Dispersion of Fibers in Ultra-High-Performance Concrete

Tests show that suitably proportioned mixtures can be prepared using a drum mixer

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Ultra-high-performance concrete (UHPC) is an advanced cementitious material with compressive and tensile strengths exceeding 150 and 15 MPa (21,760 and 2180 psi), respectively.[1-3] UHPC mixtures are generally designed with relatively high dosages of silica fume, high-range water-reducing admixtures (HRWRA or superplasticizer), steel fibers, relatively small concentrations of small-size aggregates, and portland cement typically blended with fly ash or slag cement.[4,5] Some distinguishing features of UHPC include an optimized gradation of the granular matter for realizing a high packing density, a water-cementitious materials ratio (*w/cm*) of less than 0.25, and a relatively high volume fraction of discrete (steel) fibers.[6]

Production of UHPC mixtures generally requires the use of specialty mixers or extended mixing times to ensure production of a homogenous fresh mixture. The sequencing of the components introduced into the mixer also influences the homogeneity of the fresh mixture. The high steel fiber content of UHPC can cause a high tendency for fiber balling, which can be more pronounced in large-scale production efforts. This is one reason many producers resort to the use of specialty mixers, but requiring such equipment limits the availability and raises the cost of UHPC. Figure 1 shows balls of steel fibers formed when a UHPC batch was produced in a concrete truck. Figure 2 shows balls of fibers in a core taken from a large UHPC placement in which mixing was accomplished using a concrete truck. Successful introduction of UHPC to mainstream construction applications would benefit from resolving the challenges associated with dispersion of fibers in conventional rotary drum mixers (that is, concrete trucks).[7,8]

Fiber balling is a challenge in scale-up of UHPC production using conventional concrete mixing practices. The selection of fiber type and volume fractions should be made to balance desired engineering properties of UHPC

Fig. 1: Fiber balls observed in a large-scale UHPC batch produced in a concrete truck

Fig. 2: UHPC core taken from a large UHPC placement in which mixing was performed in a concrete truck: (a) view of the circumference; and (b) a cross section with a fiber ball

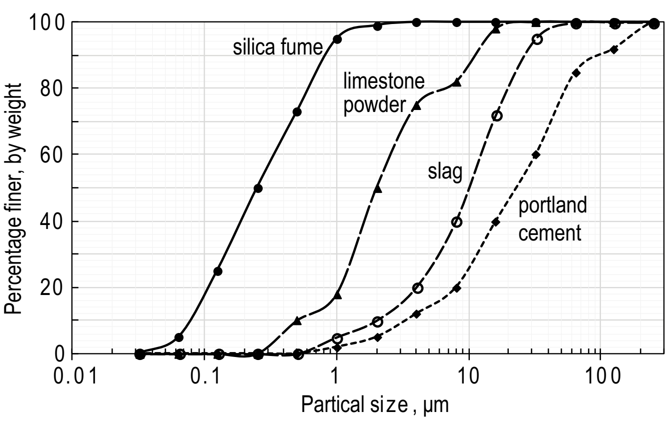

Fig. 3: Particle size distributions of cementitious materials and limestone powder

Table 1:
Particle size distributions of aggregates

Sieve size, mm	Amount passing, %		
	Coarse aggregate	Coarse sand	Fine sand
0.15 (No. 100)	0	0	0.05
0.18	0	0.1	0.3
0.30 (No. 50)	0	0.3	6.8
0.60 (No. 30)	0	6.7	86
1.18 (No. 16)	0	86	100
2.00	0	100	100
2.36 (No. 8)	0.9	100	100
4.75 (No. 4)	3.8	100	100
9.5 (3/8 in.)	54	100	100
12.5 (1/2 in.)	98	100	100
19 (3/4 in.)	100	100	100

Note: 1 mm = 0.04 in.

against the potential for fiber balling in large-scale UHPC production. The conventional approach to resolving balling of steel fibers in UHPC—by using multiple fibers bonded together with water-soluble adhesives—was found in this investigation to be ineffective. Therefore, efforts were made to select the steel fiber types with a reduced tendency toward balling that would also provide desirably high values of compressive strength. It is worth mentioning that, unlike normal- and high-strength concrete, reinforcement with properly selected discrete fibers can produce a significant increase in the compressive strength of UHPC.[9]

Materials and Methods

The granular raw materials used in this investigation can be divided into two categories: cementitious materials and fine filler (limestone powder), and aggregates. The former included Type I portland cement, undensified silica fume (with approximately 200 µm mean particle size, about 15 m^2/g specific area, and greater than 105% 7-day pozzolanic activity index), ground-granulated blast-furnace slag (with specific gravity of 2.9 and bulk density of 1200 kg/m^3) ground to less than 45 µm particle size, and limestone powder with 2 µm mean particle size. The particle size distributions of cementitious materials and limestone powder are shown in Fig. 3. The aggregates used in the UHPC mixtures included limestone coarse aggregate with 12.5 mm (1/2 in.) maximum size, coarse silica sand with mean particle size of 0.8 mm (0.03 in.) and specific gravity of 2.67, and fine silica sand with mean particle size of 0.4 mm (0.015 in.) and specific gravity of 2.65 (refer to Table 1 for size distributions). A polycarboxylate-based HRWRA with 1.06 specific gravity and 30% solids content was also used in the mixtures. The steel fibers are listed in Table 2; those with 0.2 mm (0.008 in.) diameter were brass-coated. Broad varieties of fibers were considered because the effect of fiber selection and blending on balling of fibers was found to be significant.

UHPC mixtures were prepared using the following procedure and using a rotary drum mixer with 0.035 m^3 (1.24 ft^3) capacity (Fig. 4):

- Add all aggregates and powders to the mixer in the

Table 2:
Fiber types used in the UHPC mixtures

Type	Diameter, mm	Length, mm	Supplier
Fine steel fibers	0.2	13	Bekeart
Medium steel fibers	0.2	30	Bekeart
Glued fibers	0.55	30	Bekeart
Hooked fibers	1	60	Bekeart
Glass fibers	0.1	19	Buddy Rhodes
Carbon fibers	1	15	Zoltek

Note: 1 mm = 0.04 in.


Fig. 4: The laboratory-scale rotary drum mixer used in this investigation

following sequence—coarse aggregate, fine aggregates, and powders (cement, silica fume, slag cement, and limestone powder);
- Mix for 2 minutes;
- Add water with half of the HRWRA over 2 minutes, and mix for an additional 30 seconds;
- Add the rest of the HRWRA to the mixture over 1 minute;
- Continue mixing until a wet paste forms (usually 4 to 9 minutes);
- Add the steel fibers to the mixture; and
- Mix until a total mixing duration of 15 minutes is reached.

Note: A rotary drum mixer was used here to reproduce the effects of mixing UHPC in a concrete truck.

Fiber ball formation typically occurs when fibers of 0.2 mm diameter and 13 to 15 mm (0.5 to 0.6 in.) in length are used. The approach we evaluated for resolving the fiber balling problem involved using different types (including blends) and volume fractions of fibers (Table 3). The focus was on resolving the fiber balling problem without compromising the compressive strength of UHPC.

The fresh workability of each UHPC mixture was assessed using the flow table test procedure per ASTM C124, “Method of Test for Flow of Portland-Cement Concrete by Use of the Flow Table (Withdrawn 1973).” Cube specimens of 50 mm (2 in.) dimensions were prepared from the UHPC mixtures. They were consolidated using external vibration and were demolded after 24 hours. Specimens were then cured at 100% relative humidity and 90°C (194°F) over 48 hours. The specimens were then allowed to cool down and stored at 50 ± 5% relative humidity and 22 ± 2°C (72 ± 3.5°F) until 7 days of age, when they were subjected to compression testing per ASTM C109/C109M, “Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens).” Eight cube specimens were prepared and tested for each mixture.

Table 3:
Relative proportions of different steel fiber types used in UHPC mixtures

Case No.	Fine steel fibers, %	Hooked steel fibers, %	Medium steel fibers, %
1	50	50	0
2	50	0	50
3	75	0	25

Table 4:
The UHPC mixture proportions used in this investigation

Material	Quantity, kg/m³ (lb/yd³)
Coarse aggregate	612 (1032)
Coarse silica sand	500 (843)
Finer silica sand	500 (843)
Cement	604 (1018)
Silica fume	268 (452)
Slag cement	120 (202)
Limestone powder	216 (364)
Water	144 (243)
HRWRA	57.6 (97)
Steel fibers	148 (249)

Results and Discussion

Figure 5 compares the steel fiber balls formed during mixing of the base UHPC mixture from Table 4 with different steel fibers. Figure 5(a) shows the steel fiber balls for UHPC prepared with 0.2 mm diameter and 13 mm long brass-coated steel fibers. The fiber balls comprised steel fibers, cementitious materials, minor quantities of fine aggregates, and hardly any coarse aggregates. After removal of the steel fiber balls, the resulting UHPC provided a compressive strength of 224.0 ± 4 MPa (32,490 ± 580 psi).

Replacement of steel fibers with glass fibers at equal volume fraction resolved any visual indication of fiber balling, but the dispersion of fibers was less than perfect. The high specific surface area of glass fibers raised the water requirement of the mixture by 20%. In spite of this rise in water content, the fresh mixture still had a dry consistency (flow of 480 mm [19 in.]), and exhibited a tendency toward formation of pellets comprised largely of the cementitious paste (Fig. 5(b)). The resultant concrete produced a relatively low compressive strength of 122.0 ± 6 MPa (17,690 ± 870 psi).

Use of carbon fibers instead of steel fibers at the same volume fraction produced trends that were similar to (but less pronounced than) those observed with glass fibers (Fig. 5(c)). The extra water required to produce a flow of 560 mm (22 in.) was 10% of the original water content. The compressive strength achieved with carbon fibers was relatively low at 138.5 ± 5 MPa (20,090 ± 730 psi).

The use of steel fibers with water-soluble glue resolved the problem with fiber balling (Fig. 5(d)); however, about 45% of fibers remained glued together and did not separate. Furthermore, the dissolution of the water-soluble glue in UHPC produced a viscous fresh mixture with compromised workability. This can be attributed to the high dissolved concentration of the glue in the mixing water, considering that UHPC mixtures have distinctly low water contents. The compressive strength achieved with glued steel fibers was relatively low at 133.6 ± 5 MPa (19,380 ± 730 psi).

When half of the quantity of fine steel fibers was replaced with hooked fibers, the problems with formation of steel fiber balls and cementitious paste pellets were resolved (Fig. 6(a)). The fresh mixture also provided a desired

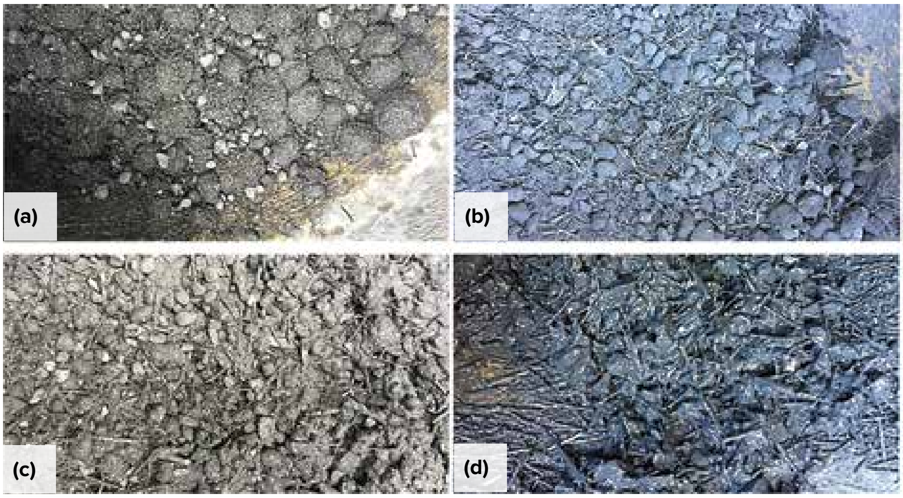

Fig. 5: Steel fiber balls formed in drum mixer for the UHPC base mixture: (a) with brass-coated steel fibers; (b) with glass fibers: (c) with carbon fibers; and (d) with glued steel fibers

Fig. 6: The appearance of the fresh UHPC mixture in a drum mixer when: (a) 50% of fine steel fibers are replaced with steel hooked fibers; (b) 50% of fine steel fibers are replaced with medium-sized steel fibers; and (c) 25% of fine steel fibers are replaced with medium-sized steel fibers

Fig. 7: Pictures of a core extracted from a UHPC placement prepared in a concrete truck where 50% of fine steel fibers was replaced with medium-sized steel fibers

flow of 640 mm (25 in.). The compressive strength was 176.0 ± 4 MPa (25,530 ± 580 psi), which is reasonably high (qualifying the material as UHPC) but still lower than that achieved with only small steel fibers (after removal of the fiber balls). In short, a combination of fine and hooked steel fibers offers a solution to the fiber balling problem when UHPC mixtures are prepared in conventional drum mixers.

Replacement of 50% of fine steel fibers with steel fibers of medium size also was effective in resolving the fiber balling problem (Fig. 6(b)). This also provided a desired fresh mixture workability represented by a flow of 720 mm (28 in.)—better than that achieved with 100% finer fibers—and a desirably high compressive strength of 198.5 ± 3 MPa (28,790 ± 440 psi). These represent the best balance of fresh mixture and hardened material properties produced in this work, suggesting that a combination of fine and medium steel fibers at equal weights offers a viable solution to the fiber balling problem (without a tendency toward compromised fresh mixture workability and formation of cementitious paste pellets).

An attempt was made to reduce the replacement level of fine fibers with medium fibers to raise the UHPC compressive strength. A fiber blend comprising 75% fine and 25% medium steel fibers also did not exhibit any visual indications of fiber ball formation after 20 minutes of mixing (Fig. 6(c)). There was a minor tendency toward fiber balling after 15 minutes of mixing, which was resolved with 5 minutes more of mixing. The fresh mixture flow was 680 mm (27 in.), and the resulting compressive strength was 210.0 ± 4 MPa (30,460 ± 580 psi). While this blend of steel fibers seems to be preferred, one should be concerned about the scale-up effects from laboratory to an industrial-scale drum mixer. Our field experience indicates an increased tendency toward fiber balling in a concrete truck when compared with a laboratory-scale drum mixer. Therefore, some sacrifice of compressive strength may be required for ensuring the scalability of this process.

Based on this investigation, a viable solution to fiber balling involves replacement of 50% of fine fibers with medium-sized fibers. Production of this UHPC mixture in a concrete truck indicates a successful resolution of the fiber balling problem. The cores extracted from this UHPC (Fig. 7) did not exhibit any indications of fiber balling, in contrast to those produced with 100% fine steel fibers (Fig. 2).

Summary and Conclusions

Relatively high steel fiber contents are commonly used to enhance ductility and strength of UHPC mixtures. Specialized mixing procedures are generally employed to ensure the homogeneity of UHPC mixtures and thorough dispersion of steel fibers because production of UHPC in commonly used drum mixers tends to result in fiber balling. These tendencies tend to be more pronounced in industrial-scale production of UHPC (that is, in concrete trucks).

Investigations were conducted to resolve the fiber balling problem encountered in production of UHPC mixtures using drum mixers. The options considered included the use of glass and carbon fibers in lieu of steel fibers, and blending of steel fibers of different size. Glass and carbon fibers raised the water demand for achieving adequate fresh mixture workability, and their use resulted in lowered compressive strength of the UHPC mixtures.

Blending of fine fibers and hooked steel fibers at equal proportions was effective in resolving the fiber balling problem for a UHPC mixture reinforced with 1.5% steel fibers by volume. This investigation was conducted using a laboratory-scale drum mixer. The blends of fine fibers and coarse hooked fibers considered in this investigation produced compressive strengths that were somewhat lower than those obtained with fine fibers, but they mitigated the fiber balling problem.

Blending of fine and medium-sized fibers provided the greatest promise in terms of producing a desired balance of fresh mixture workability, resistance to fiber balling, and UHPC compressive strength. Scaled-up production of the

UHPC mixture reinforced with 1.5% of fine and medium-sized steel fibers by volume at equal proportions confirmed that fiber balling could be controlled when mixing of UHPC was accomplished in a concrete truck.

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Note: Additional information on the ASTM standards discussed in this article can be found at **www.astm.org**.

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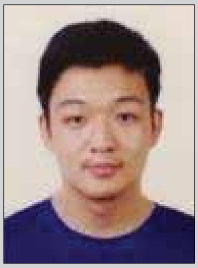

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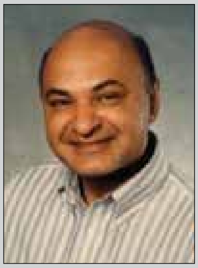

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