Journal of Asian Concrete Federation
Vol. 11, No. 1, pp. 31-43, March 2025
ISSN 2465-7964/ eISSN 2465-7972
DOI http://dx.doi.org/10.18702/acf.2025.11.1.31

Technical Paper

Guidelines for UHPC Materials

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(Received: 18-Jan-2025; Revised: 13-Mar-2025; Accepted: 21-Mar-2025; Published online: 29-Mar-2025)

Abstract: As UHPC exhibited ultra-high strength, good toughness, and superior durability that can be intended for use in precast/cast-in-situ structures, precast structure elements, and repairs for buildings and civil engineering structures and non-structural elements, the guidelines cover the following aspects: (1) Definitions of the terminology, classifications, requirements associated with fresh and hardened properties of UHPC, (2) Constituents and mixture design for UHPC, (3) Production controls and assessment of UHPC at different stages of manufacture. This guideline also proposes methods for bending test, uniaxial tensile test, and chloride migration test. We look forward to the ready integration of UHPC into the construction industry and hope UHPC will find a variety of applications. We also hope the guidelines are instrumental in the design and construction of this novel and versatile material. Finally, we would extend our sincere appreciation for those who involved in the preparation of the guidelines.

Keywords: UHPC; Requirement; Mixture design; Production controls; Assessment; Bending test; Uniaxial tensile test; Chloride migration test

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1. Scope

UHPC is intended for use in precast/cast-in-situ structures and precast structural elements as well as repairs for buildings and civil infrastructure and non-structural elements. This guideline presents a meticulously structured and comprehensive framework specifically designed for UHPC, thereby distinguishing itself from extant literature. While existing reviews predominantly focus on isolated aspects of UHPC, such as variations in mix proportions or specific properties, they often fail to provide a systematic and integrative approach to the formulation and application of conventional UHPC. In stark contrast, this guideline consolidates and delineates detailed requirements across the entire spectrum of UHPC production and utilization, encompassing the terminology, classifications, requirements associated with fresh and hardened properties of UHPC, constituents, and mixture design for UHPC as well as the production controls and assessment at different stages of the manufacturing. By addressing these interconnected facets, the guideline ensures a holistic understanding of the preparation processes, test methods, and performance requirements for UHPC, which will aid in the design and construction of this novel and versatile material.

2. Definitions

Ultra-High Performance Concrete (UHPC) is defined as a cementitious composite containing discrete fibers for tensile post-cracking ductility. Under 28 days of standard curing (temperature: 20 ± 2 °C, humidity ≥ 95%), the steel fiber reinforced UHPC represents a minimum specified compressive strength of 120 MPa and flexural strength of 14 MPa or direct tensile strength of 5 MPa, and maximum non-steady chloride migration coefficient of 2×10^{-14} m^2/s for the matrix. Supplementary cementitious materials is the materials that, when used in conjunction with ordinary portland cement-based materials, contribute to the properties of hardened concrete through hydration and/or pozzolanic activity. Examples of supplementary cementitious materials include ground granulated blast furnace slag (GGBFS), a by-product of blast furnace, fly ash, a by-product of coal combustion in power plants, silica fume, a byproduct of the production of elemental silicon or ferro silicon alloys. Filling powder characterizes the powder materials that do not have hydraulic and/or pozzolanic activity, and fill the voids between solid particles in concrete. In addition, conventional sand demonstrates the natural and manufactured sand after sieving with size less than 4.75 mm, including river sand, mountain sand, and desalination sea sand, etc. The natural and artificial sand with bulk density no more than 1200 kg/m^3 is the porous sand. Pre-mixed dry UHPC mixture describes a uniform mixture of all dry constituents in UHPC mixture proportioning, including or excluding fibers, produced in the plant, intended for the production of UHPC in precast plants or on-site or placed in the market with an identity card. Heat curing shows a curing process aiming to accelerate hardening of UHPC by application of moderate heating at a relatively high temperature (of the order of 90 °C) at a degree of humidity greater than 90% for 48 - 72 hours. Specified property value is a required value of concrete fixed at the design stage, which is irrelevant to mixture proportion and material fabrication, etc. While characteristic property value represents the value of a required property outside of which lies a specified percentage of 95% of all the values of the population.

3. Classification

3.1 Classes according to environmental exposures

The environmental exposures are classified by exposure classes in accordance with Table 3.1.

Table 3.1 Exposure classes related to environmental conditions [1]

Class	Description of the environment	Occurring cases
1. No corrosion		
X0	For concrete without reinforcement or embedded metal: all exposures except where there is freeze/thaw, abrasion or chemical attack For concrete with reinforcement or embedded metal: very dry	Concrete inside buildings with very low air humidity
2. Corrosion induced by carbonation		
XC1	Dry or permanently wet	Concrete inside buildings with low air humidity Concrete permanently submerged in water
XC2	Wet, rarely dry	Concrete surfaces subject to long-term water contact Many foundations
XC3	Moderate humidity	Concrete inside buildings with moderate or high air humidity External concrete sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2
3. Corrosion induced by chlorides		
XD1	Moderate humidity	Concrete surfaces exposed to airborne chlorides

XD2	Wet, rarely dry	Swimming pools Concrete components exposed to industrial waters containing chlorides
XD3	Cyclic wet and dry	Parts of bridges exposed to spray containing chlorides Pavements Car park slabs
4 Corrosion induced by chlorides from seawater		
XS1	Exposed to airborne salt but not in direct contact with seawater	Structures near to or on the coast
XS2	Permanently submerged	Parts of marine structures
XS3	Tidal, splash and spray zones	Parts of marine structures
5. Freeze/thaw attack		
XF1	Moderate water saturation, without a de-icing agent	Vertical concrete surfaces exposed to rain and freezing
XF2	Moderate water saturation, with a de-icing agent	Vertical concrete surfaces of road structures exposed to freezing and airborne de-icing agents
XF3	High water saturation, without de-icing agents	Horizontal concrete surfaces exposed to rain and freezing
XF4	High water saturation with de-icing agents or seawater	Road and bridge decks exposed to de-icing agents Concrete surfaces exposed to direct spray containing de-icing agents and freezing Splash zone of marine structures exposed to freezing
6. Chemical attack*		
XA1	Slightly aggressive chemical environment	concrete structures exposed to natural soils and groundwater, such as tunnel lining structure, pile foundation., etc.
XA2	Moderately aggressive chemical environment	concrete structures exposed to natural soils and groundwater, such as tunnel lining structure, pile foundation., etc.
XA3	Highly aggressive chemical environment	concrete structures exposed to natural soils and groundwater, such as tunnel lining structure, pile foundation., etc.

Note: *, The classification is based on the chemical characterization of soil according to [2] and [3]. It also includes salt crystallization attack.

3.2 Classes according to fresh UHPC

Fresh UHPC shall remain homogeneous and shall not show segregation of fibers or a solid fraction of the constituents. It shall be classified into three categories according to its workability, as shown in Table 3.2.

(1)W I: self-compacting, i.e., the UHPC is generally able to be placed without vibration or use of a mechanical flow aid;

(2)W II: viscous, i.e., the UHPC is generally able to be placed without vibration but requires the use of a mechanical flow aid;

(3)W III: exhibits a flow threshold, i.e., the UHPC is generally able to flow under the effect of dynamic shearing but whose free surface at rest may keep sloping

Table 3.2 Workability classes for UHPC [1]

Class	Flow table test (in accordance to standard EN12350 - 5 or each country's equivalent standard) (mm)	Flow table test with ASTM conical mould without jolting (adapted from standard ASTMC230/C230M or each country's equivalent standards) (mm)	Slump flow test (by reference to standard EN 12350 - 8 or each country's equivalent standards) (mm)
W I	Without vibrating: ≥560	≥ 270	≥ 760
W II	Without vibrating: 420 to 560 After 15 joltings: >560	230 to 270	660 to 760
W III	Without vibrating: <420 After 15 vibratings: > 560	< 230	< 660

NOTE: The choice of the test is determined by mutual agreement between the specifier, the user, and the supplier of UHPC.

3.3 Classes according to hardened UHPC

The classes and mechanical performance of UHPC shall conform to the requirements in Table 3.3. It can obtained that regardless of the grade of UHPC, the elastic modulus is required as ≥ 40 GPa, and the direct tensile strength and flexural strength should be ≥ 8 MPa and ≥ 14 MPa.

Table 3.3 Grade and specified mechanical performance of UHPC.

Grade	Compressive strength[1], MPa	Elastic modulus, GPa	Direct tensile strength or flexural strength[2], MPa
U120-W I			
U120-W II	≥ 120		
U120-W III			
U140-W I	≥ 140		
U140-W II			
U140-W III			
U160-W I			
U160-W II	≥ 160	≥ 40	≥ 8 or ≥ 14
U160-W III			
U180-W I			
U180-W II	≥ 180		
U180-W III			
U200-W I			
U200-W II	≥ 200		
U200-W III			

Note: (1) It can be 100 × 100 × 100 mm cubes, 100 × 100 × 200 mm prisms, and Φ100 × 200 mm cylinders. The conversion coefficient in compressive strength of 100 mm cubes to Φ100 × 200 mm cylinders is 0.85 to 0.98, depending on mixture proportion. The conversion coefficient in compressive strength of 100 mm cubes to 100 × 100 × 200 mm prisms is 0.74 to 0.99 with an average value of 0.88, depending on mixture proportion [4, 5], (2) The tensile strength and/or flexural strength depends on the type and amount of fibers used, so only minimum strength is prescribed.

4. Constituent Materials of UHPC

4.1 General

UHPC can be manufactured using cement, supplementary cementitious materials, filling powder, aggregate, fiber, and chemical admixture, etc. The constituent materials for UHPC are chosen to conform to the fresh properties as described in Section 3.2 and hardened properties as specified in Section 3.3.

4.2 Cement

The commonly used cement for UHPC is portland cement (equivalent to CEM I in [6], or [7] Type III, or [8, 9]) conforming to the requirements for cement in each country's specifications. In addition, other types of speciality cements can be used for different UHPC applications, subject to performance specifications. When cement of 4.2 (1) is not used, preliminary tests, such as setting time, mortar strength, soundness, MgO content, and CaO content, shall be conducted to verify whether required performance proper to UHPC shall be secured.

4.3 Supplementary cementitious materials (SCMs)

Silica fume, fly ash, granulated blast furnace slag, metakaolin, rice husk ash, etc. can be used as SCMs for UHPC [10, 11]. These SCMs used for UHPC shall conform to the requirements in each country's specifications. When these SCMs are used, preliminary tests, such as specific surface area and SiO_2 for silica fume, water demand, soundness, and ignition loss for fly ash, as well as specific surface area and reactivity index for GGBS, shall be conducted prior to their utilization to verify whether required performance suitable for UHPC shall be secured.

4.4 Filling powders

Quartz and limestone powders, etc. with sizes in the range of 1 - 100 μm, can be used as filling powders for UHPC. The filling powders used for UHPC shall conform to the requirements in each country's specifications. When these filling powders are to be used, preliminary tests, such as density and specific gravity, shall be conducted prior to their utilization to verify whether sufficient performance suitable for UHPC shall be secured.

4.5 Aggregates

Quartz sand, natural sand, crushed stone, etc. shall be used as aggregates for UHPC, depending on their required performance of UHPC as specified in Sections 3.2 and 3.3. The aggregates shall conform to the requirements in each country's specifications. In addition, preliminary tests, such as grading, fineness modulus, content of clay lump, bulk density, impurities, soundness, and deleterious materials, shall be conducted on the sand prior to its utilization to verify whether required performance suitable for UHPC shall be secured.

When normal sand is used, management shall be done to cope with surface moisture variation of sand [12]. Moreover, Porous sand can be used to partially replace normal sand to reduce autogenous shrinkage. The replacement percentage and performance of the porous sand shall be tested whether required performance suitable for UHPC shall be secured. An optimal porous sand content, ranging from 10% to 25%, by the volume of total aggregate, is recommended. Porous sand shall be soaked in water for at least 24 h before use. For the sake of high autogenous and low shrinkage of UHPC, porous sand with a nano-size porosity between 15% - 35% is preferred.

4.6 Fibers

Various fibers, such as steel fiber, organic fiber, and synthetic fiber, can be used to satisfy the required performance of UHPC. High-strength micro-steel fiber shall be used as discrete reinforcement for UHPC; its performance index shall conform to the requirements in Table 4.1. The commonly used steel fiber is characterized with a length in the range of 12 - 16 mm, and diameter of 0.18 to 0.22 mm. In addition, other types of fibers can be used in UHPC, such as polymer fibers and specially constructed steel fibers, conforming to the requirements for fibers in each country's specifications. Preliminary tests, such as elongation and tensile strength, etc. shall be conducted on the fiber prior to its utilization to verify whether required performance proper to UHPC shall be secured.

Table 4.1 Performance index of steel fiber [13]

Item	Performance index
Tensile strength, MPa	≥ 2000
Proportion of fiber with a length in the range of 12 - 16 mm, % [A]	≥ 96
Proportion of fiber with a diameter of 0.18 to 0.22 mm, % [B]	≥ 90
Rate of qualified shape, %	≥ 96
Impurity content, %	≤ 1.0

NOTE: (1) A, Average length of 50 fiber samples is in the range of 12 - 16 mm, (2) B, Average diameter of 50 fiber samples is in the range of 0.18 - 0.22 mm.

4.7 Chemical admixtures

The utilized chemical admixtures for UHPC include superplasticizer, shrinkage-reducing agent (SRA), and anti-foaming agent, etc. Chemical additives may be incorporated in UHPC to improve selected properties or provide them with specific properties. High-range water reducer with a water-reducing rate greater than 30% shall be used. When newly developed chemical additives are used, the composition of the UHPC with and without additives shall be considered different, and then a new design test shall be carried out.

4.8 Mixing water

General suitability for use is established for potable water and groundwater compliant with the standards and the standard concrete construction specifications from each country.

5. Mixture Design for UHPC

5.1 General

The mixture proportions of UHPC shall be designed to meet the required performance of UHPC as defined in Sections 3.2 and 3.3. The mixture proportions and constituent materials of UHPC can vary according to the environmental exposure conditions specified in Section 3.1, conditions of the site and structures. The mixture proportions of UHPC shall be determined after testing and checking whether the required performances are satisfied by means of a trial mixing.

5.2 Procedure

Mixture design of UHPC is proposed in the following procedure:

The method for mix design of UHPC can be established by considering the situation of each country, the conditions of structures and sites. Determination of the required performance of UHPC as defined in Sections 3.2 and 3.3 considering the environmental exposure conditions of 3.1 and the conditions of structures and constructions etc.

Choose constitutive materials of UHPC to satisfy the required performance as specified in Sections 3.2 and 3.3.

Select unit water amount, water to cementitious materials ratio (w/cm), amount of cement, supplementary cementitious materials, and filling powder and aggregate, etc.

Choose type and amount of fibers.

Choose type and amount of chemical admixtures.

Trial mixing.

Verify the required performance of fresh UHPC as defined in Section 3.2 and other fresh performance.

Select curing methods.

Verify the required performance of hardened UHPC as defined in Section 3.3 and other hardened performance.

Determine specified mixture proportions of UHPC.

6. Manufacturing of UHPC

6.1 General

UHPC develops different properties according to the applied mixer and mixing method. Therefore, the mixer and mixing method shall be decided carefully in advance. The mixing of UHPC shall be executed sufficiently until obtaining a homogeneously mixed material. And the manufacture of UHPC is based on the standard concrete construction specifications in each country or [14].

6.2 Storage of raw materials

6.2.1 Powder materials

The powder materials shall be stored and marked separately according to their types, grades, and manufacturers, etc. It should be noted that the powder materials in storage, including cement and SCM, shall not be higher than 60°C and shall be weatherproof. Moreover, manufacturers shall not use damp, agglomerated, and contaminated cement and shall not use cement with a shelf life of more than three months. If the defective quality of powder materials is suspected, the quality check shall be imperatively performed through a preliminary test prior to the utilization for UHPC manufacturing.

6.2.2 Aggregates

The aggregates for UHPC shall be stored separately according to their types, sizes, and gradings to avoid mixed up and batch their fractions separately. Moreover, the aggregates for UHPC shall be of good quality, uncontaminated, and uniform in grading and moisture content. When normal sand is used, management shall be done to or cope with surface moisture variation of the sand. There is no limit for the period of use of aggregate. However, if the defective quality is suspected, the quality check shall be imperatively performed through a preliminary test prior to the utilization of UHPC manufacturing.

6.2.3 Chemical admixtures

The chemical admixtures shall be stored and marked separately according to their types and manufacturers. Powder-type admixtures shall prevent agglomeration. If there is agglomeration, the test shall be carried out, and the quality shall meet the requirements. Liquid-type admixtures shall be stored in a closed container and shall be sun-resistant and anti-freezing. If there are precipitation and other abnormal phenomena, it shall be tested before use. If the quality of chemical admixtures is deemed to be defective, the quality check shall be imperatively performed through preliminary tests prior to the utilization.

6.2.4 Fibers

The fibers shall be stored and marked separately according to types, specifications, and manufacturers, and shall be weatherproof and rust-proof. When a large portion of the steel fibers has experienced corrosion or distortion due to extended exposure to the atmosphere, these steel fibers shall not be used. However, usage is permitted provided that a proper check has been completed through the preliminary test, and it is judged that there is no anomaly in the performance of UHPC.

6.3 Measurement of raw materials

The measuring method and equipment of each raw material shall be adapted to the manufacture of UHPC and shall provide accuracy within the prescribed measuring tolerance. The measurement equipment shall have a valid certificate issued by the legal department and shall be verified on a regular basis. The producer shall be self-inspected at least once a month. Before starting each work class, zero the calibration of the measurement equipment. The measuring tolerance shall follow the values given in Table 6.1 or each country's specifications.

Table 6.1 Allowable measuring tolerance [1, 13, 15]

Type of material	Measurement unit	Maximum allowable tolerance
Water	Mass or volume	-2%, +1%
Cement	Mass	-1%, +2%
SCMs	Mass	-1%, +2%
Filling powders	Mass	±2%
Aggregate	Mass	±2%
Chemical admixtures	Mass or volume	±1%
Fibers	Mass	±1%
Premixed dry mixture	Mass	-1%, +2%

6.4 Mixing of UHPC

6.4.1 General

Proper mixing is critical to produce uniform mixtures and ensure UHPC achieves desired properties.

Accordingly, the type of mixer to be applied shall be considered in advance to determine the adequate introduction sequence of the materials, mixing method, and mixing time. Since UHPC usually contains several types of raw materials and strict requirements for mixing, pre-mixing of all dry raw materials in UHPC shall be conducted in-plant if UHPC is cast on site.

6.4.2 Pre–mixed dry mixture

A proper mixer shall be selected for the preparation of the pre-mixed dry mixture. The pre-mixed dry mixture may include all dry ingredients in UHPC mixtures, such as cement, supplementary cementitious materials, filling powders, aggregates, powder-type chemical admixtures, fibers, etc. They shall be precisely weighed following the designed mixture proportion and mixed to produce a uniform mixture. Fibers may not be included in the pre-mixed dry mixture, but added during the mixing of wet UHPC mixture following the designed mixture proportion. The pre-mixing materials can be delivered in different ways (bulk, ton, bag, sack, etc.) according to conditions on the site.Identically to ordinary cement, careful attention shall be paid for the storage of the pre-mixing materials. Products of which quality seems suspicious shall be checked for quality prior to their utilization.

6.4.3 Mixing procedure of UHPC mixture

Compulsory concrete mixers are recommended to better disperse materials. The mixing of UHPC generally proceeds with the following sequence: firstly, dry mixing of powder materials and aggregate, etc. for approximate 1 - 2 minutes; secondly, the introduction of water and all or part of the chemical admixture with mixing duration of 5 - 10 minutes until securing sufficient workability; thirdly, the input of the fibers and the rest of the liquid-based chemical admixture within 1 - 2 minutes until securing uniform distribution of fibers; and in the final phase, discharge of fresh UHPC. After completion of the fiber introduction, mixing shall be performed continuously at a constant speed to secure the targeted flowability and distribution of the fiber.

7. Testing of Fresh and Hardened Properties of UHPC

7.1 Fresh properties of UHPC

7.1.1 Workability

It shall be done with reference to one of the tests, as listed in Table 3.2, depending on the aspect ratio of the fibers and the aggregate used in UHPC. The primary test method for evaluating the workability of UHPC shall be the slump flow test. The slump flow test shall comply with the method of test for the slump flow of fresh concrete in each country's specifications or [16-20]. In the case of testing by mini-slump flow instead of slump flow, the mini-slump flow test shall comply with the test method for the flow of hydraulic cement mortar in each country's specifications. In conditions not requiring self-consolidation, the consistency of UHPC shall comply with the standards and the testing methods in Table 4.2 or each country's specifications.

7.1.2 Air content

The air content of UHPC shall be measured following testing methods specified in each country's standards or [21]. It shall be equal to or less than 5%.

7.1.3 Times of setting

The setting time of UHPC mixtures without fiber shall be measured for the times of setting of mortar or concrete following the methods specified in each country's standards.

7.2 Preparation and curing of test specimens

7.2.1 General

Prepare and cure test specimens in the laboratory in accordance to each country's specifications, with the exceptions described in this guideline. If test specimens of UHPC are prepared in the field, cast and initially cure the specimens in accordance with each country's specifications, with the exceptions described in this guideline. The specimen sizes for hardened properties of UHPC shall comply with Section 7.3, as summarized in Table 7.1. The fresh UHPC mixture shall be judged by visual examination during production process. During casting, the flow distance shall be controlled to avoid segregation or balling.

Table 7.1 Summary of hardened properties and recommended specimen sizes of UHPC

Hardened properties	Specimen size
Cubic compressive strength	100 × 100 × 100 mm cubes
Axial compressive strength	100 × 200 mm cylinders, 100 × 100 × 200 mm prisms
Flexural strength	100 × 100 × 400 mm prisms
Direct tensile strength	Dog-bone specimen
Static modulus of elasticity and Poisson’s ratio	Φ100 × 200 mm cylinders, 100 × 100 × 200 mm prisms
Drying shrinkage	25 × 25 × 285 mm (no fiber and aggregarte), 75 × 75 × 285 mm (with fiber), and 100 × 100 × 400 mm prisms (with coarse aggregate)
Autogenous shrinkage	-
Creep	Φ100 × 200 mm cylinders, 100 × 100 × 400 mm prisms
Resistance to abrasion	Φ152 × 76 mm cylinders
Resistance to freezing and thawing	100 × 100 × 400 mm prisms
Non-steady rapid chloride migration coefficient	Φ100 × 30 mm disk cut cylinders

7.2.2 Molding of specimens

The molding of specimens shoulf be considered as follows:

(1) The molding of specimens shall comply with this guideline as described in Section 8.3.

(2) Fill fresh UHPC into molds in one pour.

(3) Tamping rods and vibrators shall not be used in fabricating and consolidating UHPC specimens.

(4) Consolidate all specimens by tapping the sides of the mold 30 times with a mallet.

7.2.3 Curing of specimens

The curing of specimens shall comply with this guideline as described in Section 8.

7.3 Hardened properties of UHPC

7.3.1 General

The compressive strength, flexural strength, and/or direct tensile strength of UHPC shall be tested. The other tests shall be performed selectively according to the exposure environment conditions and the required performance of structures, etc. In the stage of UHPC mixture design, all tests shall be carried out so that they can be reflected in the design and construction/fabrication of the UHPC structures.

7.3.2 Compressive strength

The compressive strength of UHPC shall be determined in accordance to each country’s specifications [22-25], with the exceptions described in this guideline on materials and structures. The load shall be applied at a rate of movement (platen to crosshead measurement) corresponding to a stress rate of 1.2 - 1.4 MPa/s. The specimen size of compressive strength shall comply with Section 7.2.1, as summarized in Table 7.1. Prior to testing, all cylinders shall be ground such that the ends do not depart from perpendicularity to the axis by more than 0.5° (approximately equivalent to 1 mm in 100 mm). The ends of the cylinders shall be ground plane to within 0.050 mm. Capping compounds and unbonded neoprene pads shall not be used.

7.3.3 Flexural behavior

Flexural strength of UHPC shall be determined in accordance with each country’s specifications or [26], with the exceptions described in this guideline. The specimen displacement rate at the middle span shall be 0.25 ± 0.05 mm/min. The prisms for flexural strength measurement of UHPC shall be 100 × 100 × 400 mm. Dissipated energy T150 of UHPC specimens at a mid-span deflection of L/150, i.e. area under load-deflection curve with deflection from 0 to L/150, shall be determined.

7.3.4 Direct tensile strength

Direct tensile strength of UHPC shall be determined in accordance with each country’s specifications with the exceptions described in this guideline on materials and structure. In the case of known first-cracking strength, i.e. tensile strength of non-fiberous UHPC matrix, the direct tensile strength of UHPC made with different fiber characteristics shall be inferred according to the following equations:

$$f_{tk} = f_{t0,k}(1+\alpha_f \lambda_f) \tag{8.1}$$

$$\lambda_f = \rho_f l_f / d_f \tag{8.2}$$

where f_{tk} (MPa) is the characteristic value of direct tensile strength of UHPC; $f_{t0,k}$ (MPa) is the characteristic value of direct tensile strength of nonfiberous UHPC matrix; α_f (unit-less) is the factor associated with steel fiber, which is 0.15; λ_f (unit-less) is the parameter related to steel fiber content; ρ_f (unit-less) is the steel fiber content; l_f (mm) is the length of fiber; d_f (mm) is the fiber diameter. The characteristic value direct tensile strength of UHPC shall be determined by experiment. If no experimental result is available, it shall be determined according to Table 7.2.

Table 7.2 Characteristic value of direct tensile strength of UHPC

Strength	Strength Grade				
	U120	U140	U160	U180	U200
$f_{t0,k}$ (MPa)	5.6	6.6	7.5	8.5	9.4

7.3.5 Static modulus of elasticity and Poisson´s ratio

Static modulus of elasticity and Poisson's ratio of UHPC shall be determined in accordance to each country's specifications or [23, 27, 28], with the exceptions described in this guideline. The specimens for measuring the static modulus of elasticity and Poisson's ratio of UHPC shall be 100 × 200 mm cylinders or 100 × 100 × 200 mm prisms. Test specimens of other shapes or dimensions can also be used according to the situation. The loading rate shall be applied as specified in Section 7.3.2.

7.3.6 Shrinkage

7.3.6.1 Autogenous shrinkage

Autogenous shrinkage of UHPC shall be determined in accordance to each country's specifications or [29]. Specimens shall be cast into tubes immediately after casting and sealed. The autogenous shrinkage data shall be recorded at intervals of at least 10 minutes until the testing age. A non-contact corrugated tube system can be employed to measure the autogenous shrinkage of UHPC. The inner diameter of the corrugated polyethylene tube shall be at least three times the length of the fiber used. In the case of non-fiberous UHPC matrix, corrugated polyethylene tube with an outer diameter of 30 mm and length of 340 ± 5 mm, shall be used. The plastic tubes are made of 0.5 ± 0.2 mm thick low-density polyethylene (PE) and have triangular-shaped corrugations in order to minimize restraint in the longitudinal direction. The distance between corrugations is 5.8 ± 0.2 mm. The mold is tightly closed with two tapered end plugs having a length of 19 ± 0.5 mm. The diameter of the plastic end plugs tapers from 21 ± 0.1 mm to 22.4 ± 0.1 mm. Time zero, corresponding to the time of the first measurement of length change, shall be carefully selected according to the experimental purpose. A gauge measures length changes at one end of the specimen. The measuring range of the gauge shall be at least 10 mm, and the resolution shall be at least 0.0025 mm, corresponding to a resolution of about 6 μm/m for the calculated strain. In addition, three replicate specimens shall be tested for each cement paste or mortar.

7.3.6.2 Drying shrinkage

Prisms measuring 75 × 75 × 285 mm or 100 × 100 × 400 mm shall be used to determine the drying shrinkage of UHPC with fiber and/or coarse aggregate, respectively. The specimens shall be demoulded 24 h after casting and then cured in standard curing room of 20 ± 1°C and relative humidity (RH) greater than 95% for 48 h. The minimum duration of the shrinkage test shall be no less than 56 d. Measure length change values for each specimen at any age to the nearest 0.001% and report average shrinkage values to the nearest 0.000001%. In addition, prisms measuring 25 × 25 × 285 mm shall be used to determine the drying shrinkage of UHPC matrix without any fiber and coarse aggregate.

7.3.7 Creep

Creep in compression of UHPC shall be determined in accordance to each country's specifications or [30, 31], with the exceptions described in this guideline. Creep specimens and preparation shall comply with Section 6.2.1 and Table 7.1. Testing specimens of other shapes or dimensions can also be used according to the situation. Creep testing shall be conducted at a sustained load of 40% of the measured compressive strength of the UHPC.

7.4 Durability of UHPC

7.4.1 Chloride transport

The non-steady diffusion coefficient of chloride ions shall be measured using the matrix specimens with the same mixture proportion of the UHPC without fiber after 28 days of moist curing at 20 ± 2 °C. The testing duration usually lasts 400 to 800 hours [32, 33]. Moreover, the abrasion resistance also needed to test, such as the specifications [34].

7.4.2 Resistance to freezing and thawing

Resistance to freezing and thawing of UHPC shall be determined in accordance to each country's specifications or [35], with the exceptions described in this materials guideline and structural guideline. Continue testing each specimen until it has been subjected to at least 300 cycles or until its relative dynamic modulus of elasticity, as defined in [35], reaches 90%, whichever occurs first unless other limits are specified. In addition, the relative dynamic modulus limit should be the same as that for normal concrete due the same testing procedure.

8. Formworks, Transportation, Placement, and Surface Finishing

8.1 Formworks

When UHPC exhibits low flowability, the formworks shall be set up following the guidelines for normal concrete in each country. Moreover, when UHPC exhibits high flowability, the form shall be set up following the guidelines for self-compacting concrete in each country.

8.2 Transport

UHPC shall be transported as soon as possible after mixing to minimize the material segregation. For cold, severe cold or hot weather conditions, the mixing tank of concrete mixing truck shall be insulated. The duration between discharge of fresh UHPC mixture from mixer to mixing truck should not be longer than 90 minutes. If prolonged transport time is needed, efficient techniques after experimental verification shall be taken. The transport vehicle shall ensure that the UHPC mixture does not produce segregation, air entrapment, and non-uniform fiber distribution during transportation.

8.3 Placement

The requirements about the placement of UHPC specimens are as follows:

(1) UHPC shall be placed once delivered to the site. The placement process of fresh UHPC shall be fixed in a manner to avoid segregation, air entrapment, upsetting the uniformity of the fiber distribution and fiber orientation.

(2) It is also recommended that UHPC be poured without interruption. In case of a discontinuous process with interrupted concreting or in case of a long delay between batches, a skin may form on the surface of the last UHPC layer. Surface drying must be avoided, and UHPC layers must be jointed together by rodding the interface surface to ensure fiber continuity

(3) In parallel with the systematic checking of workability, the uniformity of fresh UHPC shall be checked during the pouring or forming process. To achieve this, samples shall be taken to characterize the uniformity of the granular distribution, the uniformity of the distribution of fibers, absence of fibers balling, and absence of agglomerates with no fibers. It shall not demonstrate segregation of the mixture, entrapping of air or ingress of foreign materials,

and the exposure of fibers on the surfaces and at the corners.

(4)The detection of fibers balling and agglomerates with no fibers is typically carried out by visual inspection. Fiber uniformity and distribution may be verified by weighing measures after washing the samples.

(5)Drop heights over 0.5 m are not recommended. If it cannot be avoided, an appropriate test shall be carried out beforehand to demonstrate that there is no segregation of fibers from the matrix nor any form of fiber clusters. Vibration systems shall be adapted according to the flowability and consistency of UHPC.

(6)The vibration conditions need to be optimized due to the repercussions of fiber alignment in the in-situ UHPC.

(7)The merging joint with the subsequent part during the placement of UHPC may create a defect that shall preferably be prevented using appropriate measures. If such a joint is unavoidable, it is recommended to disperse the steel fibers using a tamping rod.

(8)The conformity of UHPC to this standard implies that it has been produced, transported, and placed when the ambient temperature is higher than - 5 °C and lower than 40 °C. For placement temperatures outside this range, the placement shall conform to the standard concrete construction specifications in each country.

8.4 Surface finishing

The surface finishing of UHPC after casting shall follow the procedures for conventional concrete in each country.

9. Curing

9.1 General

Proper curing regimes such as moist curing, steam curing or a combination of them shall be selected and applied to UHPC to achieve the required performance based on the production and construction conditions, such as the specifications [36-38].

9.2 Initial curing

Immediately after casting and finishing, UHPC shall be kept in a moist environment with relative humidity higher than 95% to prevent moisture loss from the UHPC. Curing compounds or equivalent procedures can also be applied to avoid moisture loss from the UHPC.

9.3 Removal of shoring

Removal of UHPC forms shall follow the procedures for conventional concrete.

9.4 Moist curing

Within 30 min upon removing the molds, specimens shall be cured with free water maintained on their surfaces complying with the requirements as specified in Sections 9.4 and 9.5. It should be noted that sufficient moisture curing shall be executed for a certain period of time based on the performance requirements for the UHPC. Moreover, the moist curing procedure shall comply with Section 9.2.

9.5 Heat curing

(1) If heat curing is required, it is necessary to set up the temperature, duration and other conditions of heat curing to achieve the required performance of UHPC according to the type, construction requirements, location conditions, and environmental conditions of the construction as well as its purpose. The temperature and duration of heat curing shall be set through a test in advance according to the required performance of the UHPC as described in Section 3.3. The maximum temperature of steam curing shall be lower than 90 °C and the temperature shall be lowered down with a rate of less than 15 °C/h to the condition in which the difference in the surface temperature of construction member and ambient temperature is not more than 20 °C, and the rapid cracking (pattern) shall not occur during the cooling.

10. Quality Control

10.1 Raw materials

The raw materials of UHPC shall be inspected following each country's specifications.

10.2 UHPC

The quality control testing of UHPC shall follow Table 10.1.

Table 10.1 Quality control of UHPC.

Item	Testing method	Frequency	Quality criteria
Mixing	Weighed value of each material	Every segment or every 50 m^3	Within allowable values
State of fresh concrete	Observation of the external appearance	Every segment or every 50 m^3	- Stable with good workability and homogeneous quality - Eventual dispersion and lumping of steel fiber
Slump flow		Every segment or every 50 m^3	Suitability with decided conditions
Air content			3.5±1.5%
Temperature	Temperature measurement		Suitability with decided conditions
Compressive strength		Every segment or every 50 m^3 (fabrication of more than 5 specimens, an average of minimum 3 specimens)	- Average larger than design characteristic compressive strength - Not more than 1 test value lower than 100% but higher than 90% of the design characteristic compressive strength
Direct tensile strength (notched specimen)		Every segment or every 50 m^3 (fabrication of more than 5 specimens, an average of minimum 3 specimens)	

11. Summary

Ultra-high performance concrete (UHPC) has received widespread attention due to its ultra-high strength, high toughness and excellent durability. This article mainly introduces the assessment gudilines for UHPC through terminology, classifications, and properties requirements. First of all, the definitions and classification associated with fresh and hardened properties of UHPC were given. For the constituent materilas of UHPC, the cement, supplementary cementitious materials, filling powders, aggregates, fibers, chemical admixtures, and mixing water were introduced. The mixture design, manufacturing, and production controls of UHPC was also proposed. Finally, this paper also proposes methods for fresh properties test, bending test, uniaxial tensile test, and chloride migration test.

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