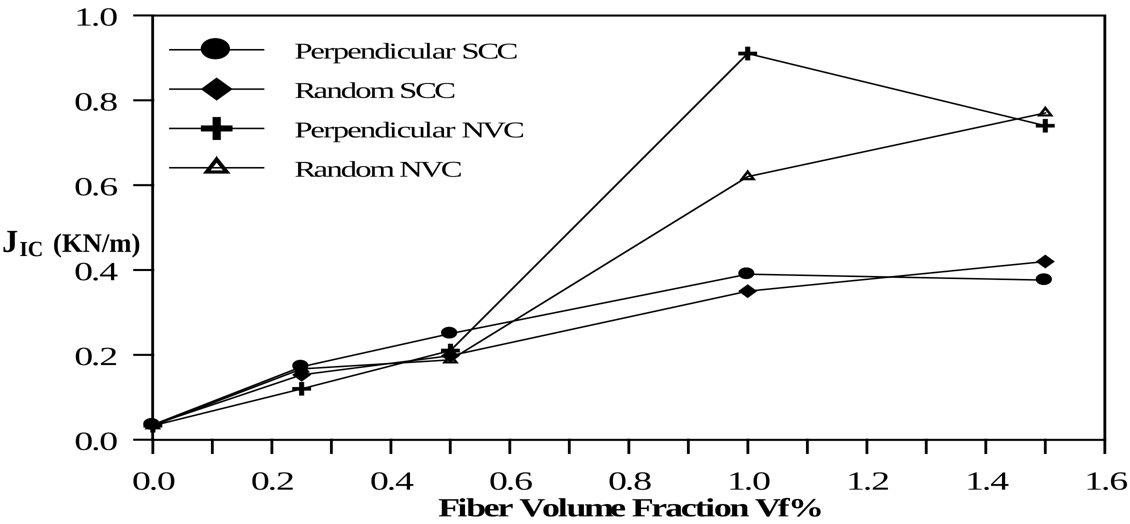

Fig.2- Relation between JIc and fiber volume fraction Vf% for SCC and NVC

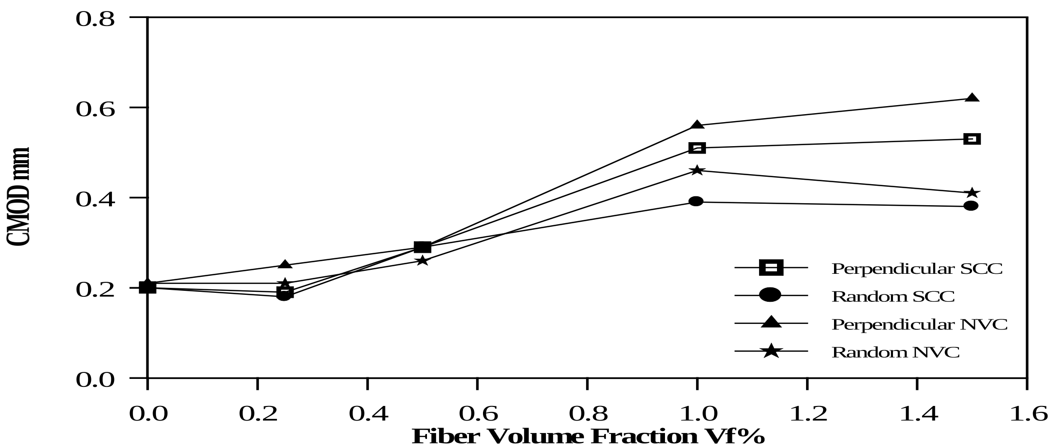

Fig.3- Load vs crack mouth opening displacement for SCC and NVC

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