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Use of Shrinkage Reducing Admixture to Improve Flexural Performance of Fiber Reinforced Ultra Lightweight Cement Composites

Jun-Yan Wang, Kok-Seng Chia, Richard J.Y. Liew, and Min-Hong Zhang

Department of Civil & Environmental Engineering, National University of Singapore, 1 Engineering Drive 2, Singapore 117576
** Jun-Yan Wang, ceewangj@nus.edu.sg; Kok-Seng Chia, kschia@nus.edu.sg; Richard J.Y. Liew, ceeljy@nus.edu.sg; Min-Hong Zhang, mhzhang@nus.edu.sg*

ABSTRACT

This paper presents an experimental study on the effect of shrinkage reducing admixture (SRA) on flexural performance of ultra lightweight cement composites (ULCC) with 0.5Vol% fibers. Low density of the ULCC is achieved by using cenospheres from coal-fired power plants as micro aggregates. Straight steel fibers, polyethylene fibers, or a combination of these were evaluated. ULCC with density of 1474 kg/m^3, compressive strengths of 68.2 MPa, flexural strength of 8 MPa, and deflection hardening behaviour can be produced. Such good performance could be attributed primarily to the SRA which reduced entrapped air in paste matrix and densified fiber-matrix interface. The improvement on the flexural performance of the ULCC depends on fibers used and bond between fibers and matrix. Cohesive bond due to chemical reaction between brass coating on steel fibers and cement paste leads to more significant improvement on flexural performance than adhesive bond between PE fibers and matrix.

Keywords: Flexural performance; Polyethylene fiber; Steel fiber; Shrinkage reducing admixture; Ultra lightweight cement composite

1. INTRODUCTION

Ultra lightweight cement composite (ULCC) (Chia, 2011) is a type of composites characterized by a combination of low densities < 1500 kg/m^3 and high compressive strengths ≥ 60 MPa with specific strength of up to 47 kPa/kg.m^{-3}. The ULCC was designed for potential structural applications in steel-concrete sandwich composite structures (Liew, 2010). Low density of the ULCC is achieved by using cenospheres obtained from coal-fired thermal power plants (Wandell, 1996) as micro-lightweight aggregates. The cenospheres consist of hollow interior covered by thin shell with typical thicknesses of 2.5 to 10.5 % of its diameter (Ngu, 2007). To achieve high strength, a water / binder ratio of 0.35 and silica fume dosage of 8% by mass of total binder were used which makes the ULCC a brittle material. Therefore, small amount of fibers are incorporated in the ULCC to improve its flexural toughness and energy absorption capacity.

Due to high amount of fine particles of cenospheres, cement, silica fume plus fibers, the ULCC may contain high volumes of entrapped air. This leads to poor contact between the fibers and cement paste or mortar matrix and weak bond between them, which influences the flexural performance of the composites after matrix cracking. Recent research (Wang, 2012) shows that the use of shrinkage reducing admixture (SRA) can reduce surface tension of pore solution, air content of mortar matrix, and contact angle between fibers and mortar matrix, thus significantly improve the flexural toughness of fiber reinforced mortars due to the densification of transition zone between the fiber and matrix. This suggests that the SRA may be useful in improving flexural performance of fiber reinforced ULCC.

This paper presents an experimental study on the development of fiber-reinforced ultra lightweight cement composites (ULCC) at a low fiber volume fraction of 0.5% with a focus on flexural performance of the ULCC. Effects of SRA and types of fibers (straight steel fibers with brass coating and polyethylene (PE) fibers) on compressive strength and flexural performance of the ULCC were investigated and discussed.

2. EXPERIMENTAL DETAILS

2.1. Materials

Cenospheres used in the ULCC had an average particle density of approximately 870 kg/m^3. Particle size distribution of the cenospheres is given in Fig. 1, and most of the particles had sizes from 10 to 300 μm. The shrinkage reducing admixture used in this study was a commercial product[1] which is in colorless liquid form without water. Properties of steel fibers (ST) coated with brass and polyethylene (PE) fibers used in this study are given in Table 1. The PE fiber had slightly higher tensile strength but lower elastic modulus than the steel fiber. ASTM Type I Portland cement and silica fume were used in all mixtures. A polycarboxylate based superplasticizer (SP) was used to obtain comparable flow at 200±10 mm for all mixtures according to BS EN 1015-3.

2.2. Mix proportions and specimen preparations

Twelve mixtures were included in this study with two plain ULCC and ten fiber-reinforced ULCC. Proportions of the mixtures are given in Table 2, in which “ST” denotes steel fibers, “PE” denotes polyethylene fibers, and “HY” denotes a combination of ST and PE fibers. The SRA dosage of 2.5% was selected based on preliminary tests that air content in the ULCC would not be reduced significantly beyond this dosage.

For each mixture, four 100 x 100 x 400-mm prisms and six 100-mm cubes were cast on a vibration table for flexural performance and compressive strength test, respectively. The specimens were covered by plastic sheets and demolded within 48 hrs after casting. They were then stored in a fog room at temperatures of 28-30 ^{o}C (simulating tropical environment) until testing at 7 and 28 days.

2.3. Test methods and procedures

2.3.1. Density, air content and compressive strength of ULCC

Density of all the ULCC specimens was determined after demolding using water displacement method. Air content of the specimens was calculated by gravimetric method according to ASTM C138-08. Density of the cement and cenospheres used for the calculation of the air content was measured by AccuPyc 1330 Pycnometer based on gas displacement principle. Compressive strength was determined at 28 days using 100-mm cubes according to BS EN 12390-3:2002.

[1] Eclipse® Floor, W.R. Grace Pte. Ltd

2.3.2. Flexural performance

Flexural performance of 100×100×400 mm prisms was determined at 28 days with third-point loading (4-point bending, span length 300 mm) using an Instron closed-loop, servo-controlled testing system as per ASTM C1609. During the test, both applied load and mid-span deflection of the specimens in the direction of the applied load were recorded. Four specimens were tested for each mixture, and the flexural load-deflection curves were averaged by using Average Multiple Curves (AMC) function from Origin 8.5 software.

3. RESULTS AND DISCUSSION

3.1. Density and compressive strength of ULCC

Table 3 presents the average density, compressive strength, specific strength, and air content of the ULCC. The specific strength is defined as strength-to-density ratio. For the ULCC without SRA, the addition of the fibers resulted in decreases in the density from 1295 kg/m^3 to 1125 – 1230 kg/m^3 and increases in air content from 15% to 20 – 26%. Compressive strength of the ULCC was also decreased from 47 MPa to 27 – 36 MPa due to the incorporation of the fibers. This was probably due to the effect of fibers on air void content in the ULCC which led to reductions in their densities, compressive strengths, and specific strengths due to increased entrapped air in the mixtures.

The incorporation of the SRA in the ULCC reduced entrapped air, increased density, compressive strength, and specific strength of the ULCC substantially (Table 3). It was observed that the density, compressive strength, and specific strength of the ULCC with SRA were reasonably consistent, and were less affected by the type and content of the steel and PE fibers incorporated. The air content, density, and compressive strength of the ULCC with SRA ranged from 4.0 to 6.8%, 1421 to 1474 kg/m^3, and 63.1 to 68.2 MPa, respectively.

The above results might be related to the surface tension of the solution and wettability of the fibers in the ULCC which were affected by the SRA. According to a previous study (Wang, 2012), addition of the SRA in the solution greatly reduced its surface tension and contact angles between the fibers and the solution. The reduction in the former destabilized air voids and consequently reduced air content and increased the density of the ULCC. The reduction in the contact angles indicates better wettability of the fibers and probably increased density of the interfacial transition zone between the fibers and surrounding matrix.

3.2. Flexural performance

Load-deflection curves of the ULCC with 0.5% fibers without and with SRA are shown in Fig. 2 and Fig. 3, respectively. All the curves are plotted with dual-Y axis (load and flexural strength). Flexural parameters derived from these curves according to ASTM C1609 are summarized in Table 4. Flexural performance of the fiber-reinforced ULCC was characterized by first-peak strength (f_1) prior to the formation of matrix crack (i.e. pre-crack behavior) and peak strength (f_p) in the post-crack stage if deflection-hardening was observed. Deflection hardening was defined for mixtures with f_p greater than f_1, and was a phenomenon where the load required to overcome pull-out resistance of the fibers was greater than the flexural capacity of the matrix. Flexural toughness T_{150}^{100} was obtained from the area under the load-deflection curve up to 2 mm in deflection to characterize the fibre-reinforced ULCC. Residual strengths at deflections of 0.5 mm and 2 mm are also given in Table 4.

3.2.1. Effect of shrinkage reducing admixture

For the ULCC without SRA, the plain mixture without fiber had the highest first-peak strength f_1 of 5.5 MPa compared with those with fibers. This was probably also related to the increase in the entrapped air in the fiber-reinforced ULCC discussed in section 3.1. The plain ULCC failed after the f_1 was reached, whereas the fiber-reinforced ULCC exhibited load-carrying capacities after the matrix crack due to crack-bridging by the fibers. However, the post-crack behavior among the five mixtures with different types and combinations of the fibers was not significantly different (Fig. 2).

For the ULCC with SRA, however, all the mixtures had similar first peak strength f_1 of 6.25 $\pm$ 0.30 MPa (Table 4) regardless of the fiber types and combinations. The performance of the fiber-reinforced mixtures after the first crack seems to be affected by the types and combinations of the fibers substantially (Fig. 3). Two mixtures with high steel fiber contents (ST-50_SRA and HY-1_SRA) showed deflection-hardening behavior, and specimens of the mixture ST-50_SRA displayed multiple cracks in the flexural test, which indicates higher energy absorption capacity than those with a single crack. The effect of the fibers will be discussed in more details in Section 3.2.2.

The effect of SRA on the flexural performance of the ULCC is more clearly illustrated in Fig. 4. From each figure, it is apparent that the mixtures with SRA had higher first peak strength and better post crack performance than that without SRA. The incorporation of the SRA improved the flexural toughness of the fiber-reinforced ULCC substantially compared with that of the control mixtures without SRA. The higher first peak strength of the ULCC with SRA might be attributed mainly to the increased density of the matrix due to the reduced surface tension of the solution and reduced air content. However, their better post crack performance might be attributed to the reduced contact angle between the fibers and solution which led to denser transition zone at the fiber-matrix interface and increased pull-out resistance of the fibers (Wang, 2012). The incorporation of the SRA also increased residual strength of the ULCC which indicates better load-carrying capacity of the composites after cracking. However, the extent of increase in the residual strength at a given deflection was affected by the type and combination of the fibers used. The reason will be discussed in the next section.

3.2.2. Effect of fiber types and combinations

In the ULCC without SRA, there was no clear trend on the effect of types and combinations of the fibers on their flexural performance. This was due to the fact that the performance of the lightweight composites is affected by air void content of the composites. The ULCC with SRA, however, had comparable density, compressive strength, and first-peak flexural strength (f_1) regardless of the type and combination of the fibers used. This indicates that the fiber type and combination did not have significant effect on the matrix of the ULCC with SRA. However, the flexural behavior of the ULCC with SRA after the first peak seems to be affected by the fibers significantly (Fig. 2). The results indicate that the steel fibers were more efficient in enhancing the flexural performance of the ULCC than the PE fibers. As shown in Fig. 3, the load-carrying capacity of the ULCC after the first peak seems to be increased with the increase in the steel fiber content. The flexural toughness T_{150}^{100} of the ULCC was also increased with the increase in steel fiber content (Table 4). It was also observed from Fig. 4 that the difference between the flexural performance of the ULCC with and without SRA after the first peak was increased with the increase in the steel fiber content.

For example, T_{150}^{100} of ST-50_SRA was almost 2.6 times that of ST-50, whereas T_{150}^{100} of PE-50_SRA was only 1.3 times that of PE-50. These might be related to the bond between the fibers and matrix as the matrix of the various ULCC mixtures with SRA was similar.

Chan and Li (Chan, 1997) conducted single fiber pull-out tests, and found out that the bond strength between brass fibers and cement paste is roughly seven times of that between PE fibers and the same cement paste. The PE fibers they used were the same as those used in this study. They attributed the significant different bond strengths to different bond failure modes, and suggested "cohesive" bond failure for brass-cement paste system (torturous failure path through transition zone) and "adhesive" bond failure for PE-cement paste system (smooth failure path through fiber-matrix interface). According to Al-Khalaf and Page (Al-Khalaf, 1979), the bond of brass with cement paste is mainly due to the chemicophysical properties of brass that allows chemical reactions to occur while in contact with cement material. Chan and Li (Chan, 1997) further suggest that the densification of the transition zone may not be effective in improving bond strength if the bond failure is governed by adhesive failure at the interface, whereas bond strength improvement can be achieved by densification of the transition zone if the bond failure is governed by cohesive failure in the transition zone. The results shown in Fig. 4 indicate that the effect of brass coating on the steel fibers in combination with the reduced contact angle due to the use of SRA contributed to the deflection hardening behavior of the ULCC with only 0.5% fibers (ST-50_SRA).

From Fig. 4, it seems that the SRA was not as effective in enhancing the flexural performance of the ULCC with PE fibers after the matrix crack compared to that with the steel fibers. This might be due to the different failure modes between fibers and matrix as described by Chan and Li (Chan, 1997). Lower effect of the SRA on the flexural performance after the matrix crack was also reported for normal weight mortar with polypropylene (PP) fibers in comparison to that with the steel fibers (Wang, 2012). In that research, the addition of SRA improved the toughness of steel fiber reinforced mortar by 51%, whereas the improvement for the PP fiber reinforced mortar was only 16%.

4. CONCLUSIONS

Based on the experimental results, the following conclusions are drawn:

1. The addition of SRA in the ultra lightweight cement composites (ULCC) increased their density, compressive strength, specific strength, and flexural performance, which may be attributed to reduction in entrapped air content in the matrix, densification of fiber-matrix transition zone, and increase in pull-out resistance of the fibers in the ULCC derived from the effect of SRA.

2. Although the SRA improved the fiber-matrix interface, the consequent improvement on the flexural performance of the ULCC depends on the type of the fibers used and bond between the fibers and matrix. Cohesive bond due to chemical reaction between the brass coating on the steel fibers and cement paste leads to more significant improvement of flexural performance than adhesive bond between the polyethylene (PE) fibers and matrix.

3. ULCC with low unit weight of 1474 kg/m^3, high compressive strength of 68.2 MPa, high flexural strength of 8 MPa, and deflection hardening and multiple cracking behaviour can be produced with only 0.5% steel fibers in combination with SRA.

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Table 1. Properties of fibers

Fiber types	Tensile strength (MPa)	Elastic modulus (GPa)	Length (mm)	Diameter (μm)	Aspect ratio	Density (kg/m^3)
Polyethylene (PE)*	2610	79	12	39	308	0.97
Steel (ST)**	2500	200	13	160	81	7.85

* Spectra® fiber 900

** Dramix® OL13/.16, straight with brass coating

Table 2. Mixture proportions of ULCC

Mix ID	Fiber (Vol %)		Mixture proportion of matrix by mass of total binder				
	Steel	PE	Water/ Binder	Binder		Cenosphere/ Binder	SRA/ Binder
				Cement	SF*		
Plain	0	0	0.35	0.92	0.08	0.42	0
ST-50	0.500	0	0.35	0.92	0.08	0.42	0
HY-1	0.375	0.125	0.35	0.92	0.08	0.42	0
HY-2	0.250	0.250	0.35	0.92	0.08	0.42	0
HY-3	0.125	0.375	0.35	0.92	0.08	0.42	0
PE-50	0	0.500	0.35	0.92	0.08	0.42	0
Plain_SRA	0	0	0.325	0.92	0.08	0.42	0.025
ST-50_SRA	0.500	0	0.325	0.92	0.08	0.42	0.025
HY-1 _SRA	0.375	0.125	0.325	0.92	0.08	0.42	0.025
HY-2_SRA	0.250	0.250	0.325	0.92	0.08	0.42	0.025
HY-3_SRA	0.125	0.375	0.325	0.92	0.08	0.42	0.025
PE-50_SRA	0	0.5	0.325	0.92	0.08	0.42	0.025

* Silica fume

Table 3. Average density, compressive strength, specific strength and air content of ULCC

MIX ID	Density (kg/m^3)	Compressive strength (MPa)	Specific strength ($kPa/kg{\cdot}m^{-3}$)	Air content *(%)
Plain	1295	46.9	36.2	15.3
ST-50	1195	29.5	24.7	23.5
HY-1	1232	36.3	29.4	20.2
HY-2	1139	27.1	23.8	25.7
HY-3	1125	28.5	25.3	26.2
PE-50	1186	29.1	24.5	21.8
Plain_SRA	1424	67.0	47.0	6.8
ST-50_SRA	1474	68.2	46.3	5.1
HY-1 _SRA	1468	68.0	46.3	5.0
HY-2_SRA	1474	67.7	45.9	4.0
HY-3_SRA	1441	63.1	43.8	5.6
PE-50_SRA	1421	63.3	44.5	6.4

*Air content is the volume of voids in the composite, but does not include the enclosed voids inside cenospheres.

Table 4. Flexural parameters (according to ASTM C1609)

MIX ID	P_1 /kN	P_p /kN	δ_1 /mm	δ_p /mm	f_1 /MPa	f_p /MPa	P_{600}^{100} /kN	f_{600}^{100} /MPa	P_{150}^{100} /kN	f_{150}^{100} /MPa	T_{150}^{100} /J
Plain	18.26	-	0.08	-	5.48	-	-	-	-	-	0.75
ST-50	13.10	-	0.07	-	3.93	-	11.26	3.38	8.78	2.63	18.81
HY-1	14.58	-	0.07	-	4.37	-	10.87	3.26	8.85	2.66	17.50
HY-2	14.17	-	0.08	-	4.25	-	9.35	2.80	7.18	2.15	16.18
HY-3	12.67	-	0.06	-	3.80	-	8.56	2.57	6.67	2.00	16.01
PE-50	15.10	-	0.08	-	4.53	-	11.64	3.49	8.94	2.68	20.95
Plain_SRA	20.38	-	0.07	-	6.11	-	-	-	-	-	0.85
ST-50_SRA	20.72	26.62	0.07	0.99	6.22	8.00	25.51	7.65	23.75	7.12	48.78
HY-1 _SRA	19.87	22.60	0.06	0.70	5.96	6.80	21.72	6.52	20.07	6.02	41.71
HY-2_SRA	21.82	-	0.07	-	6.55	-	20.06	6.02	16.96	5.09	37.42
HY-3_SRA	19.81	-	0.07	-	5.94	-	17.94	5.38	14.98	4.49	32.68
PE-50_SRA	20.04	-	0.07	-	6.01	-	15.85	4.75	11.62	3.49	28.11

P_1 – first-peak load; P_p – peak load; δ_1 – net deflection at first-peak load; δ_p – net deflection at peak load; f_1 – first-peak flexural strength; f_p – peak flexural strength; P_{600}^{100}, P_{150}^{100} – residual loads at net deflections of L/600 (0.5mm in this study) or L/150 (2mm in this study), respectively; L – Span length (300mm in this study); f_{600}^{100}, f_{150}^{100} – residual strength at net deflections of L/600 or L/150, respectively; T_{150}^{100} – flexural toughness (area under load-deflection curve up to a deflection at 2 mm).

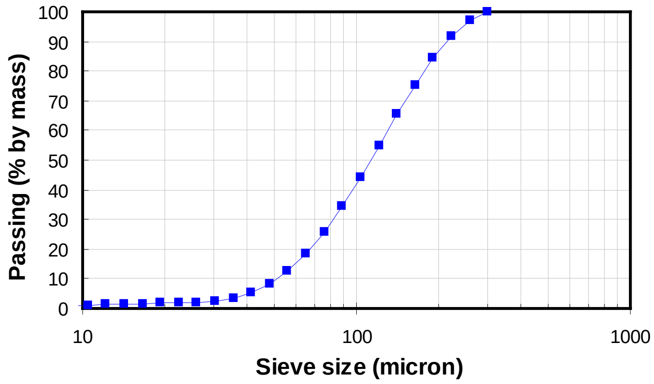

Fig.1. Particle size distribution of cenosphere

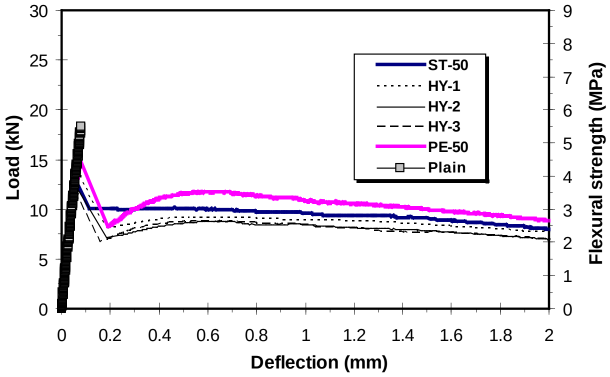

Fig.2. Average load-deflection curves of fiber reinforced ULCC without SRA

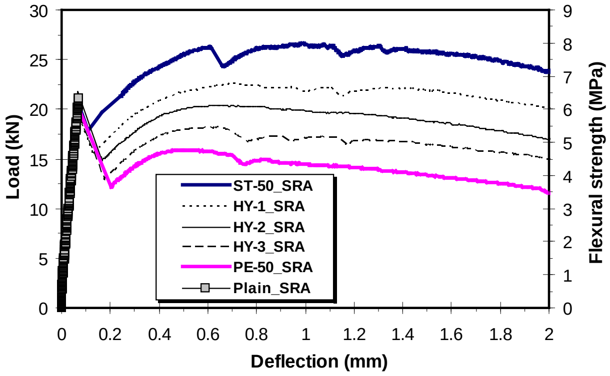

Fig.3. Average load-deflection curves of fiber reinforced ULCC with SRA

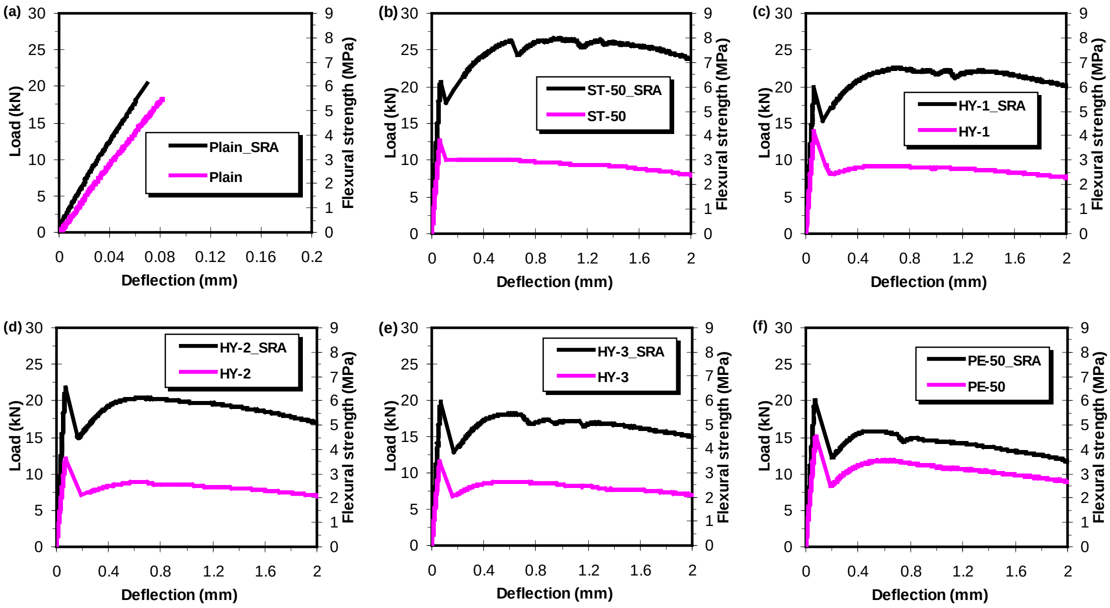

Fig.4. Comparisons of load-deflection curves of the ULCC with and without SRA