Fracture Mechanics of Concrete Structures,
Proceedings FRAMCOS-2, edited by Folker H. Wittmann,
AEDIFICATIO Publishers, D-79104 Freiburg (1995)

EFFECTS OF FIBER ON FRACTURE PROPERTIES OF LIGHT WEIGHT CONCRETE MADE WITH FLY-ASH PELLETIZED AGGREGATES

T.P. Chang, C.Y. Lin, and C.L. Hwang,
Department of Construction Engineering, National Taiwan Institute of Technology, Taiwan, R.O.C.
M.M. Shieh,
Taiwan Provincial Hsiu-Shui Vocational School, Hsiu-Shui, Chang-Hua, Taiwan, R.O.C.

Abstract

This study presents the experimental results of fracture properties of lightweight concrete made with cold-pelletized fly-ash aggregates incorporating three different steel fiber concentrations, 1%, 2% and 3% of cement weight respectively. Experimental results showed that the increase of fiber amount increased the compressive, splitting tensile and flexural strengths, and toughness of concrete. Compressive strengths of ϕ100x200 mm cylindrical concrete specimen at 28 days ranged from 33.9 (no fiber) to 37.72 MPa (3% fiber). By means of size effect law, it was found that the fracture energy increased from G_f = 37.2 N/m (no fiber) to 62.7 N/m (3% fiber), respectively. Predictions of structural response on the three-point bending specimen from R-curves were also presented.

1 Introduction

Lightweight concrete is defined as having an oven-dry density range of approximately 300-2000 kg/m^3 [Clarke 1993]. The compressive strength of lightweight concrete larger than 15 MPa is considered to be the structural concrete by RILEM/CEB. In this study, fly-ash was used as the major raw material for making the lightweight aggregate through the pelletization with a cold-bonding method [Bijen 1986] based on the ecological considerations and the advantage of much less energy consumption. In addition, various fiber reinforcements have been incorporated into the concrete mixture to increase the toughness and ductility of the concrete [Swamy 1989]. The main function of these fibers is to inhibit the propagation of cracks through the brittle cementitious matrix. This function is especially important for lightweight concretes, since the strength of aggregate is usually weaker than that of hardened cement paste such that aggregates can not offer a crack arrest mechanism, resulting in a brittle fracture. An understanding of effects of steel fiber reinforcement on the fracture properties of lightweight concrete appears to be important. This study presents experimental results of the properties of the pelletized fly-ash lightweight aggregate and the concrete incorporating these aggregates. Three different amounts of steel fiber reinforcement, 1%, 2% and 3% of cement weight were used. Fracture properties were obtained on the base of size-effect law [RILEM 1990].

2 Fracture energy and structural response by size-effect law

Test method based on the size-effect law is a simple and effective way for calculating fracture parameters of concrete. With this method, the only measured values in the experiment are the maximum loads of several sufficiently different sizes of specimens with geometrically similar shape. The minimum size range for specimen is 1 to 4 [RILEM 1990]. The fracture energy G_f calculated by size-effect law for the Single-Edge-Notch-Three-Point-Bending (SENTPB) beam specimens, as shown in Fig. 1, can be expressed as

$$G_f = \frac{B^2(f_u)^2}{c_n^2 E} d_0 g(\alpha_0) \tag{1}$$

where E = Young's modulus; $c_n = (1.5\ell)/[d(1-\alpha)^2]$; d = height; ℓ = span; $\alpha = c/d$; c = effective crack extension; $\alpha_0 = a_0/d = 1/6$; a_0 = length of notch; f_u = tensile strength; d_0 and B = unknowns to be found; $g(\alpha)$ = shape factor as given in Eq. (2).

$$g(\alpha) = \left[\frac{6.647\sqrt{\alpha}(1-2.5\alpha+4.49\alpha^2-3.98\alpha^3+1.33\alpha^4)}{(1-\alpha)^{1.5}}\right]^2 \tag{2}$$

The values of B and d_0 are calculated from the maximum failure load P_u, tensile strength f_u and nominal stress σ_N through the linear regression

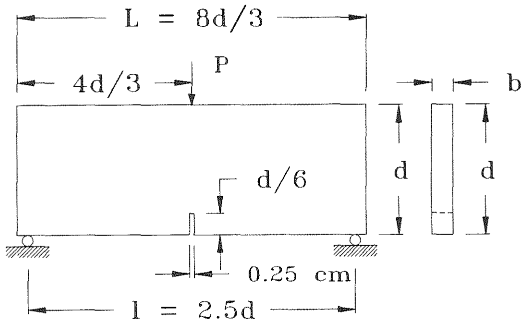

Fig. 1 SENTPB beam specimen

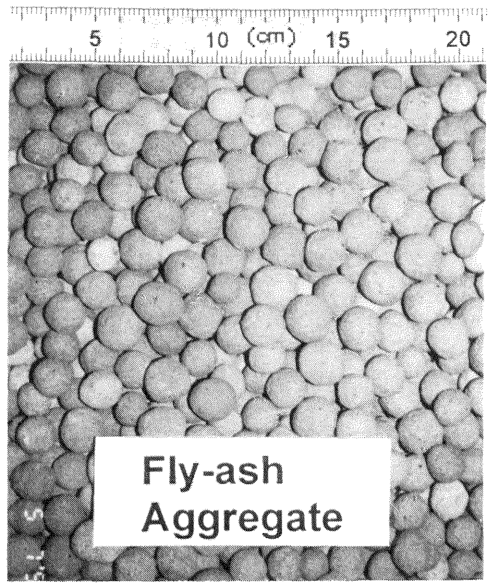

Fig. 2 Fly-ash aggregate

equation as expressed in Eqs. (3) and (4):

$$Y = AX + C \tag{3}$$

$$X = d \; ; \; Y = \left(\frac{f_u}{\sigma_N}\right)^2 \; ; \; \sigma_N = c_n \frac{p_u}{bd} \; ; \; B = \frac{1}{\sqrt{C}} \; ; \; d_0 = \frac{C}{A} \; . \tag{4}$$

where b = thickness of specimen. The fracture properties determined by Eqs. (1) to (4) are those values extrapolated from the laboratory specimen sizes to the specimens with sufficiently large sizes. Therefore, G_f is assumed to be the material property. On the other hand, it has been known that the crack resistance (R curve) varies with the amount of crack growth. For concrete, as a crack extends a damaged zone, a microcracking zone (fracture process zone) is created ahead of the tip of the initial crack or notch such that the crack resistance increases with the crack extension until the peak load reaches, e.g., a completed damaged zone has been developed. Thus crack resistance for concrete specimen is strongly dependent on its geometry. The R-curve equation for concrete derived from size-effect law can be expressed by [Gettu 1990]:

$$R(c) = G_f \frac{g'(\gamma)}{g'(\alpha_0)} \frac{c}{c_f}; \quad in\ which \quad \frac{c}{c_f} = \frac{g'(\alpha_0)}{g(\alpha_0)} \left[\frac{g(\gamma)}{g'(\gamma)} - \gamma + \alpha_0 \right] \tag{5}$$

The equation of R-curve together with LEFM relations can be used to predict the load-deflection curves for SENTPB beam specimens. Let u_c = deflection at mid-span due to fracture, u_b and u_s = elastic deflections due to bending and shear respectively, and $u = u_c + u_b + u_s$ = total displacement of beam specimen at mid-span. The equations required for this calculation are summarized as follows [Gettu 1990]:

$$u_c = \frac{2P}{Eb}\int_0^{\alpha} g(t)dt \;; \qquad P = b\sqrt{\frac{Ed}{g(\alpha)}R(c)} \tag{6}$$

$$u = u_c + u_b + u_s, \quad u_b = \frac{Pl^3}{4bd^3E}, \quad u_s = 0.6(1+\nu)\frac{Pl}{bdE} \tag{7}$$

where ν = Poisson's ratio. Choosing different values of α or c, one can calculate the complete load-deflection curve of the SENTPB beam specimen from Eqs. (5) to (7). Note that the R-curve value in Eq. (5) is constant after the peak load, since the fracture process zone is fully developed and separated by a traction-free crack in the post-peak regime.

3 Experimental materials

3.1 Coarse lightweight aggregate

The coarse fly-ash lightweight aggregates used in this study were made of the mix compound of bottom ash, fly ash (passing through sieve #4), cement (Type I) and hydrated lime [Shieh 1994]. Water was the wetting agent acting as coagulant such that the wet fly ash would be pelletized with other adhesive materials through the rolling motion. In this study, the diameters of those manufactured fly-ash aggregates ranged from 5 mm to 25 mm. Only those passing through sieve #1/2" (12.7 mm) and retaining at sieve #4 (4.75 mm) were selected as the coarse aggregates, as shown in Fig. 2. The OD specific gravity of the aggregate was about 1.33; the average moisture-absorption ratios were about 16.4%, 20.5% and 24.7% at 30 minutes, 24 hours and 14 days respectively [Shieh 1994]. Those fly-ash aggregates were submerged in water for about 30 minutes before mixing into concrete. By placing a piece of pelletized aggregate on a flat base plate of a material testing machine, and then applying a compressive load gradually from the vertical direction to the particle, the volume average compressive strength of aggregate, $\overline{\sigma}_{22}$, can be calculated by the following equation [Chang 1995]:

$$\overline{\sigma}_{22} = -\frac{F_2 \times h}{V^a} \tag{8}$$

where F_2 = vertical failure load; h = distance between two points of applied load. Various sizes of lightweight fly-ash aggregates were selected for the compressive test and the strength calculation according to Eq. (8). The average compressive strength of aggregates was about 12.2 MPa [Shieh 1994]. For comparison purpose, the volume average compressive strength of the normal crushed gravel used for high-strength concrete ranged from 94 to 157 MPa using same formula [Chang 1995].

3.2 Fine aggregate, cement, admixture and steel fiber

Natural river sand with round shape and highly siliceous composition was used. The FM value of natural sand excluding the size larger than sieve #4 was 2.60. The specific gravity and moisture absorption ratio of natural sand were 2.68 and 1.75% respectively. The sand met the requirements of ASTM C-33. Type I cement meeting the requirements of ASTM C150 was used. A small dosage of Type F superplasticizer was used as an admixture to improve the properties of concrete. Steel fibers, as shown in Fig. 3, having a diameter of 0.6 mm, a length of 25 mm and hooked ends which offered strong mechanical anchorage in the concrete were used. A small amount of those steel fiber reinforcements (SF) with 1%, 2% and 3% of cement weight respectively was mixed into the concrete.

4 Experimental program

Basically, the concrete proportioning method used in this study follows similar concepts provided in the specification of ACI 221.2 standard. The materials of mix proportions for 1 m^3 concrete used in this study were: Cement = 522 kg; water = 157 kg; coarse aggregate = 586 kg; fine aggregate = 636 kg. Type F superplasticizer of 6.53 kg/m^3 was also used for all the mixes. Cylindrical concrete specimens with size of ϕ10 cm by 20 cm were used for compressive and splitting tensile tests. Beam specimen of 7.5x7.5x22.5 cm was used for the flexural test. All the concrete specimens were stored in lime water until 24 hours before they were tested. The specimen for compressive strengths were performed by a 2000 KN test machine according to ASTM C469 and C496 respectively. Specimens for flexural strength and fracture property were carried out by a 50 KN MTS machine with a close-loop-controlled stroke system. Four different sizes of SENTPB specimens (4x4x11, 4x8x21, 4x16x43 and 4x32x85 cm) were used for the fracture experiment, tested with loading at a constant strain rate of 0.1 mm/min. Typical set-up is shown Fig. 4.

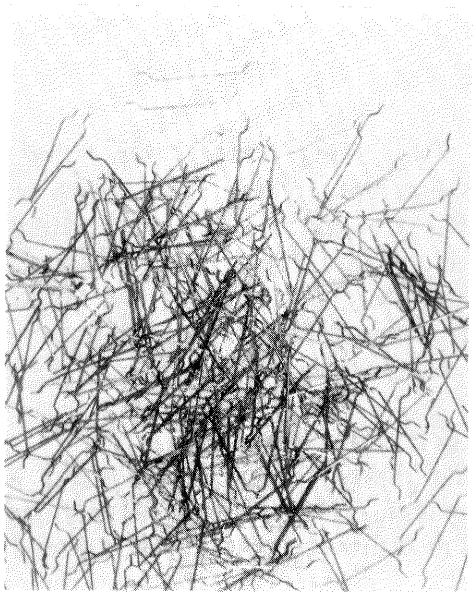

Fig. 3 Short steel fiber

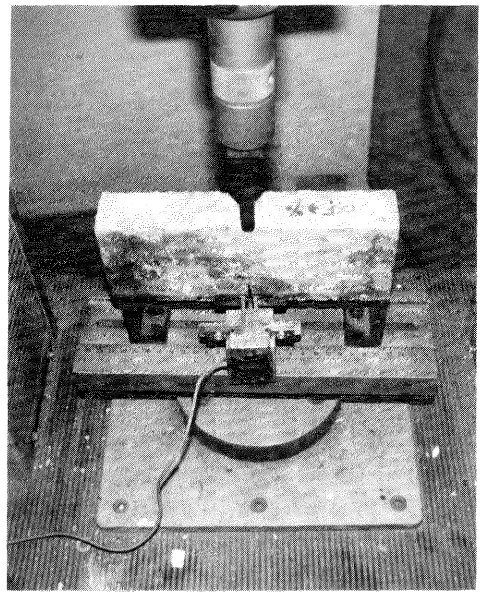

Fig. 4 Typical test set-up

5 Test results and discussions

Test results of lightweight concrete are shown in Table 1. The 28-day compressive strength ranged from 33.9 MPa (0% SF) to 37.7 MPa (3% SF). The ratio of improvement was about 11%. Increasing the steel fiber content increased the density of concrete and compressive strength, but decreased the Poisson's ratio and workability. Average value of Poisson's ratio for high-strength light-weight concrete had been reported as about 0.2 regardless of concrete strength, test age and curing condition [Slate 1986]. In this study, the Poisson's ratios ν dropped from 0.22 to 0.16, which were smaller than the values of 0.23 to 0.32 for normal-weight concrete [Slate 1986]. The reason for this could be due to the fact that the void ratio was high for fly-ash aggregate so that it was prone to having a larger deformation in axial direction under compression test. The splitting tensile strengths f_{sp} and flexural strength f_r ranged from 2.92 to 3.42 MPa and from 2.37 to 2.53 MPa respectively. Addition of steel fiber increased both strengths to 22.6% and 6.8% respectively. The ratios of splitting tensile to compressive strength and flexural to compressive strength for normal-weight concrete ranged from about 0.08 to 0.14 and about 0.11 to 0.23, respectively. For the concrete tested in this study, those ratios dropped to 0.09 and 0.07 respectively as shown in Table 1.

It is known that fiber addition greatly improves the toughness of

Table 1 Engineering properties of lightweight concrete

SF	γ_c kg/m^3	f_c' MPa	E_c GPa	f_{sp} MPa	f_r MPa	Slump cm	υ
0%	2084	33.9	22.26	2.92	2.37	14	0.22
1%	2098	34.9	22.75	3.16	2.45	13	0.20
2%	2104	35.8	23.24	3.39	2.46	11	0.19
3%	2107	37.7	23.54	3.58	2.53	8	0.16

Notes: (1) $E_c = \{3.31(f_c')^{0.5}+6.86\}(\gamma_c /2320)$ GPa; f_c' in MPa, γ_c = density of concrete; (2) All test data above were the average of three tested specimens at age of 28 days.

concrete and enhances concrete a considerable amount of ductility. Due to those properties, linear elastic fracture mechanics (LEFM) had been found to be inadequate to the fiber reinforced concrete [Rossi 1986]. Various nonlinear fracture mechanics models have been proposed to either predict the load-deflection curve or to determine the fracture energy of fiber reinforced concrete [Jenq 1986, Hillerborg 1980]. Size-effect model was used in this study for determining the fracture properties of fly-ash light-weight concrete. The fracture test results are shown in Table 2.

Table 2 Maximum loads P_{max} on SENTPB beam specimens (N)

d	P_{max} (0% SF)			P_{max} (1% SF)			P_{max} (2% SF)			P_{max} (3% SF)		
cm	#1	#2	#3	#1	#2	#3	#1	#2	#3	#1	#2	#3
4	1432	1383	1361	1353	1594	1601	1550	1594	1445	-	-	-
8	2406	2128	2273	2661	2319	2383	2868	2769	2598	2711	2810	3045
16	4994	4556	4640	5279	4606	4723	5529	5284	4674	-	4664	4964
32	6828	6755	6779	7478	6755	7147	7502	7747	7821	8846	8348	8275

During the experiment, it was observed that the failure planes for all 48 pieces of beam specimens exhibited same failure mechanism, i.e., failure planes usually cutting through the aggregates. Linear regression lines by size-effect model for both plain and fiber-reinforced lightweight concretes were shown in Fig. 5. Figs. 6 and 7 showed the relevant size-effect curves. By means of Eqs. (1) to (4) and data in Table 2, the fracture energies were found to be 37.2, 37.9, 44.4 and 62.7 N/m for lightweight concrete with SF content of 0, 1, 2 and 3% respectively. The coefficients of errors (vertical deviations from the regression line) were $\omega_{Y|X}$ = 15.3, 16.3, 11.9 and 9.3% respectively. The increase of G_f was

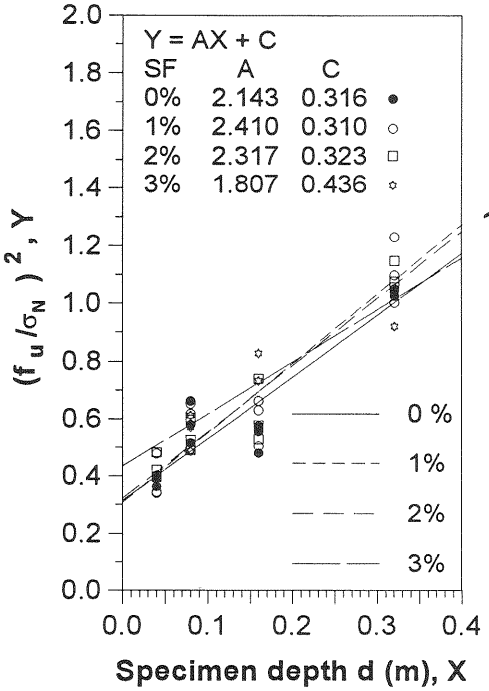

Fig. 5 Linear regression lines

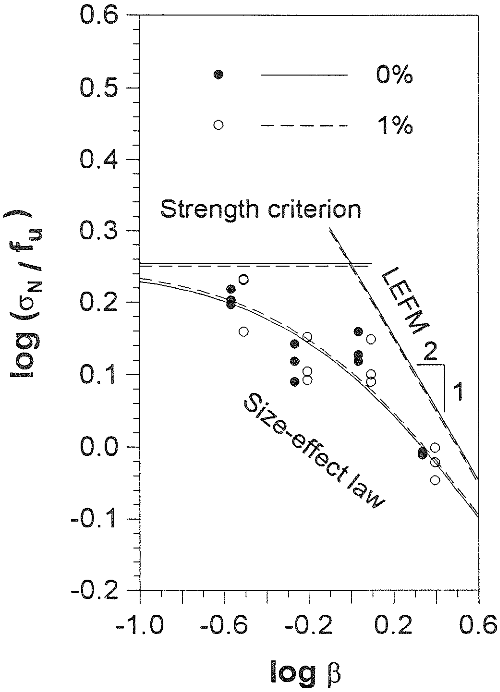

Fig. 6 Size-effect curves (1)

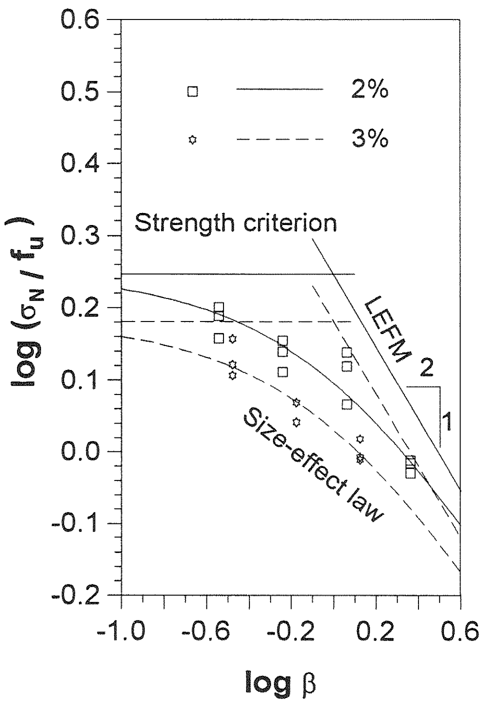

Fig. 7 Size-effect curves (2)

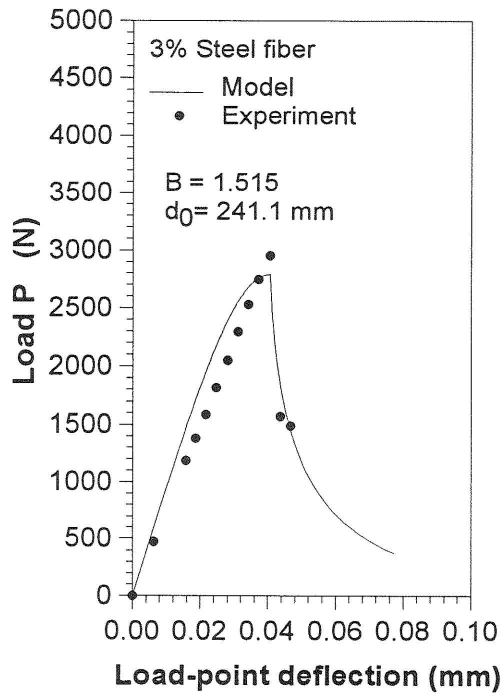

Fig. 8 Load-displacement curves

about 68.5% (3% SF). For normal strength concrete (f'_c = 34.1 MPa), the value of G_f was about 38.4 N/m, but this value was smaller for high-strength concrete [Gettu 1990]. Although the addition of steel fiber reinforcement only made a negligible variation of the compressive strength, it improved the toughness significantly. By using Eqs. (5)-(7), a typical load-point deflection for the SENTPB beam specimen was shown in Fig. 8. Young's modulus of 16.3 GPa, taken from the initial compliance of the beam specimen, and Poisson's ratio assumed to be 0.2 were used in the structural response calculation.

6 Conclusions

1. Although the size-effect law used in current study does not explicitly consider the effects of steel fiber reinforcement in its derivation, but it does provide a quantitative information on the improvement of fracture properties of fly-ash aggregate lightweight concrete resulting from various amounts of added steel fiber. For an addition of 1% steel fiber only a negligible enhancement on the compressive strength and fracture energy was observed. But if the amount of added steel fiber increased to 2 and 3%, the ratio of improvement on fracture energy had risen by 19 and 69% respectively. Such reinforcing technique is especially useful to develop structural members made of lightweight aggregates. Other fracture properties such as effective length and size of fracture process zone, and critical effective crack-tip opening displacement can also be calculated easily from the size-effect law.

2. For a constant value of G_f, the structural response calculated from R-curve values mainly depends on the fracture parameters d_0/d, $\_{0}$, etc. and the geometry and material properties of the tested specimen as implied in the original derivation. Thus the resulting load-deflection curve predicted from size effect law need to be computed individually. Once the values of those necessary parameters are defined, the R-curves can be easily used to predict satisfactory results of structural response on the lightweight concrete specimen with different amounts of added steel fiber.

Acknowledgement

The financial support from NSC83-0410-E011-028, R.O.C. is highly appreciated.

References

Bazant, Z.P. and Kazemi, M.T. (1990) Determination of fracture energy, process zone length and brittleness number from size effect, with application to rock and concrete, **Int. Journal of Fracture**, 44, 111-131.

Bijen, J.M. (1986) Manufacturing process of artificial lightweight aggregates for fly ash, **The Int. Journal of Cement Composite and Lightweight Concrete**, 8,(3), 191-199.

Chang, T.P. and Su N.K. (1995) Estimation of coarse aggregate strength in high-strength concrete", to be published in **ACI Material Journal**.

Clarke, J. L. (1993) **Structural Lightweight Aggregate Concrete**, Blackie. Academic & Professional, First Ed., Chapman & Hall.

Gettu, R., Bazant, Z.P., and Martha, E.K. (1990) Fracture properties and brittleness of high-strength concrete. **ACI Material Journal**, Nov-Dec., 608-618.

Hillerborg, A. (1980) Analysis of fracture by means of the fictitious crack model, particularly for fibre-reinforced concrete, **International Journal of Cement Composites**, 2(4), 177-184.

Jenq, Y.S. and Shah, S.P.(1986) Application of two parameter fracture model to concrete and fiber reinforced concrete, in **Fracture Toughness and Fracture Energy of Concrete**,(ed. F. H. Wittmann), Elsevier, 499-511.

RILEM Draft Recommendation (1990) Size-effect method for determining fracture energy and process zone size of concrete, **Materials and Structures**, 23, 461-465.

Rossi, P. et al. (1986) Comparison between plain concrete toughness and steel fibre reinforced concrete toughness. **Cement and Concrete Research**, 16(3), 303-313.

Shieh, M.M. (1994) Effects of fiber reinforcement on engineering properties of lightweight concrete, Master Thesis, National Taiwan Institute of Technology, Taiwan (in Chinese).

Slate, F.O., Nilson, A.H. and Marthinez, S. (1986) Mechanical properties of high-strength light-weight concrete. **ACI Journal**, 61-68.

Swamy, R.N. and Barr, B. (1989) **Fiber Reinforced Cements and Concretes: Recent Developments**. Elsevier Science Publishers Ltd.