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Review

A review of the applications of ultra-high performance concrete in flat components and the associated fire-induced spalling risk

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Supplementary

Table S1. Summary of previous research for UHPC at or after high temperature (material parameters).

Ref.	Essential ingredients of UHPC (mass/cement mass)	Additive or aggregate	Volume of fiber
[1]	Silica fume (0.14, 0.19, 0.36); fly ash (0.28); sand (1.23, 0.69, 0.59); slag (0.32, 0.36); w/b (0.20, 0.145, 0.125); gypsum (0.08, 0.09)	AG-13 mm (1.62, 1.33, 1.12)	PP (0.25%, 0.075%); Ny (0.15%, 0.075%)
[2]	Silica fume (0.26); sand (0.69); HRWR (0.08); w/b (0.20)	–	SF (2% or 158 kg/m^3); PP (4 kg/m^3)
[3]	Silica fume (0.16); fly ash (0.13); HRWR (0.009); w/b (0.16)	Steel slag (1.29)	SF (0%, 1%, 2%); PP (0%, 2%)
[4]	Commercial Ducorit® product; w/b (0.076)	–	SF (0%, 0.5%, 1%); PP (0%, 0.1%, 0.25%, 0.5%)
[5]	Silica fume (0.26); sand (0.26); HRWR (0.03); w/b (0.20)	AG-600 μm (1.09)	SF (0, 79, 157, 236 kg/m^3); PP (0, 2, 4, 6 kg/m^3)
[6]	Silica fume (0.25); sand (0.25); HRWR (0.04); w/b (0.22)	AG-600 μm (1.09)	SF (0%, 2.5%); PP (0%, 0.33%)
[7]	Silica fume (0.25); sand (0.25); HRWR (0.04); w/b (0.20)	AG-600 μm (1.09)	PP (3 kg/m^3)
[8]	Pre-blended binding materials, pre-blended aggregates, and waste porous ceramic fine aggregate		JF (0.3%); PP (0.3%, 0.5%)
[9]	Silica fume (0.11); sand (0.44); HRWR (0.02); w/b (0.22)	–	PP (0.1%, 0.3%, 0.5%); PE (1.4%, 1.2%, 1.0%)
[10]	Silica fume (0.25); sand (0.25); HRWR (0.04); w/b (0.20)	AG-600 μm (1.1)	JF (3, 5, 10 kg/m^3)
[11]	Silica fume (0.16); fly ash (0.13); sand (1.29); HRWR (0.009); w/b (0.16)	Steel slag (1.29)	SF (1%); PP (2%)
[12]	Mix (sand, cement and silica fume): 2085.6 kg/m^3; HRWR: 28.7 kg/m^3; water: 194 kg/m^3; w/b (0.19)	–	PP (0.82, 1.64, 2.46, 3.27, 1.5, 3, 4.5, 2.3, 65.73 kg/m^3); PAN (0.81, 1.61, 2.42, 3.22 kg/m^3)
[13]	Silica fume (0.25); silica sand (1.1); silica flour (0.3) HRWR (0.067); w/b (0.20)	–	SF (0%, 0.5%, 1.5%, 2.0%); PP (0.1%, 0.2%, 0.3%, 0.4%, 0.5%, 0.6%); PVA (0.1%, 0.3%, 0.5%); PE (0.1%, 0.3%, 0.5%, 1.0%, 1.5%); Ny (0.1%, 0.2%, 0.3%)
[14]	Silica fume (0.11); HRWR (0.03); w/b (0.24)	Fine AG (0.88); Coarse AG (1.48)	SF (0%, 0.5%, 1.0%, 1.5%, 2.0%); PP (0%, 0.5%, 1.0%, 1.5%, 2.0%)

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Ref.	Essential ingredients of UHPC (mass/cement mass)	Additive or aggregate	Volume of fiber
[15]	Silica fume (0.16); fly ash (0.33); GGBS (0.16); sand (1.14, 2); HRWR; w/b (0.18)	Basalt AG: 5–10 mm and 10–16 mm with a mass ratio of 3:7 (1.72)	SF (0%, 1%); PP (0%, 0.15%)
[16]	Silica fume (0.44); slag (0.20); limestone powder (0.36); natural sand (1.07); silica sand (0.59); HRWR (0.10); w/b (0.14)	Carbonate AG-12.7 mm (1.01)	SF (0, 125 kg/m^3); PP (0, 1.6 kg/m^3)
[17]	Silica fume (0.17); quartz powder (0.26); quartz sand (1.4); HRWR (0.029); w/b (0.16)	–	PET (0.025%, 0.05%, 0.10%); PP (0.05%, 0.10%)
[18]	Silica fume (0.25); river sand (1.1); silica sand (0.25); HRWR (0.03); w/b (0.20)	–	SF (0 kg/m^3, 157 kg/m^3); PP (0 kg/m^3, 3 kg/m^3)
[19]	Silica fume (0.25); fly ash (0.35); quartz sand (1.44); HRWR (0.032); w/b (0.17)	–	SF (1.5%, 2.0%, 2.5%, 3.0%); PP (0.1%, 0.2%,0.3%)
[20]	Silica fume (0.25); silica sand (0.25); HRWR (0.04); w/b (0.20)	Fine aggregate-size < 0.6 mm (1.1)	PP (0, 3 kg/m^3); PET (0, 3 kg/m^3); PA (0, 3 kg/m^3); LLDPE (0, 3 kg/m^3); UHMWPE (0, 3 kg/m^3)
[21]	Silica fume (0.25); silica sand (0.25); HRWR (0.04); w/b (0.20)	Fine aggregate-size < 0.6 mm (1.1)	PP (0.33%)
[22]	Silica fume (0.25); silica sand (0.25); HRWR (0.04); w/b (0.20)	Fine aggregate-size < 0.6/2.36/4.75 mm	SF (0, 2 kg/m^3); PP (0, 2 kg/m^3)
[23]	Silica fume (0.31); fly ash (0.25); HRWR (0.015); w/b (0.20)	Fine bauxite aggregate-0.12 to 0.83 mm (1.37)	SFRP: OP (0%, 1.0%, 2.0%); MP (0%, 1.0%, 2.0%)
[24]	Cement + GP (800 kg/m^3); SF (240 kg/m^3); HRWR (82 kg/m^3); w/b (0.14)	Waste glass-size < 4.75 mm (1200 kg/m^3)	Basalt fiber (8.1 kg/m^3)
[25]	Silica fume (0.30); fly ash (0.20); quartz sand (1.0); HRWR (0.01); w/b (0.14)	–	SF (0%, 1%); CNT (0%, 0.05%, 0.1%); CSW (0%, 1%, 3%); CF (0%, 0.4%, 0.8%); PE (0%, 1%)
[26]	Silica fume (0.11); sand (0.74); HRWR (0.02); w/b (0.15)	Coarse basalt aggregate-5 to 15mm (1.1)	SF (0.5%); PP (0.15%)

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Ref.	Essential ingredients of UHPC (mass/cement mass)	Additive or aggregate	Volume of fiber
[27]	Silica fume (0.285); quartz powder (0.285); HRWR (0.05); w/b (0.18)	Crushed dolomite-0.36 to 4.75 mm (0.72)	SF (68.0-117.0 kg/m^3); PP (0, 0.5, 0.67, 1 kg/m^3); PVA (0, 4.5, 6, 9 kg/m^3); JF (0, 1.75, 2.35, 3.5 kg/m^3)
[28]	Silica fume (0.25); Fly ash (0.25); Silica Sand (1.1); w + SP/b (0.206)	–	SF (0%, 1.0%, 1.5%, 2.0%); Basalt fiber (0%, 0.5%, 1.0%)
[29]	Silica fume (0.15, 0.25); HGM (0, 0.09); WGP (0.15, 0.25); w/b (0.147)	River sand + shale-expanded lightweight aggregate-size 0.3-1.18 m)	SF (109 kg/m^3)
[30]	Silica fume (0.27); quartz powder (0.11); HRWR (0.032); w/b (0.14)	Silica sand size < 0.6 mm; crumb rubber-1 to 2 mm (0.05, 0.1)	SF (0, 2.0%)
[31]	Silica fume (0.143); fly ash (0.286); HRWR (0.17); w/b (0.19)	River sand; manufactured sand; basalt coarse aggregates < 10 mm	SF (0, 1.5%); PP (0, 0.15%, 0.3%)
[32]	Silica fume (0.187); fly ash (0.063); HRWR (0.0375); w/b (0.16)	Quartz sand-0.04 to 0.07mm; coarse basalt aggregate-5 to 10mm	SF (2.0%)

Note: SF-steel fiber; PP-polypropylene fiber; PVA-polyvinyl alcohol fiber; PE-polyethylene fiber; Ny-nylon fiber; JF-jute fiber; PA-polyamide fiber; PAN-acrylic fiber; LLDPE-linear low-density polyethylene; UHMWPE-ultra-high molecular weight polyethylene; PET-polyester fiber; SFRP-synergistic flame-retardant polymer fiber; OP-organic polymer fiber; MP-modified polymer fiber; GP-geranium plant waste; CNT-Carbon nanotubes; CSW- calcium sulfate whisker; CF-carbon fiber; HRWR-high-range water reducer (also known as SP-superplasticizer); GGBS-ground blast furnace slag; HGM-hollow glass microsphere; WGP-waste glass powder; in the column 'Additive or aggregate,' additive represents the additional mixing substance.

Table S2. Summary of previous research for UHPC at or after high temperatures (testing parameters).

Ref.	Specimen dimension (mm)	Ambient compressive strength (f_c/MPa)	Curing method	Rate of heating (°C/min) (+holding time)	Cooling process	Spalling behavior
[1]	Φ100 × 200 (spalling and f_c)	100 150 200	Moist curing for a week; dry curing for 300 days (60% RH, 20°C)	UHPC with fibers: ISO 834 fire curve up to 900°C (50 min) UHPC no fibers: 1 (+0 h)	Examined under high temperatures	UHPC no fiber: spalling 100 & 200 MPa UHPC, >0.15% PP & NY: no spalling 200 MPa UHPC, 0.15% PP & Ny: surf spalling UHPC, 0.25% fiber or 0.15% hybrid fibers: no spalling
[2]	100 × 100 × 100	100 (Cold-cured) 150.6 (Hot-cured)	Cold water curing: 22 °C (28 days) Hot water curing: 90 °C (7 days)	10 (+1 h)	Outside and natural cool	Spalling starts earlier in the hot-cured elements than in the cold-cured ones
[3]	50 × 50 × 50 (f_c)	90.0–187.5	Hot water curing: 90 °C (1 day)	1, 4, 8 (+2 h)	Spontaneous cooling to environment temp	323-400°C (1°C/min heating rate); 357–400°C (4°C/min heating rate); 422–563°C (8°C/min heating rate)

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Ref.	Specimen dimension (mm)	Ambient compressive strength (f_c/MPa)	Curing method	Rate of heating (°C/min) (+holding time)	Cooling process	Spalling behavior
[4]	Φ100 × 200 (f_c)	144.1–183.0	Lab environment (85% RH; 30°C day-time; 25°C night); fog room (100% RH; 28°C); sealed with aluminum foil	5, 30 (+4 h)	Spontaneous cooling to environment temp	PP (0%) + SF (1%)-490 °C
[5]	50 × 50 × 50 (f_c), 36 × 18 dog-bone (f_t), Φ75 × 150 (spalling), Φ150 × 48 (permeability)	141.2–165.7	27-day lime-saturated water at room temp	ISO 834 fire for 1 h (+0 h)	Spontaneous cooling to environment temp	PP (0 kg/m^3) + SF (0, 79, 157, 236 kg/m^3); PP (2 kg/m^3) + SF (0, 79, 157, 236 kg/m^3); PP (4 kg/m^3) + SF (0 kg/m^3); PP (6 kg/m^3) + SF (0 kg/m^3);
[6]	50 × 50 × 50 (f_c) 36 × 18 dog-bone (f_t), Φ150 × 48 (permeability), 300 × 300 × 120 (spalling)	145.0–172.1	14-day lime-saturated water at room temp	2	–	Spalling in C, AG, ST No Spalling in PP, PPST, PPAG
[7]	Φ150 × 45 (permeability), Φ50 × 100 (spalling)	148.6 159.9	27-day lime-saturated water at room temp	ISO 834 curve for 1 h	Spontaneous cooling to environment temp	Severe spalling in UHPC without PP; Slight spalling in UHPC with PP

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Ref.	Specimen dimension (mm)	Ambient compressive strength (f_c/MPa)	Curing method	Rate of heating (°C/min) (+holding time)	Cooling process	Spalling behavior
[8]	Φ50 × 100	170–220	Steam curing for 48 h at 90°C	ISO 834 curve for 30 min	–	UHPC without fibers: severe spalling situation UHPC with 0.3% jute fibers: occurrence of small spalling UHPC with 0.5% jute fibers and internal curing: small spalling
[9]	Φ50 × 100 (spalling), Φ150 × 50 (residual permeability)	125–140	Room temperature lime-saturate water for 27 days	ISO 834 curve for 1 h	Spontaneous cooling to environment temp	Spalling in UHPC with PE fibers and PP fibers (less than 0.1% volume content)
[10]	Φ50×100 (spalling)	120–140	27-day lime-saturated water at room temp	ISO 834 curve for 1 h	Spontaneous cooling to environment temp	Spalling depends on the dosage of jute fibers (more than 10 kg/m^3)
[22]	Φ50×100 (spalling) 50 × 50 × 50 (f_c) 40 × 40 × 160 (f_t)	125–150	27-day lime-saturated water at room temp	1	Spontaneous cooling to environment temp for about 12 h	Only 2 kg/m^3 of PP fiber can eliminate spalling
[11]	50 × 50 × 50 (f_c)	162.8	Hot water curing: 90 °C (1 day)	4 (+2 h)	Spontaneous cooling to environment temp	Most spalling occurred near 370 °C. From 360 to 400 °C, PP turned into various volatiles, boosting pore pressure.

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Ref.	Specimen dimension (mm)	Ambient compressive strength (f_c/MPa)	Curing method	Rate of heating (°C/min) (+holding time)	Cooling process	Spalling behavior
[12]	40 × 40 × 80 (spalling)	–	Room temperature, RH < 90% for 28 days	Blowtorch test: 1800°C flame (distance = 10 or 15 cm) for 5 min	Spontaneous cooling to environment temp	Spalling between 300°C and 350°C. Increased concentration or specific surface area of PP seemed to mitigate spalling; PAN is less effective than PP fibers.
[13]	Φ100 × 200 (f_c); 13 × 30 dog-bone (f_t); 100 × 100 × 400 (f)	166–211	Hot water curing: 90 °C (2 days)	ISO 834 curve for 2 h	Spontaneous cooling to environment temp	Steel fiber specimens showed spalling. PVA fiber was most effective against spalling, trailed by PP and PE fibers. The combination of PP and Ny fibers was more efficient in decreasing explosive spalling.
[14]	100 × 100 × 100 (f_c); 50 × 50 × 250 + 50 × 63 × 350 (f and spalling)	114.7–139.8	Cold water curing: 20 °C (14 days)	ASTM-119-98 standard temperature-time curve	Spontaneous cooling to environment temp	Specimens with a steel fiber content above 1% suffered explosive spalling exposed to nearly 650 °C; Specimens with PP fibers showed no spalling up to 1000 °C.

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Ref.	Specimen dimension (mm)	Ambient compressive strength (f_c/MPa)	Curing method	Rate of heating (°C/min) (+holding time)	Cooling process	Spalling behavior
[15]	100 × 100 × 100 (spalling and f_c), Φ100 × 210 (vapor pressure)	145.0–156.5	Cold water curing: 20 °C (56 days)	10 and 2 (+2 h)	Spontaneous cooling to environment temp	All UHPC specimens spalled, except the hybrid fiber-reinforced UHPC with coarse agg. (25% moisture).
[16]	50 × 50 × 225 (spalling)	151–168	Steam curing for 48 h; dry-cured for 90 days (60% RH; 20 °C)	0.5 (+1 h)	Spontaneous cooling to environment temp	Spalling in UHPC with steel fibers or no fiber at around 200°C.
[17]	40 × 40 × 40 (f_c, spalling and water absorption rate)	132.5 (28 days) 164.4 (91 days)	Moist-cured (25 °C)	5 or 10 (+1 h)	Spontaneous cooling to environment temp	Higher dosages of PET fibers are required to reduce spalling in UHPC compared with PP fibers.
[18]	50 × 50 × 50 (f_c); 36 × 18 dog-bone (f_t); Φ250 × 120 (spalling)	136.1–157.6	27-day lime-saturated water at room temp	ISO 834 curve for 1 h	Spontaneous cooling to environment temp	Hybrid PP and steel fibers sufficiently prevent explosive spalling. Steel fibers reduce thermal damage due to the bridging effect. Thermal stress appears to be the main trigger for concrete cracking, while pore pressure is the driving force for increased spalling.

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Ref.	Specimen dimension (mm)	Ambient compressive strength (f_c/MPa)	Curing method	Rate of heating (°C/min) (+holding time)	Cooling process	Spalling behavior
[19]	100 × 100 × 100 (spalling)	–	Lab environment curing for 56 days	ISO 834 curve for 1 h	Spontaneous cooling to environment temp	Spalling in UHPC with lower PP fiber content and length/diameter and steel fiber alone
[20]	50 × 50 × 50 (f_c); 200 × 200 × 150 (pore pressure)	133.9–144.0 (28 days) 156.0–173.7 (90 days)	27-day lime-saturated water at room temp	5 (+1 h)	Spontaneous cooling to environment temp	UHMWPE fibers and PET fibers showed no effective prevention of UHPC spalling, whereas LLDPE, PP and PA fibers were effective in mitigating spalling. U-control and U-UHMWPE are split into small pieces. UHPC with LLDPE and PET fibers exhibited whole-layer spalling.
[21]	Φ100 × 200 (spalling)	135–158	27-day lime-saturated water at room temp	ISO 834 curve for 1 h	Spontaneous cooling to environment temp	The L/D ratio of 300 is the critical value for UHPC spalling protection. Longer and finer fibers seem to work better.

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Ref.	Specimen dimension (mm)	Ambient compressive strength (f_c/MPa)	Curing method	Rate of heating (°C/min) (+holding time)	Cooling process	Spalling behavior
[22]	50 × 50 × 50 (f_c); Φ50 × 100 (spalling) 40 × 40 × 160 (f_t)	125–148	27-day lime-saturated water at room temp	ISO 834 curve for 1 h	Spontaneous cooling to environment temp	PP fibers and large-size fine aggregates showed synergistic effects in mitigating spalling.
[23]	100 × 100 × 100 (f_c and spalling)	137–144.8	Cold water curing for 27 days	5 (+2 h)	Spontaneous cooling to environment temp	2.0% MP fibers minimize thermal performance and efficiency in terms of UHPC thermal-induced damage.
[24]	100 × 100 × 100 (f_c and spalling); Φ100 × 200 (f_t); 100×100×500 (f)	139.8 (28 days) 158 (90 days)	Cold water curing for 28 days + 105°C oven dried for 2 days	5 (+1 h)	Spontaneous cooling to environment temp	High-density and basalt fibers decrease spalling.
[25]	50 × 50 × 50	120–135	RH ≥ 90%, 20 ± 1 °C for 90 days	5 (+2 h)	Spontaneous cooling to environment temp	Crack development is present but not spalling
[26]	100 × 100 × 100 (f_c and spalling)	136	Standard curing conditions for 28 days	10 (+4 h)	Spontaneous cooling to environment temp	Different failure modes for compressive loading at different temperatures.
[27]	Φ150 × 300; Φ100 × 200; 100 × 100 × 500	102.7–124.2	90 °C hot water curing for 7 days + standard 14-day curing	500°C for 30 min	Spontaneous cooling to environment temp	Spalling in UHPC specimens with only steel fibers.
[28]	100 × 100 × 100 (f_c and spalling)	113.4–147.6	Room temperature （20–25 °C） for 28 days	3 (+2 h)	Spontaneous cooling to environment temp	No spalling in hybrid steel-basalt fiber UHPC within 500–1000 °C.

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Ref.	Specimen dimension (mm)	Ambient compressive strength (f_c/MPa)	Curing method	Rate of heating (°C/min) (+holding time)	Cooling process	Spalling behavior
[29]	50 × 50 × 50 (f_c and spalling)	115	(I) 23 °C water curing for 27 days (II) 90 °C steam curing for 48 h (III) II + 150 °C dry heat curing for 8 h (IV) II + 200 °C dry heat curing for 8 h (V) II + 250 °C dry heat curing for 8 h (VI) II + 250 °C dry heat curing for 24 h	5	Spontaneous cooling to environment temp	Curing at 150 °C significantly reduced spalling; 250 °C dry heat curing completely inhibited spalling of L-UHPC. HGM particles were deformed upon curing at 250 °C, which greatly increased porosity and further mitigated the build-up of vapor pressure.
[30]	100 × 100 × 100 (f_c and spalling)	73-130	RH ≥ 95%, 21 °C for 28 days	7	Spontaneous cooling to environment temp	Using 2% steel fibers and 20% rubber granules provided the best resistance to spalling.
[31]	100 × 100 × 100 (f_c and spalling); 100 × 100 × 400 (f)	132.2–135.4	90 °C hot water curing for 3 days	5 (+2 h)	Spontaneous cooling to environment temp	PP fibers act as pressure relief and pressure reduction; Finer PP fibers are effective in maintaining optimal relative values for high-temperature performance.

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Ref.	Specimen dimension (mm)	Ambient compressive strength (f_c/MPa)	Curing method	Rate of heating (°C/min) (+holding time)	Cooling process	Spalling behavior
[32]	100 × 100 × 100 (f_c and spalling); 100 × 100 × 300 (f_c)	121.9–157.1	Cold water curing for 60 days	1, 5 (+1 h)	Spontaneous cooling to environment temp	Stepped and low-rate heating modes did not result in spalling.

Note: f_c-compressive strength; f_t-tensile strength; f-flexural strength; RH-relative humidity; C-cement; AG-aggregate.

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