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Cement and Concrete Research 35 (2005) 913–917

Cement and Concrete Research

Contribution of hybrid fibers on the properties of the high-strength lightweight concrete having good workability

Bing Chen[a,*], Juanyu Liu[b]

[a]Department of Civil Engineering, Shanghai Jiaotong University, Shanghai, 200240, P.R. China
[b]Department of Civil Engineering, Texas A&M University, College Station, TX 77843, USA

Received 26 February 2004; accepted 22 July 2004

Abstract

The contribution of hybrid fibers to the workability, mechanical and shrinkage properties of lightweight concrete (LWC) with high strength and workability was investigated. The results show that adding fiber to the lightweight concrete mixture greatly reduces the sedimentation of aggregates during mixing and improves the uniformity of the mix; however, the slump value is reduced. Compared with single type of fibers, hybrid fibers significantly improve the mechanical properties and brittleness of lightweight concrete, and restrain the long-term shrinkage.

Keywords: Lightweight concrete; Hybrid; Fiber; Toughness; Shrinkage

1. Introduction

Recently, with the rapid development of very tall buildings, larger-sized and long-span concrete structures, the requirements for better concrete performance are higher strength, light weight, higher toughness and others. Therefore, lightweight concrete (LWC) has been used for structural purposes for several years [1–6]. The density of LWC typically ranges from 1400 to 2000 kg/m^3 compared with that of 2400 kg/m^3 for normal-weight concrete (NWC). The use of high-strength LWC can reduce the self-weight of structures and cross-sectional areas of structural elements. However, LWC can be considered as a brittle material. The higher the compressive strength is, the higher the brittleness is. Therefore, improving the brittleness is the key point to popularize the application of LWC. It is well known that normal concrete reinforced with less than 2% of volume content of steel fibers provides better properties compared to normal concrete, especially the improvement of toughness. The research on adding steel fibers in lightweight concrete have been reported [7]. For example, Odorakopoulos and Swamy are among the very few who reported on sintered fly ash aggregate high-strength concrete with steel-fiber reinforcement. They have presented results on the mechanical properties and have highlighted the benefits of including the fibers, especially the improvement in ductility. Nevertheless, in spite of the advantages that have been reported in this area, much more research is still needed. This is especially so because the variability in the characteristics of the lightweight aggregates used. Added to that is the diversity of the types of fibers and the various choices that are available within each type [3].

Due to the light weight and inner voids, lightweight aggregates can easily absorb water and float during the mixing, which deteriorates the workability of the mixture. Fibers form a network structure in the mixture, which can effectively restrain the segregation of lightweight aggregates. Hence, the research focus of this study is the effects of different fibers on workability, mechanical properties and shrinkage of LWC.

* Corresponding author. Tel.: +86 21 5474 4255; fax: +86 21 5474 4255.
E-mail address: hntchen@sjtu.edu.cn (B. Chen).

0008-8846/$ - see front matter
doi:10.1016/j.cemconres.2004.07.035

2. Experimental study

2.1. Materials used

ASTM Type I ordinary Portland cement with 28 days compressive strength of 57.8 MPa was used for all concrete mixtures. The chemical composition of the cement used is given in Table 1. The silica fume used was a dry uncompacted powder from Elkem Materials with SiO_2 content of 92.4%. The amount retained on a 45-μm sieve was 1.6%. Detailed chemical composition is given in Table 1. The lightweight aggregate used in this study was expanded clay manufactured commercially. The particle density of the dry aggregate was 1.46 g/cm^3, and the bulk density was 700±25 kg/m^3. The particle size ranges from 5 to 15 mm with a round but irregular shape. The aggregate had water absorption of 6%, 9% and 10% at 1 h, 24 h and 7 days, respectively. Medium sand with a fineness modulus of 2.80 and an apparent specific gravity of 2.64 g/cm^3 was used. A naphthalene-based superplasticizer was used. Three types of fibers were used, steel fibers, carbon fiber and polypropylene (PP) fibers, and their properties are listed in Table 2.

2.2. Mix proportions

The mix proportions used in this study are shown in Table 3. The volume fractions of fibers in concrete were 1.0%. All mixes had 1.5% of superplasticizer by weight of cement.

2.3. Test methods

Before mixing, the moisture content of the LWA was measured. The total water in the mix was the water of mix proportion and the water absorbed by aggregate within 24 h. The mixing procedure was the following: cement, silica fume and sand were added first, then mixed for 15 s; premixed water with superplasticizer was introduced and homogenized for 100 s; after LWA was introduced and mixing for 60 s, thereafter mixing was stopped for 30 s to allow the superplasticizer to initiate. The mixtures without fibers were mixed for a further 30 s, in case of a fiber addition, the further mixing time at this stage was 90 s. Before casting the samples, the slump and slump flow tests of the mixture were performed. The "slump flow" is the average diameter of the horizontal flow (the largest diameter and the one orthogonal to this) after lifting Abrams' cone [8].

A number of standard test specimens of different sizes were cast for investigating the various parameters. One-hundred-fifty-millimeter cubes were used for studying the compressive strength at 28 days. Split tensile strength test was conducted on 100-mm cubes. Prisms of 100×100×515 mm were used for shrinkage testing. The shrinkage was measured at 3, 7, 14, 28, 60 and 90 days.

The specimens were stripped approximately 24 h after casting and placed in a fog room (95±3% RH, 22±2 °C). For shrinkage testing, after the specimens were cured in the fog room for 23.5±0.5 h, the specimens were demolded and stored in a control room maintained at 20±3 °C, RH>60% and immediately measured to get initial values. The specimens were kept in the control room for subsequent readings. The shrinkage strain was calculated according to ASTM C490-93a. Compressive strength test was carried out in a testing machine of 2000-kN capacity at a loading rate of 2.5 kN/s. The split tensile strength test was conducted on cubes at 28 days according to ASTM C 496-89. The four-point loading flexural tests were carried out at a loading rate of 0.05 mm/min on the 100×100×515 mm beams according to the requirements of ASTM C 1018.

Table 1
Chemical composition of cementitious materials

	OPC	Condensed silica fume
Chemical composition (%)		
Silicon dioxide (SiO_2)	21.6	92.4
Aluminum oxide (Al_2O_3)	4.13	0.80
Ferric oxide (Fe_2O_3)	4.57	0.50
Calcium oxide (CaO)	64.44	0.91
Magnesium oxide (MgO)	1.06	0.27
Sodium oxide (Na_2O)	0.11	–
Potassium oxide (K_2O)	0.56	–
Sulfur trioxide (SO_3)	1.74	–
Loss on ignition	0.76	2.0

Table 2
Properties of fibers

	Carbon	Steel	PP
Length (mm)	5	25	15
Diameter (um)	7	500	100
Shape	Straight, round	Crimped	Straight, round
Density (g/cm^3)	1.6	7.8	0.9
Modulus (Gpa)	240	200	8
Elongation at break (%)	1.4	3.2	8.1
Tensile strength (MPa)	2500	1500	800

Table 3
Mix proportions (kg/m^3)

Series	Cement	Water	Sand	LWA	Silica fume	Fiber volume fraction (%)		
						Carbon	Steel	PP
HSLC	500	165	540	575	50	–	–	–
HSLC-C	500	165	540	575	50	1.0	–	–
HSLC-S	500	165	540	575	50	–	1.0	–
HSLC-P	500	165	540	575	50	–	–	1.0
HSLC-C–S	500	165	540	575	50	0.5	0.5	–
HSLC-C–P	500	165	540	575	50	0.5	–	0.5
HSLC-S–P	500	165	540	575	50	–	0.5	0.5

3. Results and discussion

All test results are summarized in Table 4, and graphical representations of the results are presented in Fig. 3.

3.1. Workability

Fibers can form a network structure in concrete, which can effectively restrain the segregation of lightweight aggregates. Due to larger surface area than aggregates, fibers need to adsorb a lot of cement paste to wrap around, which increases the viscosity of the mixture. Fig. 3 shows that at 1% of volume content, different types of fibers have different effects on the slump and expansion of the mixture. Polypropylene (PP) fiber showed the lowest effect, which reduced the slump by 20.8%, while steel fibers showed the highest, which reduced the slump by 54.2%. In addition, fibers affected the slump flow more significantly than the slump. It is mainly because of the 'holding' effect of fibers distributed uniformly in concrete, which reduces the surface bleeding of concrete and the sedimentation of the aggregates, and improved the viscosity of the concrete.

Significant differences existed in the loss of the slump flow and slump with time for different types of fibers. The slump loss was small in the concrete without fibers, and the slump value was 180 mm 30 min after casting. For fiber concretes, the slump of the concretes with PP fibers and carbon fibers was 140 mm; however, the concrete with steel fiber has only 30 mm slump value.

3.2. Compressive and split tensile strength

From Table 4, when one single type of fibers was used, the increase of the compressive strength of the LWC with carbon fibers was up to 10% compared with the reference concrete; PP fibers caused a decrease of compressive strength. For those concretes with hybrid fibers, the strength increased at different degrees and the order of increase was:

$$\text{Carbon} - \text{steel fibers } (27.6\%) > \text{C} - \text{P} - \text{S } (24.3\%) > \text{S} - \text{P } (19.7\%)$$

For the split tensile strength, the concretes with carbon or steel fibers also had great improvement, and that with steel

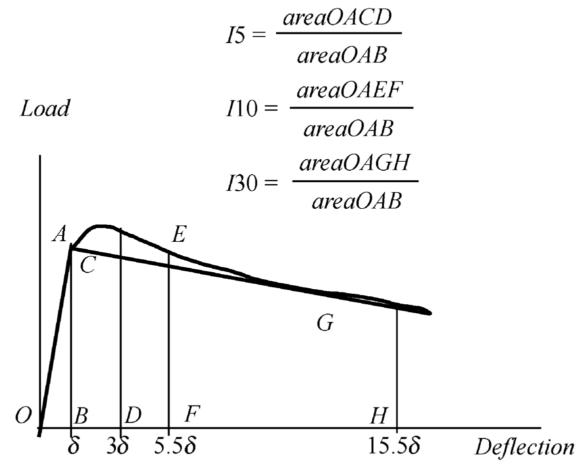

Fig. 1. Definition of toughness indices according to the testing method ASTM C1018 (1989).

fibers showed the highest split tensile strength. However, same as the result for compressive strength, PP fibers resulted in a little decrease of the split tensile strength. For those concretes with hybrid fibers, similar to the compressive strength, the split tensile strength increased and the order of increase was:

$$\text{Carbon} - \text{steel fibers } (38.3\%) > \text{C} - \text{P} - \text{S } (27.2\%) > \text{S} - \text{P } (11.3\%)$$

The positive effects of hybrid fibers on the compressive and split tensile strengths may be due to the fact that hybrid fibers with different sizes and types offer differing restraint.

3.3. Toughness index

Toughness is generally defined as energy adsorption capacity. There are a number of different standards for measuring toughness of fiber-reinforced concrete, such as ASTM C1018. The schematic illustration of the method and calculations is shown in Fig. 1. The indices I_5, I_{10} and I_{30} are calculated as ratios of the area under the load–deflection curve up to 3, 5.5 and 15.5 times the first crack deflection, divided by the area up to the first crack deflection, respectively. The toughness indices for different mixes in four-point bending tests are given in Table 4. The

Table 4
Test results of lightweight aggregate concrete

Series	Slump (mm)			Slump flow (mm)			Toughness index			Compressive strength (MPa)	Splitting tensile strength (MPa)
	0	30 min	60 min	0	30 min	60 min	I_5	I_{10}	I_{30}		
HSLC	240	180	110	540	460	300	3.13	6.10	9.82	45.5	4.40
HSLC-C	180	140	40	450	330	–	4.16	7.26	15.1	52.5	5.10
HSLC-S	80	50	–	220	–	–	4.26	7.95	23.11	50.0	5.45
HSLC-P	190	140	50	480	370	310	3.68	6.03	17.21	45.0	4.30
HSLC-C–S	100	70	20	320	250	–	4.74	8.23	30.11	58.0	6.10
HSLC-C–P	180	120	40	420	300	220	4.41	6.46	15.14	54.5	5.50
HSLC-S–P	110	70	30	330	230	–	4.07	6.49	19.01	48.5	4.90
HSLC-S–P–C	110	70	20	300	220	–	4.11	7.03	20.11	57.0	5.60

comparison between different fiber-reinforced lightweight concretes is shown in Fig. 2. It can be seen that after adding fibers, the toughness index of the concrete increased greatly. When just adding one type of fibers in the concrete, the toughness index of LWC with steel fibers I_5, I_{10} and I_{30} were all the highest, while LWC with carbon fibers had the lowest value of I_{30} and LWC with PP fibers provided lowest I_5 and I_{10}. Under the conditions of adding hybrid fibers, the combination of C–S fibers showed the highest values of I_5, I_{10} and I_{30}, which were also greater than the values under the condition of adding a single type of fibers. However, the results for other combinations were not as good as those of adding a single type of fiber.

3.4. Shrinkage

Normally, a large amount of cement is used to increase the strength of the concrete. In addition, due to the low strength and elastic modulus, the high-strength LWC has greater shrinkage than the normal concrete. Neville [9] has reported that the shrinkage of LWC is higher compared with normal concrete, while Nilsen and Aitcin [10] provided the different results after their study on LWC with expanded shale. They found that LWC had 30–50% lower shrinkage than the companion NWC after 28 days of curing and 56 days of drying. They attributed this to the presence of water inside the aggregate particles.

The shrinkage of the LWC with hybrid fibers at different ages was investigated in our study, as shown in Fig. 3. It can be seen that the high-strength LWC developed higher shrinkage deformation. It reached a strain of 1000 ìm/m at the age of 100 days. In addition, it tended to increase continuously with the age. After adding fibers, the shrinkage at the early age did not change much. However, with an increase in age, the fibers restrained shrinkage. After 60 days, the shrinkage deformation did not increase. In addition, different types of fibers still showed different abilities to restrain the shrinkage. The ability to restrain shrinkage using a single fiber is in the orders:

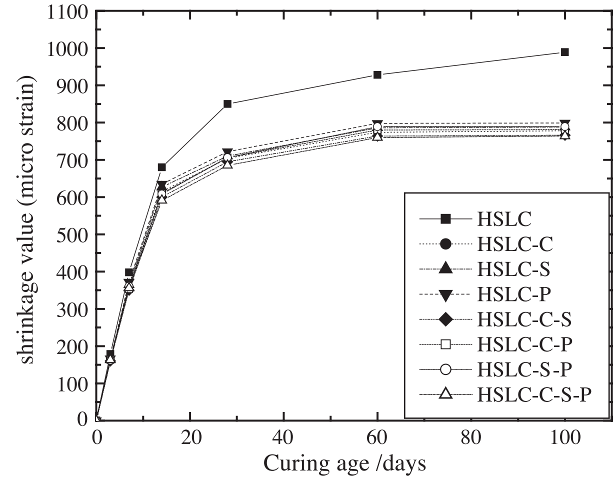

Fig. 3. Shrinkage of the fiber-reinforced lightweight aggregate concretes.

Carbon fiber>steel fiber>PP fiber

Although PP fiber showed the least restraint to shrinkage, it still reduced the shrinkage by around 24%.

Under the condition of adding hybrid fibers, the combination of these three types of fibers showed the highest restraints, i.e., reducing the shrinkage by 30% compared with no fibers. The combination of C–S fibers also provided good restraint. All cases showed better restraint effects than the conditions of adding any one type of fiber.

4. Conclusions

(1) The ‘holding’ effect of different fibers in LWC reduced the surface bleeding of concrete and the sedimentation of the aggregates, and improved the uniformity of the mixture. However, the slump of the mixture reduced somewhat as well.

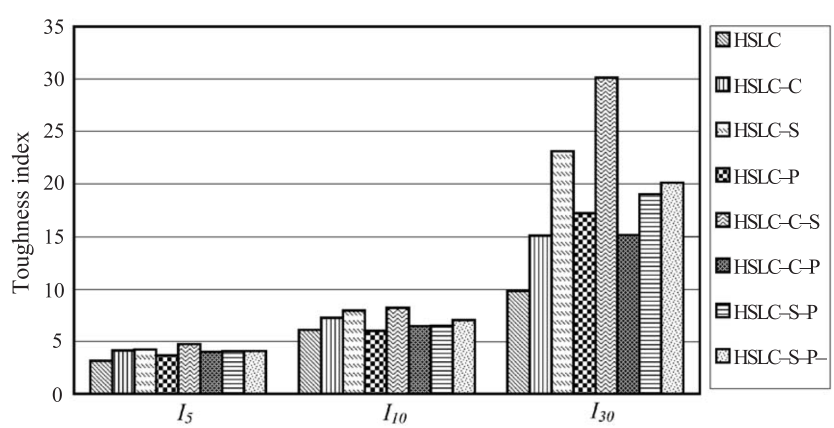

Fig. 2. Comparison of the toughness indexes of the different fiber-reinforced lightweight concretes.

(2) For single fiber types, carbon and steel fibers can both enhance LWC, and provide an increase in compressive and split tensile strengths at different levels. However, for LWC with PP fiber, the compressive strength decreased somewhat. All combinations of different types of fibers resulted in an increase in strength, among which C–S fibers combination provides the best effects, i.e., a 27.6% increase in the compressive strength and a 38.3% of increase in the spit tensile strength.
(3) Fibers significantly improved the toughness index of LWC, and the C–S fibers combination provided the lowest brittleness of the concrete.
(4) Fibers, especially C–S fibers combination, also effectively reduced the shrinkage of concrete.

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