論 文 12-4-29

폴리프로필렌 섬유보강 콘크리트의 파괴특성 연구

Fracture Characteristics of Polypropylene Fiber Reinforced Concrete

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ABSTRACT

An experimental research investigation of the fracture properties of polypropylene fiber reinforced concrete is reported. Fibers used in this experiment were two types, monofilament and fibrillated polypropylene fibers. Fiber length was 19 mm, and volume fractions were 0, 1, 2, and 3%. Also, as initial notch depths influence the fracture properties of fiber reinforced concrete, the notch depth ratios by specimen height were 0.15, 0.30 and 0.45.

The main objective of this experimental program is to obtain the load-deflection and the load-CMOD curves, to investigate the fracture properties of the polypropylene fiber reinforced concretes. Therefore, the flexural specimen testings on the four-point bending were conducted. Then, the load-load point displacement and the load-crack mouth opening displacement curves were measured.

The effects of different volume fractions of the monofilament and the fibrillated polypropylene fiber reinforced concrete on the compressive strength, flexural strength and toughness, stress intensity factor, and fracture energy were investigated through the experimental results.

국 문 요 약

본 연구에서는 폴리프로필렌 섬유보강 콘크리트의 파괴특성을 알아보기 위해 Monofilament 섬유와 Fibrillated 섬유의 두 종류 폴리프로필렌 섬유를 선택하여 10×10×50 cm 보 시편을 만들었는데, 이때 사용된 두 종류의 섬유 길이는 19 mm이고, 섬유 혼입량은 0%, 1%, 2%, 3%로 하였으며, 초

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기균열 깊이의 영향을 알아보기 위해 초기 균열깊이를 각 섬유 혼입량에 따라 1.5 cm, 3.0 cm, 4.5 cm로 하여 실험을 수행하였다.

또한, 본 연구에서는 폴리프로필렌 섬유보강 콘크리트의 파괴특성을 규명하기 위해 보 시편에 대한 4 점 하중 휨시험을 통해 하중-하중점 변위 곡선을 각 시편에 대해 측정하였고, 이때 COD 게이지를 이용하여 하중-CMOD 곡선도 측정할 수 있었다. 이러한 실험결과를 통해, 섬유혼입량과 초기 균열 깊이에 따른 압축강도, 휨강도 및 휨인성, 응력확대계수, 파괴에너지 등이 규명되었다.

이러한 결과에 대한 분석으로부터 Fibrillated 폴리프로필렌 섬유가 Monofilament 섬유보다 연성효과가 큰 것을 알 수 있었으며, 특히 하중-CMOD 곡선으로부터 계산되는 파괴에너지인 J_c가 믿을 만한 파괴특성 인자임을 알 수 있었다.

1. Introduction

Plain concrete is a brittle material, with low tensile strength and strain capacities. To overcome these problems, there has been a steady increase in the use of fiber reinforced cement and concretes. The fibers are not added to improve the strength, though modest increases in strength may occur. Rather, their role is to control the cracking of concrete, and to alter the behaviour of the material once the matrix has cracked, by bridging across these cracks and so providing some post-cracking 'ductility'. In the last few years particularly, to make the fibers more compatible with the cementitious matrix, many new fibers more compatible with the cementitious matrix, many new fiber types have been developed

Fiber reinforced cement composites represent a class of cementitious materials generally constructed by adding short fibers of small cross-sectional dimensions to the cementitious matrix. Closely spaced fibers are capable of interfering with the propagation of microcracks that initiate from internal flaws in the material, forcing them to deflect and thus dissipate additional energy during propagation. This delays the formation of an unstable crack system and, thus, increases the tensile strength and toughness of the composite material.

Upon the formation of macrocracks, in the postpeak region under tensile stress systems, fibers tend to bridge the cracks and restrain their widening by providing pullout resistance. The pullout action of fibers dissipates frictional energy, and the bridging of cracks and dissipation of frictional energy by fibers lead to improvements in the postpeak ductility and toughness characteristics of cementitious materials.

In the early 1960s, Goldfein[1] tried these fibers as concrete reinforcement in the construction of blast-resistant structures. In his research, the addition of small amounts of fibers(less than 0.5% by total volume) led to improvements in the ductility and impact resistance of the composite. His work provided an incentive for different researchers to investigate polypropylene fibers in more detail[2,3].

Polypropylene fibers are produced in a variety of shapes, and with differing properties. The main advantages of these fibers are their alkali resistance, relatively high melting point (165℃) and the low price of the raw material. The polypropylene fibers are made of high molecular weight isotactic polypropylene. Because of the sterically regular atomic arrangement of the macromolecules, it can be more readily produced in a crystalline form, and then processed by stretching to achieve a high degree of orientation which is necessary to obtain good fiber properties. The polypropyene fibers can be made in three different geometries, all of which have been studied in relation to the reinforcement of cementitious matrices: monofilaments, film, and extruded tape.

Polypropylene fiber reinforced concrete has been finding increasing applications in slabs on grade, industrial floors, overlays, and building wall and slab elements. These applications are being encouraged by the improvements in cracking properties and ductility. It is noted that polypropylene fiber reinforced concrete can maintain a significant portion of its flexural resistance at large deformations beyond the peak load[4].

The research reported here is concerned with assessing the combined effects of two different polypropylene fiber types in cement-based matrixes. The two polypropylene fibers used are monofilament polypropylene fiber and fibrillated polypropylene fiber.

The purpose of the present study is to detect the fracture characteristics of polypropylene fiber reinforced concrete. Therefore, in this study, the experimental program was designed to study influence of polypropylene fiber type, volume fraction, and initial notch depth.

2. Experimental program

2.1 Test variables and mix design

Fibers are added to concrete to improve the performance of the relatively brittle matrix. One of the primary contributions of fibers is in the area of energy absorption. Improved energy absorbing capacity provides for better toughness under various loading configurations.

Polypropylene fibers are generally manufactured in three types such as monofilament fiber, fibrillated fiber, and tape fiber. The fracture characteristics of the polypropylene fiber reinforced concrete differ according to fiber types and fiber length. Thus, two type fibers used widely, namely monofilament fiber and fibrillated fiber were investigated in this experimental study. Then, fiber length used in this experiment was 19mm.

Generally, fracture toughness increases according to fiber contents. The volume fractions of this experiment were 0%, 1%, 2%, and 3% of the mixing concrete volume. Also, initial notch depths influence the fracture properties of fiber reinforced concrete. The notch depth ratios by specimen height were 0.15, 0.30, and 0.45, in this experiment. Therefore, Table 1 is the test variables of this experiment.

Table 1 Test variables

Specimen No.	Notch Depth Ratio (a/d)	Fiber Content (%)	Fiber Type
N-Ⅰ-V_0	0.15	0	Non-Fiber
N-Ⅱ-V_0	0.30		
N-Ⅲ-V_0	0.45		
M-Ⅰ-V_1	0.15	1	Monofilament Polypropylene Fiber
M-Ⅱ-V_1	0.30		
M-Ⅲ-V_1	0.45		
M-Ⅰ-V_2	0.15	2	
M-Ⅱ-V_2	0.30		
M-Ⅲ-V_2	0.45		
M-Ⅰ-V_3	0.15	3	
M-Ⅱ-V_3	0.30		
M-Ⅲ-V_3	0.45		
F-Ⅰ-V_1	0.15	1	Fibrillated Polypropylene Fiber
F-Ⅱ-V_1	0.30		
F-Ⅲ-V_1	0.45		
F-Ⅰ-V_2	0.15	2	
F-Ⅱ-V_2	0.30		
F-Ⅲ-V_2	0.45		
F-Ⅰ-V_3	0.15	3	
F-Ⅱ-V_3	0.30		
F-Ⅲ-V_3	0.45		

As uniform dispersion of fibers is vital to the development of cement composites which take advantage of the reinforcement properties of fibers, Good mixing concrete uniformly dispersed fibers must be achieved. Fibers tend to decrease the workability of the fresh mix; a superplasticizer with naphthalene formaldehyde sulfonate as the active ingredient was used to improve workability. The matrix mix proportions of polypropylene fiber reinforced concrete are given in Table 2.

Table 2 Mix proportions of concrete (kg/m^3)

Cement content	Water	Fine aggregate	Coarse aggregate	Admixture
385	196.4	823	1005	0.77

To obtain 28-day compressive strength of each test variable, three $\Phi 10\times 20$ cm cylindrical specimens by each test variable were made. Three $10\times 10\times 50$ cm beam specimen by each test variable were also made to obtain load-deflection curves and load-CMOD curves.

2.2 Test mothods

The beam specimens were tested using four-point loading over a simply supported span of 45 cm as shown in Fig. 1. The crack mouth opening displacement (CMOD) was measured using a COD gauge clipped to the bottom of the beam and held in position by two aluminum knife edges glued to the specimen (Fig. 1). For every test, both the load versus load-point deflection and the load versus crack mouth opening displacement were measured simultaneously. A displacement-controlled loading machine was used. During the test the cross head speed of the material testing machine was maintained constant at 0.04 mm/min.

3. Results and discussions

3.1 Compressive strengths

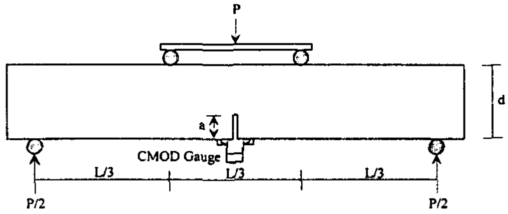

Fig. 1 Testing setup

21 compression cylinders($\Phi 10\times 20$ cm) were tested. The age at testing was 28 days. Fig. 2 shows measured compressive strengths of monofilament and fibrillated polypropylene fiber reinforced concrete specimens for each volume fraction. Fiber reinforcement effects on compressive strength generally are negative, or sometimes negligible. In this study, polypropylene fiber reinforcement effects on compressive strength are negligible as shown in Fig. 2. It is noted that compressive strength is little influenced by polypropylene fiber addition at the dosage rates commonly used in fiber reinforced concretes.

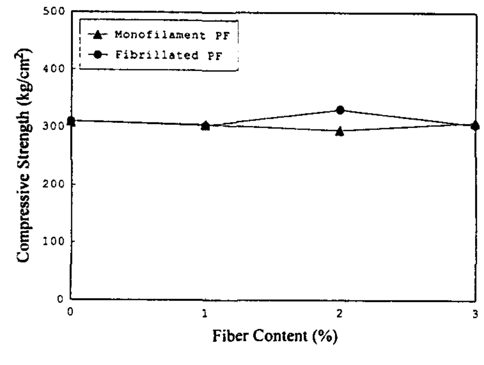

Fig. 2 Compressive strengths for each polypropylene fiber volume fraction

3.2 Load-deflection curves and load-CMOD curves

The main reason for incorporating fiber in concrete is to impart ductility to an otherwise brittle material. Fiber reinforcement improves the energy absorption, impact resistance and crack resistance of concrete. Fiber addition enables the concrete to continue to carry load after cracking, the so-called post-cracking behaviour.

The main objective of this experimental program is to obtain the load-deflection curves, to investigate the fracture properties of the polypropylene fiber reinforced concretes. To detect the influence of ductility in polypropylene fiber reinforced concretes, 63 beam specimens (10×10×50 cm) were made and tested using four-point loading over a simply supported span of 45 cm. Then, the load-deflection curves measured for various fiber content fractions were shown in Fig. 3. These load-deflection curves provide qualitative evidence for the favorable effects on flexural behavior resulting from use of the polypropylene fiber in cementitious matrices.

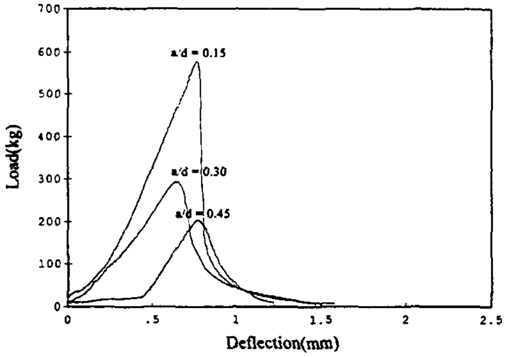

Fig. 3a Load-deflection curves according to the initial notch depth (without fiber)

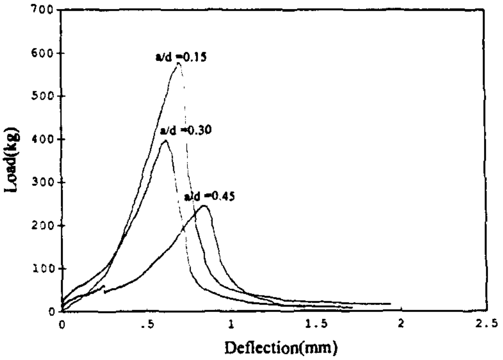

Fig. 3b Load-deflection curves according to the initial notch depth (1% monofilament PF)

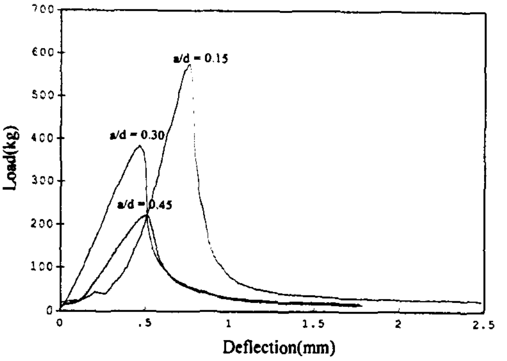

Fig. 3c Load-deflection curves according to the initial notch depth (2% monofilament PF)

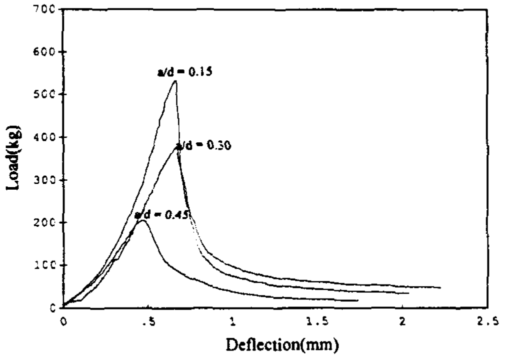

Fig. 3d Load-deflection curves according to the initial notch depth (3% monofilament PF)

The another object of this experimental program is to obtain the load-CMOD curves, to investigate the fracture properties of the polypropylene fiber reinforced concretes. Therefore, while the flexural testings were conducted, the crack mouth opening displacement (CMOD) was measured using a COD gauge as shown in Fig. 1. Then, the load-CMOD curves measured for various fiber content fractions were shown in Fig. 4. As shown in Fig. 4, it is noted that there is the ductility effects of the polypropylene fiber in cementitious matrices.

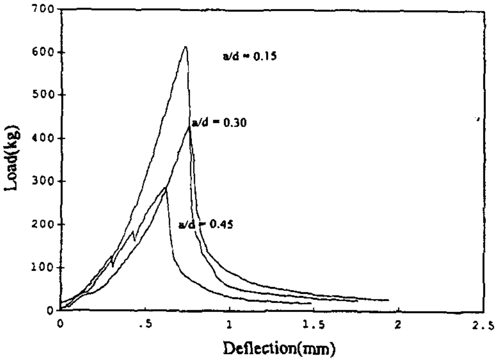

Fig. 3e Load-deflection curves according to the initial notch depth (1% fibrillated PF)

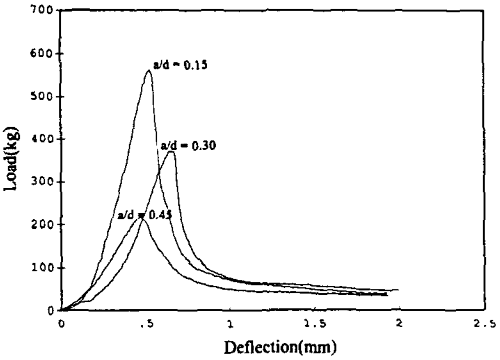

Fig. 3f Load-deflection curves according to the initial notch depth (2% fibrillated PF)

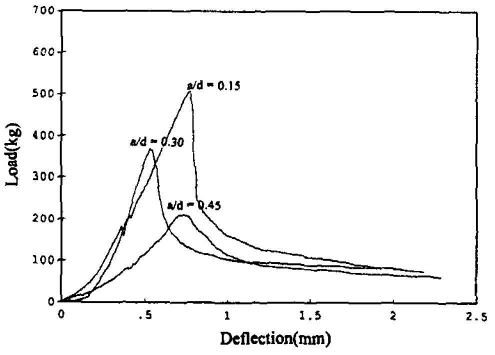

Fig. 3g Load-deflection curves according to the initial notch depth (3% fibrillated PF)

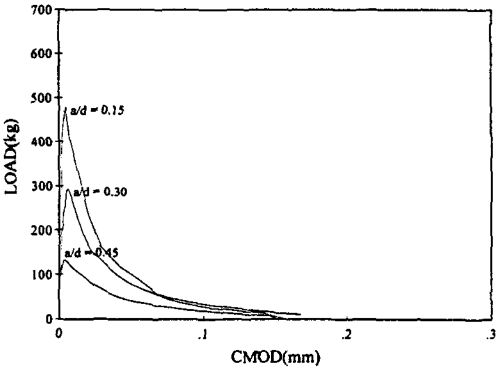

Fig. 4a Load-CMOD curves according to the initial notch depth (without fiber)

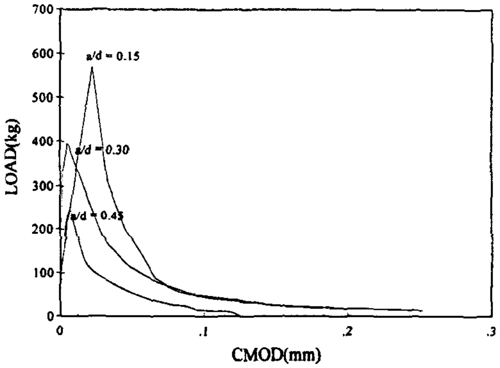

Fig. 4b Load-CMOD curves according to the initial notch depth (1% monofilament PF)

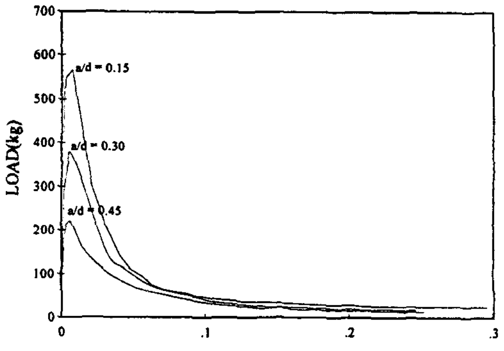

Fig. 4c Load-CMOD curves according to the initial notch depth (2% monofilament PF)

3.3 Flexural strength and equivalent flexural strength

Using the load versus load point displace-

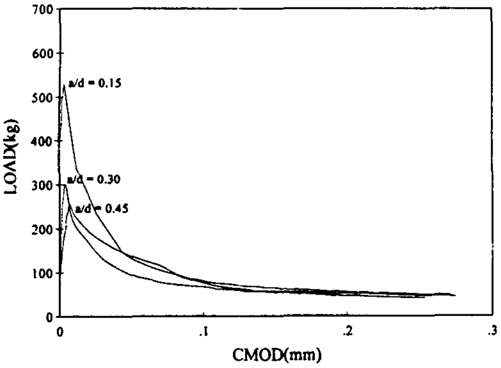

Fig. 4d Load-CMOD curves according to the initial notch depth (3% monofilament PF)

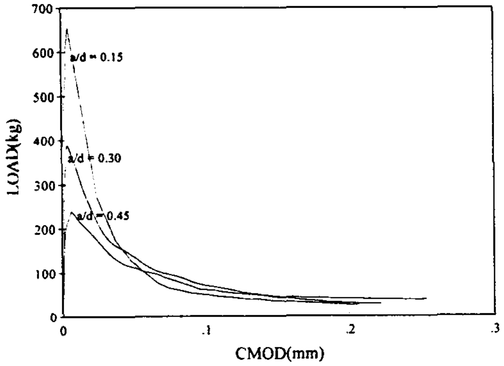

Fig. 4e Load-CMOD curves according to the initial notch depth (1% fibrillated PF)

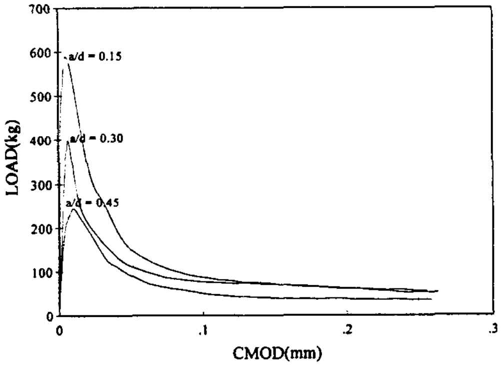

Fig. 4f Load-CMOD curves according to the initial notch depth (2% fibrillated PF)

ment curves it was possible to calculate flexural strength, σ_u and equivalent flexural strength, σ_e for each test where σ_u and σ_e are defined as[5)]

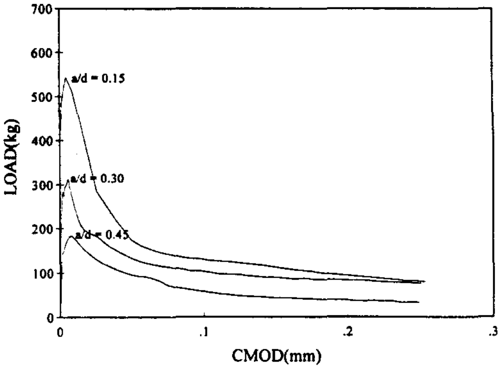

Fig. 4g Load-CMOD curves according to the initial notch depth (3% fibrillated PF)

$$\sigma_u = \frac{P_{\max} l}{b(d-a)^2} \cdots\cdots (1)$$

$$\sigma_e = \frac{T_b\, l}{b(d-a)^2 \delta_{tb}} \cdots\cdots (2)$$

where P_{max} is the maximum load, l is the span of the specimen, b is the specimen width, d is the specimen depth, a is the initial notch length, T_b is the area underneath the load-deflection curve up to a δ_{tb} deflection, δ_{tb} is a deflection equal to span length divided by 150. The flexural strengths which calculated from Eq.(1) and the maximum load of load-deflection curves are shown in Fig. 5. Fig. 5 also shows the notch sensitivity. As shown in Fig. 5, the flexural strengths are observed to increase a little with the polypropylene fiber reinforcement, while notch sensitivity tends to be constant according to the notch to depth ratio.

The equivalent flexural strengths which calculated from Eq.(2) and T_b of load-deflection curves are shown in Fig. 6. It is noted from this figure that the equivalent flexural strengths tend to increase slightly with polypropylene fiber content. It is also observed that the equivalent flexural strengths of the fibrillated fiber reinforcement increase more than that of the momofilament, as shown in Fig. 6. It is concluded that the flexural post-peak resistance of the fibrillated fiber reinforced concrete is slightly more effective than the monofilament.

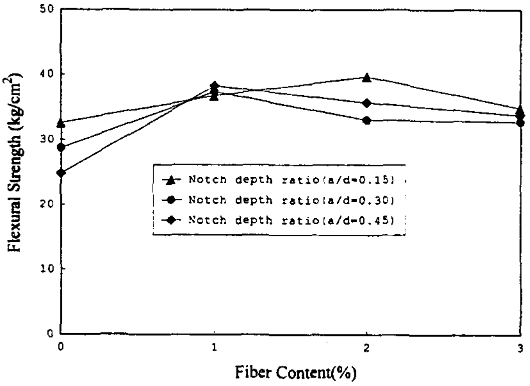

Fig. 5a Flexural strength according to the fiber content (monofilament PF)

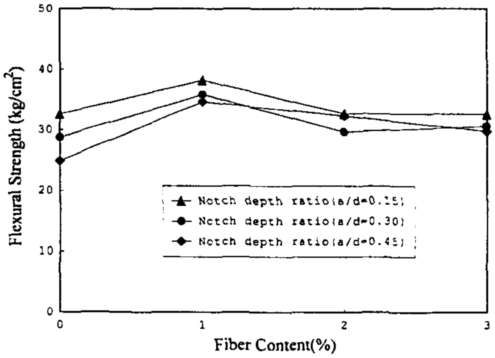

Fig. 5b Flexural strength according to the fiber content (fibrillated PF)

3.4 Critical stress intensity factor

According to the ASTM E 399 recommendation, the critical load for evaluating a valid K_I value is determined from the load-deflection curves by the secant line with a slope of 0.95 times the initial tangent slope. Instead of this procedure, the maximum load is utilized in determining K_I and this would result in a slightly K_I higher value. A similar approach has been used in determining the stress intensity factor of cementitious materials[6].

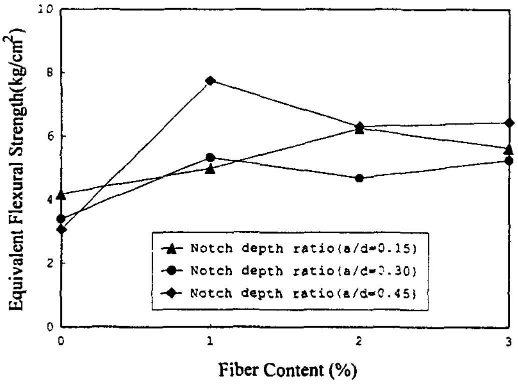

Fig. 6a Equivalent flexural strength according to the fiber content (monofilament PF)

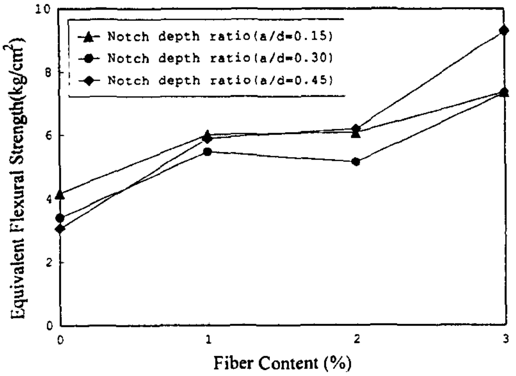

Fig. 6b Equivalent flexural strength according to the fiber content (fibrillated PF)

Assuming a beam of cross section $b\times(d-a)$ with an initial crack length a, the critical stress intensity factor was calculated by using the equation for four-point bending developed by Brown and Srawley[7]. The relationship is as follows

$$K_{IC}=\sigma_u\sqrt{\pi a}\ \{1.12-1.39(a/d)+7.32(a/d)^2-13.07(a/d)^3+13.99(a/d)^4\} \qquad \cdots\cdots\cdots\cdots (3)$$

where σ_u is the flexural strength equal to Eq.(1). Then, the critical stress intensity factor, K_{IC} is the limiting value of K_I. Fig. 7a, 7b show K_{IC} of monofilament polypropylene fiber reinforced concrete specimen and fibrillated polyropylene fiber reinforced concrete specimen according to the initial notch to depth ratio, respectively.

As shown in Fig. 7, the critical stress intensity factors decrease a little with the polypropylene fiber reinforcement, but the decrease is negligible. Therefore, it is concluded that notch to depth ratio hardly influences the critical stress intensity factor.

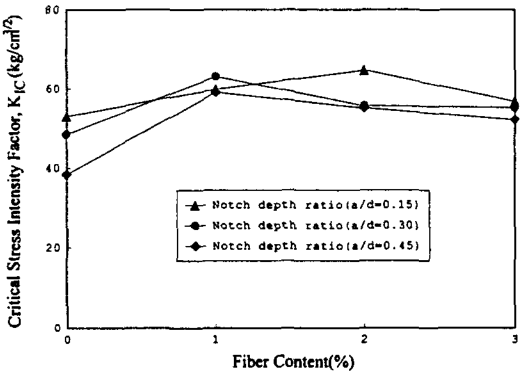

Fig. 7a Critical stress intensity factor according to the fiber content (monofilament PF)

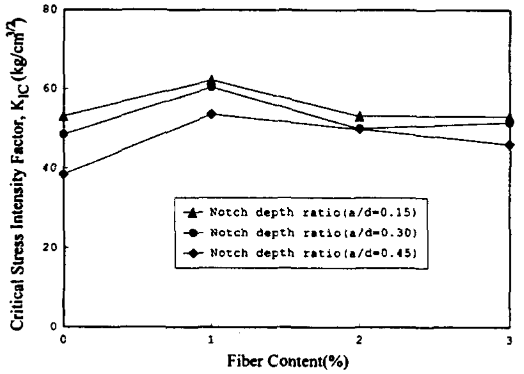

Fig. 7b Critical stress intensity factor according to the fiber content (fibrillated PF)

3.5 Fracture energy

Using the load versus load point displacement curves it was possible to calculate G_F for each test where G_F is defined as[8]

$$G_F = \frac{A}{b(d-a)} \cdots\cdots\cdots\cdots (4)$$

and A is equal to the total area under the load-deflection curve. G_F can be used as an approximate measure of fracture energy but has been shown to be dependent on the beam size used to determine it[8]. Then, Fig. 8 shows G_F values for each volume fraction.

It is noted from this figure that there is a significant increase in the energy absorption ability as the fiber volume fraction is increased. This is achieved by fiber breakage and pull-out after the matrix has cracked. It is also noted that G_F value increases a little as the fiber content is increased in both monofilament and fibrillated fiber reinforced concrete.

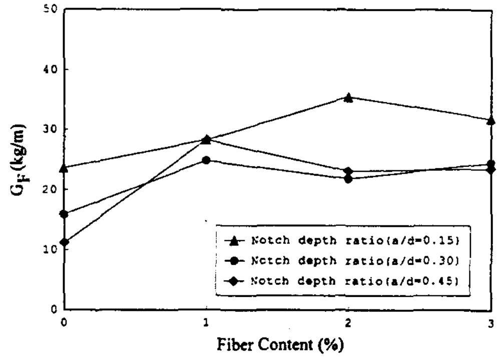

Fig. 8a Fracture energy according to the fiber content (monofilament PF)

The J-integral evaluated along a contour Γ surrounding the elongated process zone near the macrocrack tip can be expressed as

$$J(\delta) = \int_0^{\delta} \sigma(\delta)\, d\delta \cdots\cdots\cdots\cdots (4)$$

where δ is the separation at the physical crack tip and $\sigma(\delta)$ is the corresponding stress-transferring capability across the process zone. Then, the critical J-integral value, J_C is defined as

$$J_C = \int_0^{\delta_C} \sigma(\delta)\, d\delta = \frac{l}{b(d-a)^2} \int_0^{\delta_C} P\, d\delta \qquad \cdots\cdots (5)$$

where δ_C is the value of the critical crack separation at the end of the tension-softening curve, namely, the load-CMOD, when $\sigma=0$, and J_C is equal to the total area under the tension softening curve(the load-CMOD) up to CMOD = 0.2 mm. Then, Fig. 9 shows J_C for each volume fraction.

It is observed from Fig. 9 that the critical J-integral increases linearly as the fiber volume fraction is increased, similar to G_F. It is also noted that J_C doesn't decrease or increase, as the notch to depth ratio is increased, in both monofilament and fibrillated fiber reinforced concrete. It is concluded that constant J_C value with the notch to depth ratio, like this, is owing to the CMOD relatively unaffected by support settlements.

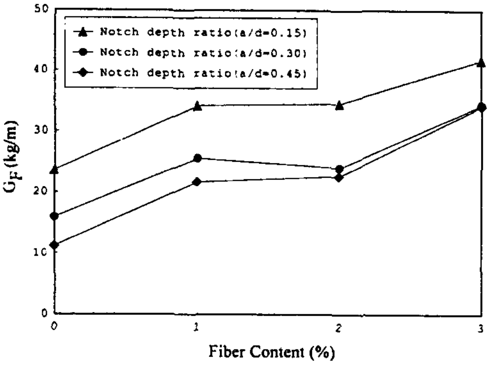

Fig. 8b Fracture energy according to the fiber content (fibrillated PF)

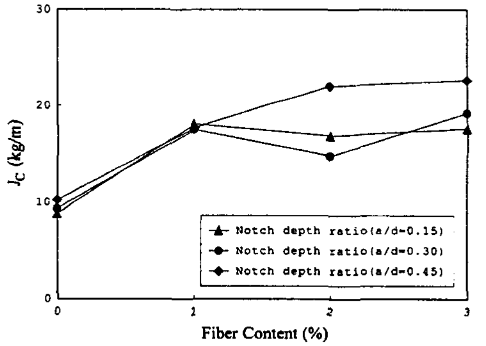

Fig. 9a Critical J-integral according to the fiber content (monofilament PF)

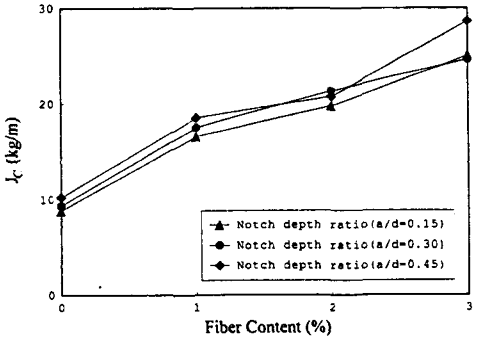

Fig. 9b Critical J-integral according to the fiber content (fibrillated PF)

4. Conclusions

An experimental research investigation was reported in the fracture properties of monofilament and fibrillated polypropylene fiber reinforced concrete. Four mixtures were constructed. Compressive strength, flexural strength, fracture toughness, and fracture energy were studied.

Based on the results presented in this paper and observations during the specimen testing, the following conclusions can be derived.

1) Generally, fibers have negative effects on the compressive strength of cement-based matrices. In this study, polypropylene fibers had little effect on compressive strength of concrete.
2) The flexural behavior of polypropylene fiber reinforced concrete can be characterized by the post-peak flexural resistance. It was found that the fibrillated polypropylene fi-

ber were slightly more effective than the monofilament for enhancing the post-peak resistance.

3) The critical stress intensity factors shows a steady constant as the fiber volume fraction is increased. Therefore, notch to depth ratio hardly influences the critical stress intensity factors.
4) The critical J-integral increases linearly a little, the same as G_F, as the fiber volume fraction is increased, but, J_C doesn't decrease or increase as the notch to depth ratio is increased, in both monofilament and fibrillated fiber reinforced concrete. This reason is that the CMOD is relatively unaffected by support settlements. Therefore, J_C value calculated from the load-CMOD curve is a more reliable parameter for predicting the fracture properties of concrete.

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