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Characteristics of Fracture Energy on Steel Fiber-Reinforced Lightweight Polymer Concrete

Youn, Joon-No* · Sung, Chan-Yong**

Abstract

In this study, unsaturated polyester resin, artificial lightweight coarse aggregate, artificial lightweight fine aggregate, heavy calcium carbonate and steel fiber were used to produce a steel fiber-reinforced lightweight polymer concrete with which mechanical properties were examined. Results of this experimental study showed that the flexural strength of unnotched steel fiber-reinforced lightweight polymer concrete increased from 8.61 to 13.96 MPa when mixing ratio of fiber content increased from 0 to 1.5%. Stress intensity factors (K_{IC}) increased with increasing fiber content ratio while it did not increase with increasing notch ratio. Energy release rate (G_{IC}) turned out to depend upon the notch size, and it increased with increasing steel fiber content.

Keywords : Steel fiber-reinforced lightweight polymer concrete, Flexural strength, Stress intensity factor, Energy release rate

I. Introduction

Advantages of structural lightweight concrete over normal weight concrete are numerous. However, the lightweight cement concrete is hardly used to structures because of decline of strength. Polymer concrete (PC) is the construction material that is possibly used for.

PC is produced by using dry aggregates and fillers and polymerizing monomers as binders. Unlike cement concrete, PC is cured in the absence of water or moisture and contains no cement. PC are being used in various fields of construction, rehabilitation and repair applications such as bridges, pipelines and other types of constructions because they are cured fast, have relatively high strength, excellent adhesion, good water tightness and chemical resistance comparing to ordinary cement concrete.[8] Both thermosetting polymers (cross linked polymers)

* Institute of Agricultural Science, College of Agriculture and Life Science, Chungnam National University

** Professor, Department of Agricultural Engineering, College of Agriculture and Life Science, Chungnam National University

** Corresponding author. Tel.: +82-42-821-5798
Fax: +82-42-825-5791
E-mail address: cysung@cnu.ac.kr

such as epoxies and polyesters, and thermo-plastics polymers such as acrylics (methyl methacrylates) are commonly used as binders in PC. The polymer concrete usually exhibits brittle failure behavior. Improving post-peak behavior is thus important. Hence, developing better PC systems and also characterizing the fracture properties and flexural strength in terms of constituents are essential for the effective use of PC[4]

In this study, steel fibers are added to matrix in order to improve the fracture behavior of PC. The method used to perform these fracture tests at room temperature is the two parameter method (TPM),[6] from RILEM, which is a direct method to calculate two size-independent fracture parameters, i.e., critical stress intensity factor (K_{IC}) and critical crack tip opening displacement ($CTOD_C$).

K_{IC} is a measurement of a material's resistance to crack extension when the stress state near the crack tip is predominantly plane strain and the plastic deformation is limited, and the opening mode monotonic load is applied. $CTOD_C$ is the displacement of the surfaces of a crack normal to the original crack plane at the tip of the fatigue pre-crack. While this TPM procedure has several advantages related to use of one specimen, immediately after peak load in highly brittle materials such as PC, a rapid decrease in strength makes it extremely difficult to initiate unloading at exactly 95% of the peak load and this can result in overestimating K_{IC}.[3] Also the fracture energy (G_f) is one of important material properties for the design of large concrete structures.

The objectives of this study are to evaluate the influence of steel fiber mixing and initial cracking using fracture mechanics concept in lightweight polymer concrete, and to intend to widen the fields of application of steel fiber reinforcement polymer concrete.

Ⅱ. Materials

1. Unsaturated Polyester Resin

Ortho-type unsaturated polyester resin is used and its general properties are shown in Table 1.

Table 1 General properties of unsaturated polyester resin

Type	Specific gravity	Viscosity (25℃, ps)	Styrene content (%)	Acid value
Ortho	1.12	3.5	37.2	26.5

2. Initiator

Mineral turpentine solution with 8% of cobalt octanoic (CoOc) solution is generally used as an accelerator, and the DMP solution with 55% of Methyl Ethyl Ketone Peroxide (MEKPO) is used as initiator. Since UP resin has already been added by hardening accelerator when it was produced in a factory, it begins to harden immediately after being added with the initiator. The properties of initiator are shown in Table 2.

Table 2 General properties of initiator

Component	Specific gravity(25℃)	Active oxygen (%)
MEKPO 55% DMP 45%	1.13	10.0

3. Shrinkage Reducing Agent

In order to reduce the shrinkage, shrinkage reducing agent(SRA) is made by dissolving the thermal hardening plastic polystyrene in styrene monomer. Its general properties are shown in Table 3.

Table 3 General properties of shrinkage reducing agent

Type	Specific gravity(25℃)	Viscosity (25℃, ps)	Styrene content (%)
SR-A	0.96	12.6	69.0

4. Filler

The fillers including powder of fly ash, heavy calcium carbonate, alumina, blast furnace slag powder, silica, cement, stone dust and so are commonly used.[9] Among these, the heavy calcium is used in this study since it is relatively cheap and easy to buy. The filler is dried at 100±5℃ for one day before use.[5] The physical properties of filler are shown in Table 4.

Table 4 Physical properties of filler

Bulk density (kg/㎥)	Specific gravity(20℃)	Specific surface(Blain) (㎠/g)
620	2.91	3,150

5. Aggregates

Coarse aggregate used is artificial lightweight aggregate and fine aggregate used is perlite. These aggregates are dried at the temperature of 100±5 ℃ for one day. The physical properties of aggregates are shown in Table 5.

Table 5 Physical properties of aggregates

Aggregate	Size (mm)	Density (20℃)	Absorption (%)	F.M	Unit weight (kg/m^3)
Coarse	4.76 - 10	1.12	21	5.60	864
Fine	1.2 - 0.15	0.40	20〈	2.00	60

6. Fiber

Fiber used is hooked-type steel fiber. The general properties of steel fiber are shown in Table 6.

Table 6 General properties of steel fiber

Length (mm)	Diameter (mm)	Aspect ratio	Specific gravity (20℃)
35	0.55	65	7.85

7. Mix Proportions

For the purpose of evaluating the effect of steel fiber content for the lightweight polymer concrete, the mix proportions as shown in Table 7 are designed. The volume percentages of steel fiber to lightweight polymer concrete are 0%, 0.5%, 1.0%, and 1.5%.

Table 7 Mix proportions of steel fiber-reinforced polymer concrete (Unit : wt. %)

Mix type	Binder		Filler	Coarse aggregate	Fine aggregate	Steel fiber
	U.P	S.R.A				
FLWPC-N	29.75	5.25	23.0	29.38	12.62	-
FLWPC-A				26.63	12.17	3.20
FLWPC-B				23.97	11.79	6.24
FLWPC-C				21.47	11.41	9.12

*FLWPC : fiber-reinforced lightweight polymer concrete

8. Manufacture and Curing of Specimens

Specimens are prepared according to the Korean Standard Testing Methods, KS F 2419 (Specimen preparation methods for strength measure of polyester resin concrete). The steel fiber-reinforced concretes are mixed by using a high performance concrete mixer. All the specimens are demolded after being cured for three hours, and cured again to the curing age 7 days. Size of flexural specimen is 50×100×500 mm according to RILEM's reports.[6] The specimens are notched by depths of 10 mm, 30 mm and 50 mm using a steel plate. The type of specimen for different notch ratio are shown in Table 8. Flexural bending test set-up is shown in Fig. 1.

Table 8 Specimen type of different notch ratios

Mix type	Steel fiber content (%)	Specimen depth (mm)	Notch depth (mm)	Ratio of notch (a/h)
N - 0	0.0	100	0	0.0
N - 1			10	0.1
N - 3			30	0.3
N - 5			50	0.5
A - 0	0.5		0	0.0
A - 1			10	0.1
A - 3			30	0.3
A - 5			50	0.5
B - 0	1.0		0	0.0
B - 1			10	0.1
B - 3			30	0.3
B - 5			50	0.5
C - 0	1.5		0	0.0
C - 1			10	0.1
C - 3			30	0.3
C - 5			50	0.5

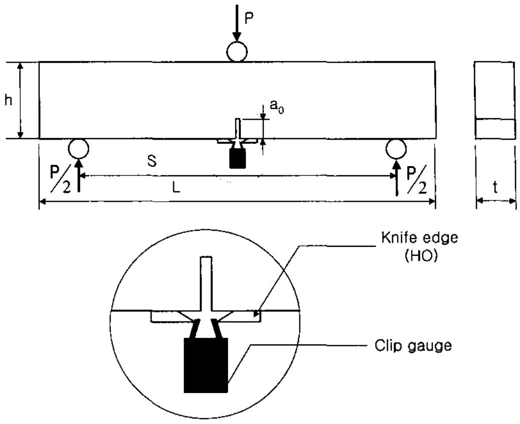

Fig. 1 Flexural bending test set-up

Photo 1 Test set-up apparatus

Ⅲ. Methodology

1. Flexural Strength

The flexural strength of the unnotched and notched beam subjected to three-point bending is calculated from the following equation:

$$f_{net} = \frac{3PS}{2\,t\,(h-a_0)^2} \quad (1)$$

where, P is peak load. S, t, h and a_0 are span, thickness, height and notch depth, respectively.

2. Stress Intensity Factor

Data are analyzed to determine the critical stress intensity factor (K_{IC}) by the two parameter method (TPM) described in RILEM's reports.[1),6)] Cross head speed of the test machine is 0.2 mm/min. All beams are tested to maintain a constant rate of increase of crack mouth opening displacement (CMOD), which is measured by a clip gauge attached to the bottom of the beam.

The modulus of elasticity E is calculated from the following equation:

$$E = \frac{6Sa_0 g_2(\alpha_0)}{C_i h^2 t} \quad \cdots\cdots (2)$$

where, C_i is initial compliance calculated from the load-CMOD curve. Geometric function $g_2(\alpha_0)$ is calculated from the following equation:

$$g_2(\alpha_0) = 0.76 - 2.28\alpha_0 + 3.87\alpha_0^2 - 2.04\alpha_0^3 + \frac{0.66}{(1-\alpha_0)^2} \quad \cdots\cdots (3)$$

where, $\alpha_0 = (a_0 + \mathrm{HO}) / (h + \mathrm{HO})$ and S, a_c, HO, h, and t are defined in Fig. 1.

Based on finite element analysis, the contribution of the clip gauge holder thickness (HO) is included in the function $g_2(\alpha_0)$.[6)] To calculate K_{IC}, the effective crack length (a_c) is a_0+stable crack growth at peak load and should be determined first. To obtain the value of a_c, the following equation has to be solved:

$$E = \frac{6Sa_c g_2(\alpha_c)}{C_u h^2 t} \quad \cdots\cdots (4)$$

where, C_u is the unloading compliance within 95% of the peak load calculated from the load-CMOD curve. The geometric function $g_2(\alpha_c)$ is given by Eq. (4), but $\alpha_c = (a_c + \mathrm{HO})/(h + \mathrm{HO})$ should be used instead of α_0.

By equating Eqs. (2) and (4), the value of the effective crack length a_c for the tested beam can be solved.

$$a_c = a_0 \frac{C_u}{C_i} \frac{g_2(\alpha_0)}{g_2(\alpha_c)} \quad \cdots\cdots (5)$$

This can be solved readily by trial and error. Then the critical stress intensity factor K_{IC} is calculated using the equation (6) below:

$$K_{IC} = 3(P_c + 0.5W_h) \frac{S\sqrt{\pi a_c}\, g_1(a_c/h)}{2h^2 t} \quad \cdots (6)$$

where, P_c is peak load, $W_h = W_{h0} \cdot S/L$, W_{h0} is self-weight of the specimen, and geometric function $g_1(a_c/h)$ is calculated as

$$g_1\left(\frac{a_c}{h}\right) = \frac{1.99 - (a_c/h)(1-a_c/h)\left[2.15 - 3.93a_c/h + 2.70(a_c/h)^2\right]}{\sqrt{\pi}\,(1+2a_c/h)\,(1-a_c/h)^{3/2}} \quad \cdots\cdots (7)$$

3. Energy Release Rate

Using calculated K_{IC}, the energy release rate of crack growth is adopted to following equation that uses liner fracture mechanics concept:

$$G_{IC} = \frac{K_{IC}^2}{E} \quad \cdots\cdots (8)$$

Table 9 Test results of steel fiber-reinforced lightweight polymer concrete

Mix type	Notch ratio (a_0/h)	Maximum load (kN)	Flexural strength using net area (MPa)	K_{IC} (MPa · $m^{0.5}$)	G_{IC} (N/m)
FLWPC-N	0.0	7.171	8.61	-	-
	0.1	3.202	4.74	1.81	140.2
	0.3	2.077	5.09	1.91	157.1
	0.5	1.258	6.04	2.59	288.0
FLWPC-A	0.0	9.120	10.94	-	-
	0.1	5.112	7.57	2.34	242.8
	0.3	3.361	8.23	2.58	296.1
	0.5	1.852	8.89	2.88	367.4
FLWPC-B	0.0	11.008	13.21	-	-
	0.1	6.251	9.26	2.97	409.7
	0.3	4.160	10.19	3.06	436.1
	0.5	2.315	11.11	3.27	496.7
FLWPC-C	0.0	11.636	13.96	-	-
	0.1	9.183	13.60	7.29	2,508.7
	0.3	5.787	14.17	7.41	2,595.8
	0.5	3.015	14.47	7.50	2,657.0

Ⅳ. Results and Discussion

1. Flexural Strength

The results of measuring the flexural strength of steel fiber-reinforced lightweight polymer concrete are shown in Table 9. When the fiber content increased from 0 to 1.5%, the flexural strength of unnotched specimen increased from 8.61 to 13.96 MPa. The ratio of increase of flexural strength were 27% to 62% depending on the fiber content. Fracture process of steel fiber-reinforced lightweight polymer concrete consists of progressive debonding of fiber, during that slow crack propagation was occurring. The final failure occurred due to the unstable crack propagation when the fiber was pulled out and the interfacial shear stress reached the ultimate bond strength. The reason for the increment in flexural strength is that, after matrix cracking, fibers lead strength to the higher load that PC can be sustained until crack occurs on the interfacial bond between fibers and matrix.[2] Fig. 2 clearly demonstrates that flexural strength increased with fiber content. The variability of results calculated from the unnotched specimens are higher than that of the notched specimens. But, the ratio of increase of flexural strength on the notched specimens is higher than that of the unnotched specimens. The ratio of increase of flexural strength on notched specimens is ranged between 47% and 187%, depending on the fiber content and notch ratio.

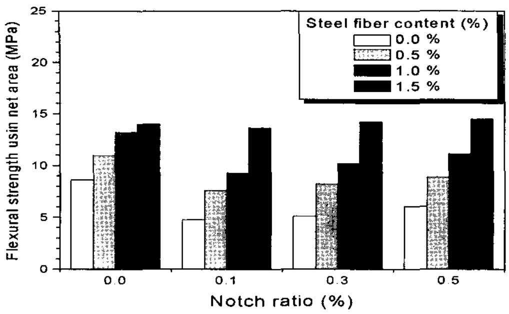

Fig. 2 Effect of fiber content ratio on flexural strength

2. Stress Intensity Factor

Typical load-crack mouth opening displacement (CMOD) curves are shown in Fig. 3 for the notched specimens. Ascending part of the curve is more linear as fiber content is low. The descending part of the stress-strain curve becomes steeper as the concrete strength increases. After peak load in load-CMOD curve, the tail of the descending branch appeared longer as there are a lot of fiber content. This indicates that toughness of the concrete decreased with strength. The magnitude of CMOD at the peak load has been very small compared to CMOD at the post peak. The mean values of CMOD at the peak load are ranged between 0.2 and 0.4 mm.

The variations of stress intensity factors (K_{IC}) are shown in Table 9 and Fig. 4 for the notched specimens. In addition, Fig. 4 shows the effect of steel fiber content on K_{IC}. Stress intensity

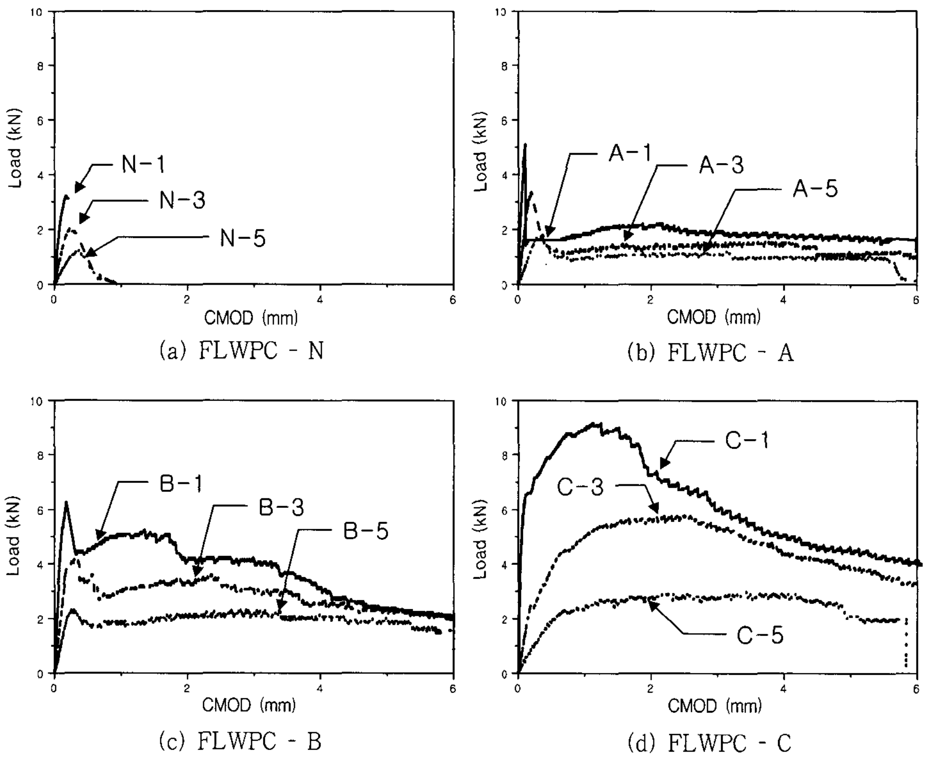

Fig. 3 Typical load-CMOD curves for steel fiber-reinforced lightweight polymer concrete

factor increased with increasing fiber content ratio. The specimen without fiber has lower K_{IC} values than that of the specimen with fiber.

According that the fiber content ratio increased by 0.5%, 1% and 1.5% of the case without fiber, the ratio of increase of K_{IC} appeared by 11~35%, 26~64% and 190~303%, respectively. And K_{IC} did not increase even for the case that notch ratio increased. It implies K_{IC} does not dependent on notch ratio.

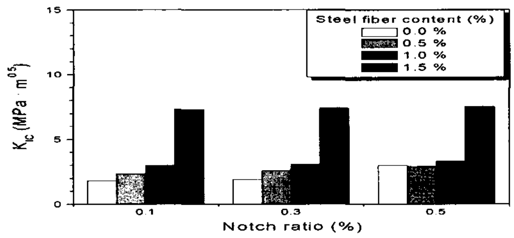

Fig. 4 Relationship between K_{IC} and notch ratio for steel fiber-reinforced lightweight polymer concrete

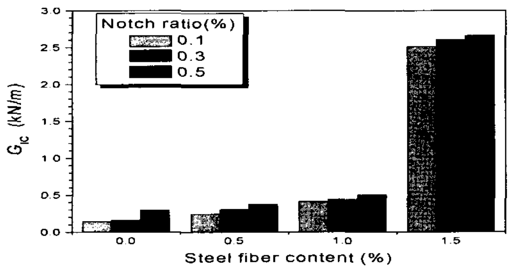

Fig. 5 Relationship between G_{IC} and notch ratio for steel fiber-reinforced lightweight polymer concrete

3. Energy Release Rate

The results of experiments for energy release rate (G_{IC}) of steel fiber-reinforced lightweight polymer concrete are shown in Table 9 and Fig. 5. The results show that G_{IC} increased with increasing notch ratio. With higher notch ratio, material is shown to have higher fracture energy. This results clearly indicate that G_{IC} is dependent upon the notch size. Also, G_{IC} increased with increasing steel fiber content. This may be attributed to the influence of fiber arresting crack.

V. Conclusions

Using fracture mechanics concept, this study was performed to evaluate the influence of steel fiber mixing and initial cracking in lightweight polymer concrete. The used materials were unsaturated polyester resin, artificial lightweight coarse aggregate, artificial lightweight fine aggregate, heavy calcium carbonate and steel fiber. The following conclusions are drawn :

1. Flexural strength increased with increasing fiber content, and the ratio of increase of flexural strength on the notched specimens was higher than that of the unnotched specimens.

2. After peak load in load-CMOD curve, the tail of the descending branch appeared longer as there are a lot of fiber content. The stress intensity factor increased with increasing fiber content. The specimen without fiber had the lower K_{IC} values than the specimen with fiber. And K_{IC} does not increase while notch ratio increases. It shows K_{IC} does not depend on notch ratio.

3. With higher notch ratio, the material shown to have higher fracture energy. This results clearly indicate that G_{IC} was dependent upon the notch size. Also, G_{IC} increased with increasing steel fiber content.

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