Pergamon

Cement and Concrete Research, Vol. 26, No. 2, pp. 181-188, 1996

0008-8846/96 $15.00 + .00

SSDI 0008-8846(95)00198-0

COMMUNICATED PAPERS

FRACTURE PROPERTIES OF LIGHTWEIGHT CONCRETE

Ta-Peng Chang
Assoc. Prof., Department of Construction Engineering
National Taiwan Institute of Technology, Taipei, Taiwan, R.O.C.

Mei-Miao Shieh
Lecturer, Taiwan Provincial Hsiu-Shui Vocational School, Chang-Hua, Taiwan, R.O.C.

(Communicated by Z.P. Bazant)
(Received November 6, 1995; in final form November 27, 1995)

ABSTRACT

This study presents the experimental results of fracture properties of concrete incorporating two kinds of domestic lightweight aggregate (LWA) manufactured through either a cold-bonding or a sintering process. The cold-bonded aggregates were mainly made of pulverized fly-ash through a cold-pelletization process at ambient temperature, while the sintered aggregates were made of clay and shale expanded by heat at a temperature near 1200°C. Experimental results show that the 28-day compressive strengths of $\phi 100 \times 200$ mm cylindrical concrete specimen made of those LWAs range from 30.1 (sintered) to 33.9 MPa (cold-bonded). By means of size effect law, it is found that the fracture energies, G_f, were 34.42 N/m (sintered) and 37.2 N/m (cold-bonded), respectively.

Introduction

Research on using the lightweight aggregate to produce high-strength structural concrete as a material of construction has always been an important field in concrete technology. Obviously, it has economical and technical advantages over ordinary concrete, such as construction saving due to the reduction of dead weight, lower handling cost, etc. This paper first presents the characteristics of two kinds of artificial lightweight aggregates. One is mainly made of fly ash, by-products of fossil power plant, through a cold-pelletizing process. The other is made of clay and shale by a sintering process at a temperature in the range of 1000 to 1200°C. From ecological considerations, the cold-bonding manufacturing process of making fly-ash aggregates can provide a relatively inexpensive way of proper disposal of industrial waste and consumes much less energy. On the other hand, the sintering process to manufacture the lightweight aggregates such as expanded clays and shales has been used for many decades [1,2]. In this study, concretes incorporating either type of lightweight aggregate, as shown in Figs. 1 and 2, can have a 28-day compressive strength beyond 30 MPa [3]. Since the compressive strength of lightweight concrete larger than 15 MPa is considered to be the structural concrete

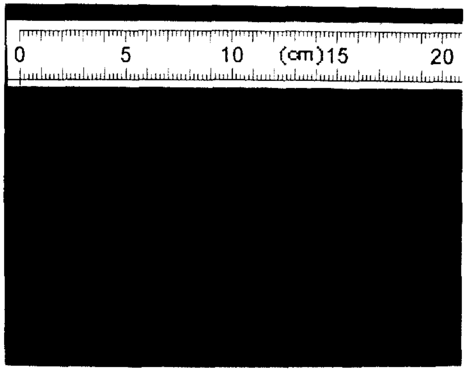

FIG. 1.
Cold-bonded LWA.

by RILEM/CEB [2], an understanding of the fracture properties for those two kinds of LWA concrete appears to be useful and important to their applications. Here, the well-known size-effect law [4-8] is used to investigate the relevant fracture properties of the LWA concrete.

Theoretical Background of Size-Effect Law

Based on size-effect law, the fracture energy G_f for the single-edge-notched three-point-bend (SEN-TPB) beam specimens, as shown in Fig. 3, can be calculated as follows [4-8]

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

where $E' = E$ (plane stress); $E' = E/(1-\nu^2)$ (plane strain); E = Young's modulus; ν = Poisson's ratio; $\alpha_0 = a_0/d = 1/6$; a_0 = length of notch; d = height of specimen; f_u = tensile strength; $c_n = (1.5\ell)/[d(1-\alpha_0)^2)$; ℓ = span; d_0 and B are two constants to be determined; $\alpha = a/d$; a = crack length; and $g(\alpha)$ is the shape factor which is given by

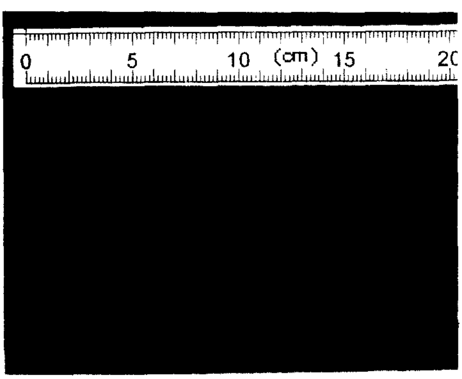

FIG. 2.
Sintered LWA.

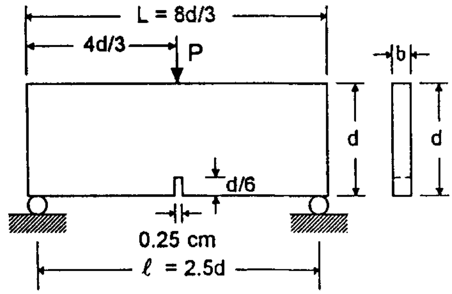

FIG. 3.
Geometry of SEN-TPB specimen.

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

The values of B and d_0 in Eq. (1) are calculated from the maximum failure load P_{max}, tensile strength f_u and nominal stress σ_N through the following linear regression equation

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

in which

$$X = d,\ Y = (\frac{f_u}{\sigma_N})^2,\ \sigma_N = c_n \frac{P_{max}}{bd},\ B = \frac{1}{\sqrt{C}},\ d_0 = \frac{C}{A} \tag{4}$$

and b = thickness. Other fracture parameters such as the effective length of fracture process zone, c_f, the critical effective crack-tip opening displacement, δ_{ef}, the fracture toughness, K_{IC}, and the size of fracture process zone, ℓ_0, can also expressed as

$$K_{IC} = \frac{Bf_u}{c_n}\sqrt{d_0 g(\alpha_0)};\ c_f = \frac{d_0 g(\alpha_0)}{g'(\alpha_0)};\ \delta_{ef} = \frac{8K_{IC}}{E'}\sqrt{\frac{c_f}{2\pi}};\ l_o = \left[\frac{K_{IC}}{f_u}\right]^2 \tag{5}$$

The fracture properties determined by Eqs. (2) to (5) represent values which are only valid for laboratory specimens or structures of sufficiently large sizes. With this understanding, they can be assumed to be the material properties independent of the test method, specimen size, specimen geometry, etc.

Experimental Materials

Coarse Lightweight Aggregate. Two kinds of lightweight aggregates, as shown in Figs. 1 and 2, were used in this study. The cold-bonded aggregate was made of the mix compound of slurry

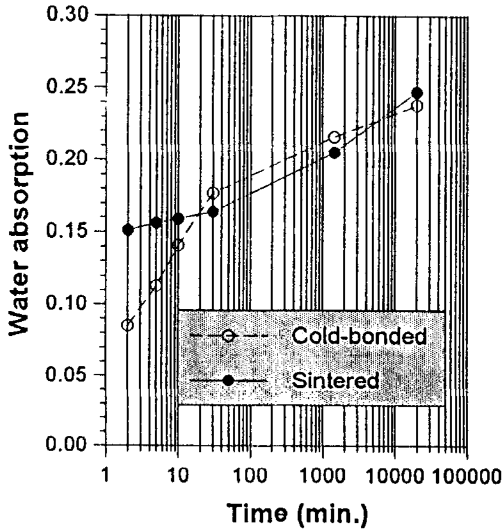

FIG. 4.
Moist absorption of LWA.

ash, fly ash (passing through sieve #4), cement (Type I) and hydrated lime [3]. Water was the wetting agent acting as coagulant such that the wet mixture would be pelletized through the rolling motion in a tilted pan. The sintered aggregate was made of clay and shale expanded at high temperature. Only aggregates passing through sieve #1/2" (12.7 mm) and retained at sieve #4 (4.75 mm) were selected as the coarse aggregates. The experimental results showed that the OD specific gravities for both aggregates were about 1.33. The average moisture absorption of the porous aggregate was measured at intervals of 2, 5, 10, 30 minutes, 24 hours and 14 days. The results are shown in Fig. 4. The maximum absorptions of 23.8% (cold-bonded) and 24.7% (sintered), respectively, indicate a large portion of open voids at the interior for both aggregates. Therefore, the aggregates were submerged in water for about 30 minutes before their mixing into concrete. The volumetric average compressive strengths of aggregate were found to be 13.41 MPa (cold-bonded) and 17.54 MPa (sintered), respectively [3]. For comparison purpose, the volumetric average compressive strength of the normal crushed gravel used for high-strength concrete ranged from 94 to 157 MPa using same formula [9].

Fine Aggregate, Cement and Admixture. 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.

Experimental Program

The mix proportions for 1 m^3 of concrete used in this study were: Cement: 522 kg; water: 157 kg; coarse aggregate: 586 kg and fine aggregate: 636 kg. Type F superplasticizer: 6.53 kg/m^3, was also used for all the mixes. Cylindrical concrete specimens of diameter 10 cm and length 20 cm were used for compressive and splitting tensile tests. Beam specimens of 7.5×7.5×22.5 cm were used for the flexural tests. All the concrete specimens were stored in lime water until 24 hours before they were tested. The tests of specimens for compressive and splitting tensile strengths were performed by a 2000 kN test machine according to ASTM C469 and C496, respectively. The tests of specimens for both flexural strength and fracture properties were carried out in a 50 kN MTS machine with a closed-loop-controlled stroke system. Four different sizes of SEN-TPB specimens (4×4×11, 4×8×21, 4×16×43 and 4×32×85 cm) were used for the fracture experiments, and were tested with loading at a constant strain rate of 0.1 mm/min. The typical test setup is shown in Fig. 5.

Test Results and Discussion

The test results for the engineering properties of LWA concretes in this study are shown in Table 1. The unit weights of fresh LWA concretes are about 85% of those for normal weight concrete. The 28-day compressive strengths are 33.9 MPa (cold-bonded) and 30.1 MPa (sintered), respectively. Poisson's ratios of 0.21 and 0.22 are close to those for other similar high-strength lightweight concretes [10]. The ratio of the splitting tensile strength, f_{sp}, to the compressive strength, f'_c, ranges between 0.09 and 0.11, and the ratio of the flexural strength, f_r, to the compressive strength, f'_c, between 0.07 and 0.08. These values are smaller than those for normal-weight concrete [11]. Therefore, the addition of fibers to the LWA concrete could be useful to improve its toughness and ductility.

Notes: (1) $E_c = \{3.31(f_c')^{0.5}+6.86\}(\gamma_c/2320)$ GPa, f_c' in MPa, γ_c = unit weight of concrete, kg/m^3; E_d = Dynamic Young's modulus measured by resonant frequency measure; (2) All the foregoing test data are the average of three tested specimens at age of 28 days.

The test results and the fracture parameters calculated from the size-effect law are shown in Table 2. During the experiment, it was observed that the failure planes for all 24 beam specimens exhibited the same failure mechanism, i.e., the failure planes usually running through the aggregates, as shown in Fig. 6. Linear regression lines and size-effect curves derived by size-effect model for both lightweight concretes are shown in Figs. 7 and 8. Note that, in order to separate two size-effect curves, the ordinate in Fig. 8 is plotted based on the values of σ_N/f_u rather than the normalized values of $\sigma_N/(Bf_u)$. By means of Eqs. (1) to (5) and using the data in Table 2, it was found that the fracture energies G_f were 37.2 and 34.42 N/m, respectively. The coefficients of errors (vertical deviations from the regression line) were $\omega_{Y|X}$ = 15.3% (cold-bonded) and 11.8% (sintered) respectively. The difference in G_f was about 8%. For normalstrength concrete (28-day 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 [5].

TABLE 1

Engineering Properties of Lightweight Concrete

Aggregrate type	γ_c kg/m^3	f_c' MPa	f_r MPa	f_{sp} MPa	E_c GPa	E_d GPa	Slump cm	ν
Cold-bonded	2084	33.9	2.37	2.92	22.3	22.2	14	0.22
Sintered	2017	30.1	2.45	3.16	19.7	21.3	13	0.21

TABLE 2

Maximum Loads P_{max} on SEN-TPB Beam Specimens and Fracture Parameters for Two Kinds of LWAs

Aggregate type	d (cm)	P_{max} (N) #1	#2	#3	c_f (mm)	ℓ_0 (mm)	δ_{cf} (10^{-3}) (mm)	K_{IC} (MPa $m^{0.5}$)	G_f (N/m)
Cold-bonded	4	1432	1383	1361					
	8	2406	2128	2273					
	16	4994	4556	4640	25.42	97.11	0.021	0.91	37.20
	32	6828	6755	6779					
Sintered	4	1804	1758	1729					
	8	2716	3021	2534					
	16	4245	4693	4920	10.44	65.83	0.014	0.82	34.42
	32	6816	7071	—					

Conclusions

From the experimental results obtained in this study, the following conclusions can be drawn:

1. The size effect curves show that the fracture behavior of concrete incorporating sintered lightweight aggregate approaches the straight line representing linear elastic fracture mechanics (LEFM). Thus, it may be assumed that its fracture characteristics follow LEFM closer than do those for cold-bonded aggregates.

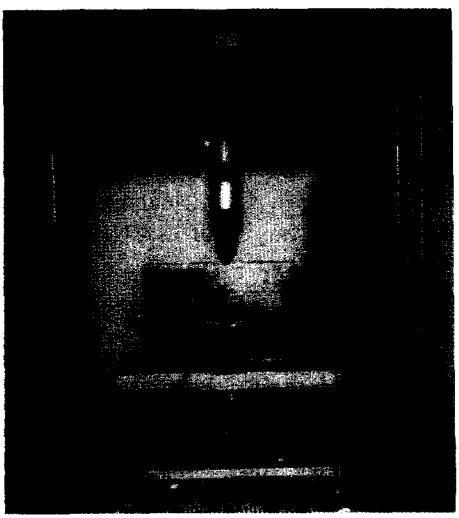

FIG. 5.
Typical test setup.

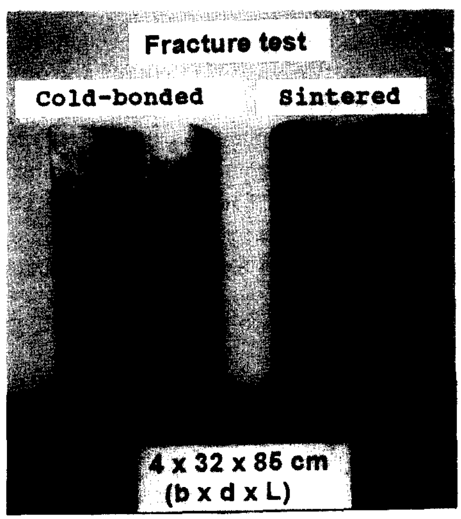

FIG. 6.
Fracture surfaces.

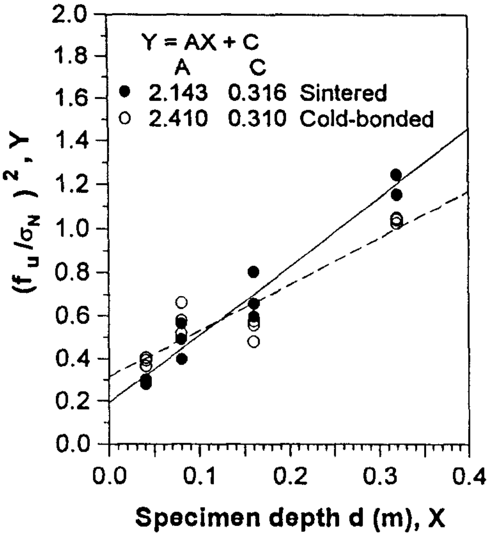

FIG. 7
Linear regression lines.

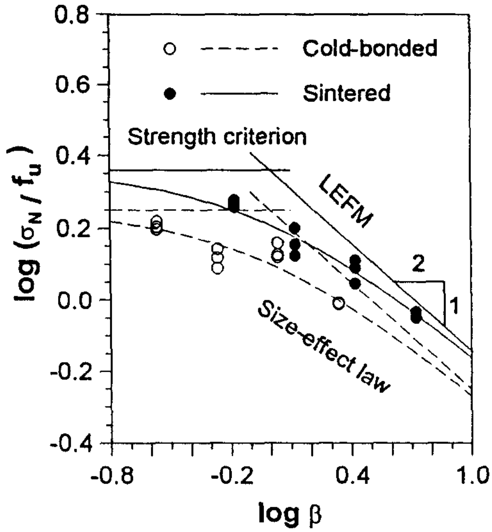

FIG. 8
Size-effect curves.

2. The effects of lightweight aggregate types on G_f in the concrete were not well recognized. The measured values of G_f were in the range between 34.42 and 37.20 N/m, which is similar to the range for normal concrete of similar strength [5,8].

Acknowledgement

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

References

1. Shoat, A. and W. Kinniburgh, "Lightweight Concrete," Applied Science Published Ltd., Third Ed, 1978.
2. Clarke, J. L., "Structural Lightweight Aggregate Concrete," Blackie Academic & Professional, First Ed., Chapman & Hall, 1993.
3. Shieh, Mei-Miao, "Effects of Fiber Reinforcement on Engineering Properties of Lightweight Concrete," Master Thesis, National Taiwan Institute of Technology, Taiwan, 1994. (in Chinese).
4. Bazant, Z. P. and M. T. Kazemi, "Determination of Fracture Energy, Process Zone Length and Brittleness Number form Size Effect, with Application to Rock and Concrete," Int. J. of Fracture, V44., pp. 111-131, 1990.
5. Gettu, R., Z. P. Bazant and E. K. Martha, "Fracture Properties and Brittleness of High-Strength Concrete," ACI Material Journal, pp. 608-618, Nov-Dec., 1990.
6. "Size-effect Method for Determining Fracture Energy and Process Zone Size of Concrete," RILEM Draft Recommendations, Materials and Structures, 23, pp. 461-465, 1990.
7. Bazant, Z. P. and M. T. Kazemi, "Determination of Fracture Energy, Process Zone Length and Brittleness Number from size Effect, with Application to Rock and Concrete," International Journal of Fracture, V. 44, pp. 111-131, 1990.
8. Bazant, Z. P. and P. A. Pfeiffer, "Determination of Fracture Energy from Size Effect and Brittleness

Number," ACI Materials Journal, pp. 463-480, Nov.-Dec. 1987.
9. Chang, T. P. and N. K. Su, "Estimation of Coarse Aggregate Strength in High-Strength Concrete", to be appeared in ACI Material Journal.
10. Slate, F. O., A. H. Nilson and S. Marthinez, "Mechanical Properties of High-Strength Light-Weight Concrete", ACI Journal, pp. 61-68, 1986.
11. Mindess, S. and J. F. Young, "Concrete", Prentice-Hall, Inc., pp. 398-400, 1981.