Construction and Building Materials 69 (2014) 381–389

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Influence of fiber reinforcement on strength and toughness of all-lightweight concrete

Jisun Choi [a], Goangseup Zi [a,*], Shinichi Hino [b], Kohei Yamaguchi [b], Soye Kim [a]

[a] *Department of Civil, Environmental and Architectural Engineering, Korea University, 1, 5-ga, Anam-dong, Seongbuk-gu, Seoul 136-713, Republic of Korea*
[b] *Department of Urban and Environmental Engineering, Kyushu University, 744, Motooka, Nishi-ku, Fukuoka 819-0395, Japan*

HIGHLIGHTS

- Steel, vinylon and polyethylene fibers were applied to an all-lightweight concrete.
- All the fibers are very effective to increase the flexural strength.
- The fracture toughness of the concrete was improved significantly with steel fibers.

ARTICLE INFO

Article history:
Received 6 February 2014
Received in revised form 19 June 2014
Accepted 23 July 2014
Available online 15 August 2014

Keywords:
All-lightweight concrete
Artificial lightweight aggregate
Fiber reinforcement
Strength
Toughness

ABSTRACT

The effect of fiber reinforcement on all-lightweight concrete in which both fine and coarse aggregates are artificially lightweight was investigated experimentally. Three different fibers (i.e., steel, vinylon and polyethylene) were compared for their effects on the compressive strength, splitting tensile strength, flexural strength, shear strength, and toughness. Normal concrete with the same compressive strength as the all-lightweight concrete was prepared as a reference. Using 1.5% vinylon fibers significantly improved the flexural strength of the all-lightweight concrete 234% higher than that of normal concrete. Using 1.2% steel fiber increased the fracture toughness of the all-lightweight concrete more than twelve times.

1. Introduction

Lightweight materials, such as lightweight aggregate concrete, can increase economic efficiency by reducing the self-weight and dimensions of the structure. In addition, the use of artificial aggregates is becoming necessary because of the exhaustion of natural aggregates and environmental sustainability issues. Many studies have examined the strength [1–3] and shear behavior of lightweight aggregate concretes for their application in the construction field [4,5].

The fracture of lightweight concrete is characterized by cracks going through artificial aggregates, which makes it more brittle than normal concrete. Especially, lightweight concrete has significantly lower fracture toughness and the tensile strength than normal concrete [6–10].

Various short fibers are often used to reduce the brittleness of lightweight concrete. Many researchers have investigated lightweight concrete containing 0.25–2.0% fiber [1,7,8,11–22]. For instance, steel fibers have been found to increases the splitting tensile strength by 16–118%. Polypropylene fibers have been found to double the splitting tensile strength of concrete [8]. Other fibers also positively influence the splitting tensile strength. In addition, the flexural strength and toughness can also be improved by the use of fibers: adding about 1.0% steel fiber increases the flexural strength and toughness of concrete by around 30% and 135%, respectively [12,14].

The mass density of lightweight concretes can be tailored by changing the weight ratio of artificial lightweight aggregates. When the coarse aggregates of concrete are artificial lightweight, the mass density is around 2.0 g/cm^3. This concrete is called sand-lightweight concretes. If the fine aggregates are also artificial lightweight, the mass density becomes around 1.6 g/cm^3, and the concrete is called all-lightweight concretes [23,24]. Most studies on lightweight concretes with fibers have been on sand-lightweight concrete [1,7,8,11–22]. Only few studies have considered all-lightweight concrete with fibers [10,25,26].

In this study, the main objective is to determine the improvement in strength and toughness of an all-lightweight concrete through the addition of three different types of commonly used

---

* Corresponding author. Tel.: +82 2 3290 3324; fax: +82 2 928 7656.
E-mail address: g-zi@korea.ac.kr (G. Zi).

http://dx.doi.org/10.1016/j.conbuildmat.2014.07.074
0950-0618/

short fibers: steel (ST), vinylon (V), and polyethylene (PE). Section 2 describes the materials, mix proportions and test methods. Section 3 presents the experimental data on the strength and toughness improvement through a comparison with normal concrete. Section 4 presents the conclusions.

2. Experimental details

2.1. Materials

Table 1 lists the properties of the cement and aggregates used in this study. The cement was ordinary Portland cement. Both the coarse and fine aggregates were 100% artificial, as shown in Fig. 1. The artificial lightweight aggregates were Asanolite aggregates made from expanded shale. These aggregates were fired at a high temperature after being crushed and sieved to obtain the proper grain sizes. Fig. 2 shows the grain size distributions of the normal and lightweight aggregates, which were almost the same. The maximum size of the lightweight aggregates was 15 mm, and the maximum size of the normal aggregates was 20 mm.

Fig. 3 shows the ST, V, PE fibers used in this study. Table 2 lists the fiber properties provided by the manufacturers. The mass density of ST fibers was much higher than the others. These three types of fibers were 30 mm in length and 0.6–0.7 mm in diameter. The ends of the ST fibers were hooked, whereas the V and PE fibers were straight and yarned, respectively. The PE fibers had a higher tensile strength than the others. The ST fibers had a higher elastic modulus than the others.

2.2. Mix proportions

Table 3 lists the mix proportions of the concretes specimens. To investigate the effect of the three types of fibers on the all-lightweight (AL) and normal (N) concrete, three mixtures with various fiber volume ratios of ST, V, and PE fibers were prepared. The number next to the hyphen in the table represents the fiber content. For instance, 05 means 0.5% fiber. The volume of ST fiber was varied between 0% and 1.2% of concrete in increments of 0.4% because of concerns over workability. The volumes of V and PE fibers were varied between 0% and 1.5% of concrete in increments of 0.5%. For the comparison, the compressive strength, air content, and slump of the mix design were fixed. The target compressive strength of the concrete after 28 days of air curing was 40 MPa. The air content was 5.0 ± 1.5% in the AL concrete, and 4.5 ± 1.5% in the N concrete. The slump was 180 ± 20 mm in both types of concrete. A superplasticizer was added to obtain sufficient fluidity in the fiber-reinforced lightweight concrete mixtures.

Table 1
Properties of cement and aggregates.

Material type	Property
Ordinary Portland cement	Density: 3.16 t/m^3
Normal fine aggregate	Surface-dry density: 2.58 t/m^3 Water-absorbing ratio: 1.79% Fineness modulus: 2.71
Normal coarse aggregate	Surface-dry density: 2.88 t/m^3 Water-absorbing ratio: 1.92% G_{max}: 20 mm
Artificial lightweight fine aggregate	Density: 1.68 t/m^3 Water-absorbing ratio: 10.0%
Artificial lightweight coarse aggregate	Density: 1.27 t/m^3 Water-absorbing ratio: 10.3% G_{max}: 15 mm
High-performance AE water-reducing admixture	Density: 1.05–1.09 t/m^3
AE auxiliaries	Density: 1.06–1.10 t/m^3

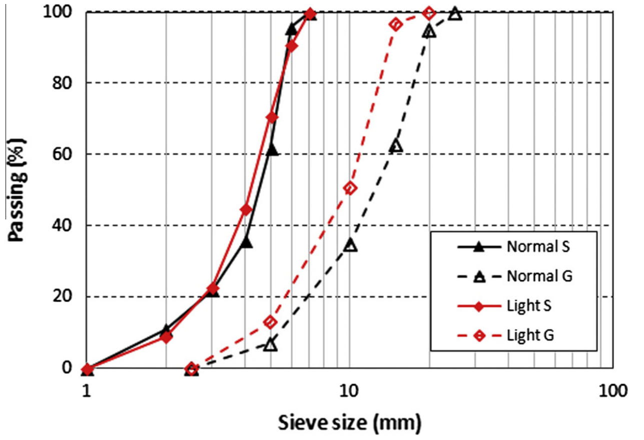

Fig. 2. Grain size distributions of normal and all-lightweight concrete aggregates.

2.3. Test methods

2.3.1. Strengths

The compressive, splitting tensile, flexural, and shear strengths were measured after 28 days. The compressive strength f_c was measured by using standard $\varnothing$100 mm × 200 mm cylinders [27,28]. Two different test methods were adopted to measure the tensile strength: the splitting tensile test by using the $\varnothing$100 mm × 200 mm cylinders [29,30] and the four-point bending test by using 100 mm × 100 mm × 400 mm beam specimens [31,32].

Fig. 4 shows the load–displacement relation of specimen N-ST-08 subjected to the splitting tensile test. The specimen had a fiber content of 0.8%. The figure shows two peaks in the load–displacement curve. The first peak was due to the fracture of the concrete matrix. After the first peak, the load increased further to the second peak because of the bridging mechanism of the fibers. In this study, the second peak was defined as the splitting tensile strength f_t.

The flexural strength f_b was measured by using the standard four-point bending test. The specimens were simply supported on two rollers. The load was applied to the specimen at the two load points on top of the specimen. Three beams were used to measure the flexural strength. The flexural strength was obtained from the maximum load applied to the specimen.

The effect of the fibers on the shear strength was studied. Fig. 5 shows the direct shear test proposed by JSCE [33] for which the same standard 100 mm × 100 mm × 400 mm specimen in the four-point bending test can be used. The concrete is under direct shear from the loading plate and the support. The maximum load divided by the shear area is the shear strength f_{cv}. The ASTM standard has not yet recommended a standard test for the direct shear strength of concrete.

2.3.2. Fracture toughness

If the damage is localized to a macroscopic crack, most of the energy dissipation is due to crack growth; this is the case for concrete without fibers. Then, the fracture energy can be calculated by the work of fracture method, where the fracture energy is the total amount of external work divided by the fracture area. However, the fracture of fiber reinforced concretes is different; numerous microscopic cracks develop

(a) (b)

Fig. 1. Artificial lightweight aggregates: (a) coarse aggregates and (b) fine aggregates.