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Application of Supplementary Cementitious Materials in Precast Concrete Industry

Amin Akhnoukh

Abstract

Supplementary cementitious materials (SCMs) are increasingly incorporated into the concrete mix design. Silica fume, fly ash, and multi-wall carbon nanotubes are used to improve concrete mix properties. The objective of this chapter is to decipher the impact of different SCMs on the fresh and hardened concrete properties, including concrete flowing ability, initial strength, final strength, modulus of elasticity, and modulus of rupture. In addition, the impact of SCMs on mitigating the alkali-silica reactivity of concrete and increasing the hardened concrete long-term performance is investigated. Developed concrete mixes, incorporating SCMs, are used in fabricating different precast/prestressed bridge girders. The impact of improved concrete properties on precast girder performance in increased flexure, shear, and span-to-depth ratio significantly improves project sustainability and reduces the overall project life cycle cost.

Keywords: silica fume, fly ash, carbon nanotubes, high strength concrete, durability, alkali-silica reactivity, supplementary cementitious materials

1. Introduction

High-strength concrete is increasingly used in the construction market in the United States and on a global scale. High-strength concrete is characterized by high early strength, high final strength, increased durability, and improved long-term performance. The use of high-strength concrete is advantageous in heavy construction projects, especially in precast/prestressed bridge construction. The mechanical advantage of high-strength concrete is attributed to the incorporation of supplementary cementitious materials (SCMs) in partial replacement of Portland cement. SCMs with different sizes and fineness are incorporated in the stepwise replacement of cement to create a binary mix (using one SCM) or ternary mix (using two SCMs). Incorporated SCMs increase the amount of the binder in the mix, which increases the mix strength. In addition, the improved packing order of the cementitious matrix reduces the mix void ratio and, hence, improve its durability and long-term performance. High-strength concrete was primarily used in the design and construction of high-rise buildings in major European cities and large/crowded American States as New York, Illinois, and California. In addition, the high compressive strength enabled bridge design engineers to precast long-span bridge girders with very high span-to-depth ratios (span/depth ratio greater than 30).

Recently, concrete mixes with higher strength and improved long-term performance were developed using SCMs, steel fibers, and a very low water-to-powder ratio. These mixes, commercially available in the United States construction market under the term *ultra-high-performance concrete*, are standardized by different agencies including the Federal Highway Administration (FHWA) in the United States, Association Francaise de Genie Civil (AFGC) in France, and the Japanese Society of Civil Engineers (JSCE). In their definition of the UHPC, the aforementioned organizations define UHPC as a cement matrix with minimum compressive strength of 150 MPa due to the high proportion of SCMs and very low water-to-powder ratio, and significant tensile strength due to the incorporation of random high-strength steel fiber. Different UHPC proprietary mixes are available in the international markets with standard characteristics. Examples of the proprietary mixes are BSI “Beton Special Industrial” (special industry concrete) developed by Eiffage, Cemtec developed by LCPC, and different kinds of ductal concrete mixes jointly developed by Bouygues, Lafarge, and Rhodia. Ductal concrete marketed by Lafarge and Bouygues is the only proprietary UHPC mix commercially available in the United States local construction market.

This chapter introduces different types and classifications of concrete mix designs, based on mix strength, workability, and long-term performance, different types of SCMs currently used in developing special concrete mixes, their impact on mix properties, and the main impediments to the widespread of SCMs application in precast/prestressed concrete industry.

2. Special concrete mix development

The complexity of construction projects, and the need to buildings structures with increased heights, bridges with longer spans, and infrastructure projects with minimized maintenance necessitates the development of concrete mixes with superior characteristics, higher durability, and minimal need for maintenance. Thus, concrete mixes with increased rheology and high flowing ability, high early and final strength are required. In addition, increased concrete durability is desired to minimize the need for regular maintenance and reduce the project life cycle cost. Special types of concrete mixes are displayed in the following section.

2.1 Ultra-high-performance concrete

Ultra-high-performance concrete (UHPC), known in the European market as reactive powder concrete, is a new class of concrete developed in the 1990s. UHPC concrete are currently used in high-rise building construction in the United States, and in specific transportation, and defense applications. UHPC mixes are characterized by self-consolidation concrete (SCC) workability, fast setting, high early strength, and final compression capacity that reaches 250 MPa [1, 2]. UHPC is characterized by improved long-term performance, low voids, higher alkali-silica resistivity due to the incorporation of SCMs, and post-cracking stiffness due to the placement of random steel fibers within the mix [3, 4]. The aforementioned characteristics represent a combination of the advantages of high-performance, self-consolidation, and fiber reinforcement inclusion, as shown in **Figure 1**.

2.2 High-strength concrete

The term high-performance concrete (HPC) is used to describe concrete produced with selected high-quality mix constituents, optimized mix design, and low

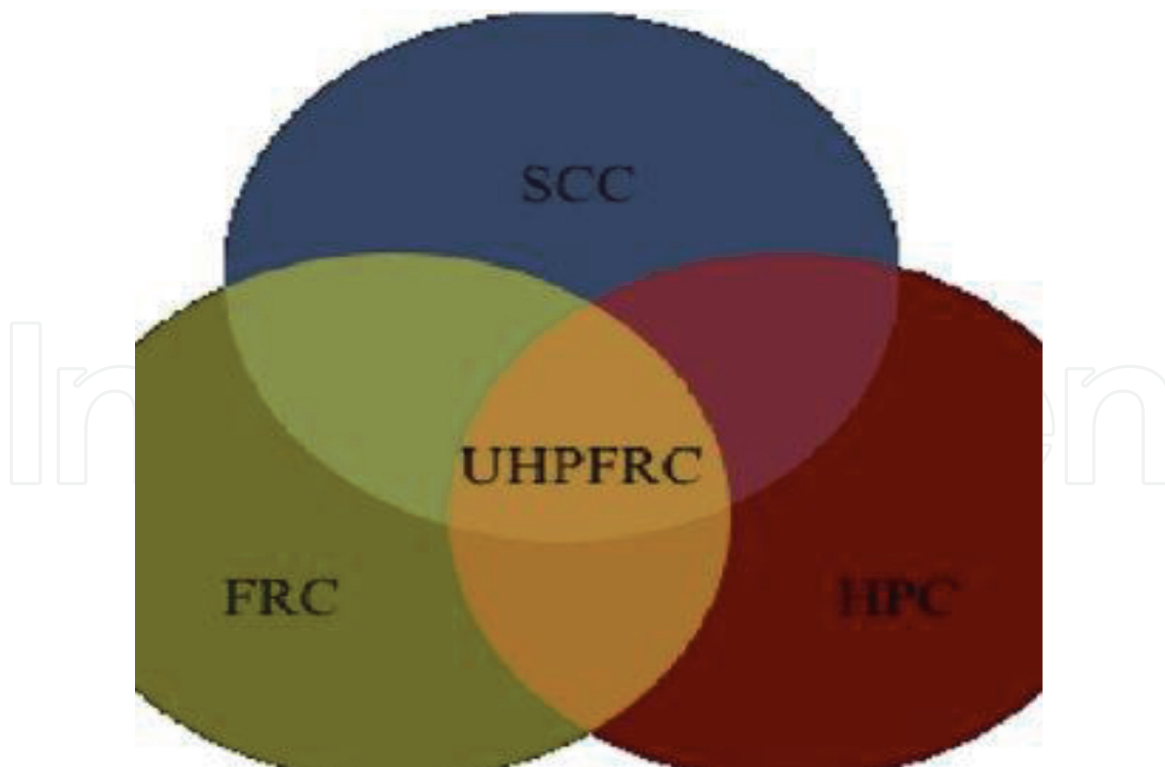


Figure 1.
Composition of UHPFRC [2].

water-to-powder (W/CM) ratio. According to the American Concrete Institute (ACI), HPC is defined as “concrete meeting special combination of characteristics and uniformity requirements,” which cannot be achieved using conventional constituents, and regular mixing and curing procedures [5]. The mix composition of HPC depends mainly on the replacement of a significant amount of Portland cement and incorporating SCMs up to 40% by weight.

2.3 Self-X concrete mixes

Self-X concrete mixes are special types of mixes that provide specific advantage (s) to address a given project challenge. Examples of Self-X concrete mixes are as follows:

1. Self-healing concrete mixes, where developed hair cracks are treated internally using epoxy capsules incorporated in the mix,
2. Self-cleaning concrete mixes, known as photocatalytic concrete, used in maintaining the concrete surface texture and cleanliness by decomposing dirt and/or pollutants affecting the concrete, and
3. Self-consolidated concrete, known as self-compacting concrete (SCC), where the fresh concrete mix has no shear strength, and attains a water-like flowing ability. SCC mixes are usually used in pouring structural members with high depth and congested with heavy reinforcement as bridge girders.

Thus, SCC mixes usually incorporate silica fume for increased strength to sustain increased loading. Self-X concrete mix improved performance is shown in **Figure 2**.

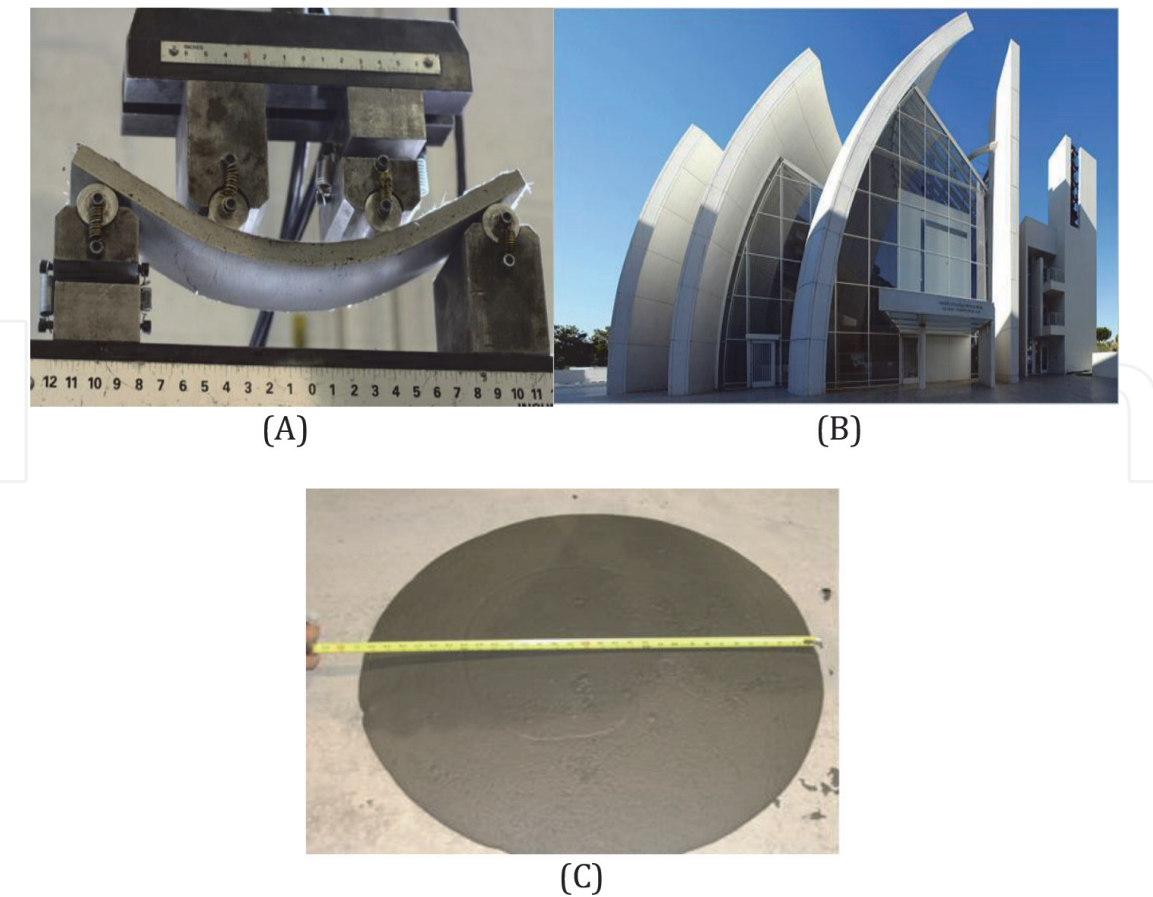


Figure 2.
(A) Self-healing concrete [6], (B) self-cleaning concrete [7], and (C) SCC concrete [8].

3. Supplementary cementitious materials (SCMs) in concrete industry

SCMs are increasingly used in concrete mix designs. Recently, binary and ternary concrete mixes are becoming the norm in heavy construction industries including the construction of bridges, tunnels, and culverts. Different types of SCMs are used according to the targeted characteristics of the developed mix. SCMs are available in granular shape with diameters ranging from nano-centimeters (as nano-silica) to a few millimeter diameter (as quartz flower). SCMs are used in partial replacement of cement. Cement weight up to 30% can be replaced by an equivalent volume of SCMs. Currently, different types of SCMs are available in the construction market including nano-silica, micro-silica, also known as silica fume, class C fly ash, class fly ash, quartz flour, blast furnace slag, and single and multi-walled carbon nanotubes. The characteristics of different SCMs, their impact on concrete mechanical properties, and their potential use are described in the following section.

3.1 Micro silica (silica fume)

Micro silica, also known as silica fume, is a byproduct of producing silicon metal or ferrosilicon alloys. Micro silica, as a mineral pozzolanic admixture, has a very fine particle size that averages 0.5 micro-meter in diameter. The average size of silica fume particle is 100 times finer than Portland cement size. Silica fume is commercially available in a densified and un-densified form, with similar chemical composition, and different densities. The chemical composition of silica fume is shown in Table 1.

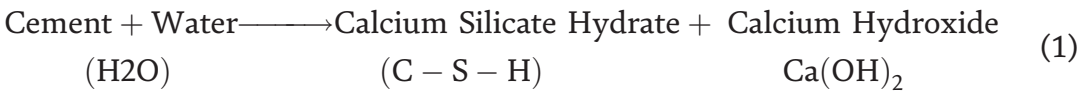
Composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	SO ₃
Percentage %	92–98	0.5	2.1	0.3	0.8	0.1	1.0	0.2

Table 1.
Chemical composition of micro-silica.



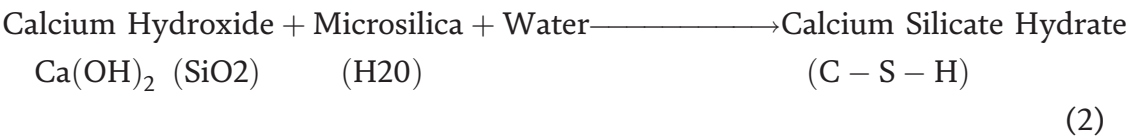
Figure 3.
Excessive surface salt due to efflorescence phenomena.

Micro-silica improves concrete mechanical properties through two different mechanisms by contributing to the Portland cement hydration. When mixing water is added to cement, without incorporating micro-silica, the following chemical reaction takes place during hydration:



The main outcome of the hydration process includes the calcium silicate hydrate that acts as a binder and is directly responsible for the compressive strength of hardened concrete. The compressive strength depends on the amount of produced binder. Thus, the quantity of cement, cement fineness, water-cement ratio, and sufficient mixing energy and time are crucial to attain the required compressive strength of concrete upon hardening. The secondary outcome of the hydration process is calcium hydroxide, $\text{Ca}(\text{OH})_2$, which does not act as a binder, and has no contribution to the strength of the mix. In addition, excessive amounts of $\text{Ca}(\text{OH})_2$ may react with carbon dioxide and form a soluble salt that could leach within the hardened concrete causing efflorescence, as shown in **Figure 3**, and reduce the long-term performance of the structure due to its susceptibility to sulfate attacks, chemical attacks, and accelerating alkali-silica reactivity (ASR).

When micro silica is included in the mix, the added pozzolan reacts with the formed calcium hydroxide to produce an additional binder, which increases the hardened concrete strength and eliminates the salt formation by halting the efflorescence. The following equation describes the chemical contribution of micro-silica:



In addition to its contribution to the concrete mechanical properties through the aforementioned reaction, micro-silica results in an improved packing order of the mixed granular material. The improved packing order results in reduced porosity

and increased resistivity to chloride attacks and de-icing salts, and reduces the rate of steel reinforcement corrosion. Improved packing order of micro-silica concrete is shown in **Figure 4**.

3.2 Fly ash

Fly ash is a fine granular powder that exists in nature as a by-product of burning coal in power plants. Fly ash is used as a low-cost recycled material in concrete mixes to improve the concrete strength, reduce concrete viscosity and improve its pump ability, mitigate the ASR and its destructive impact on hardened concrete, and reduce the final cost of the produced concrete. The chemical composition of fly ash is shown in **Table 2**.

Two types of fly ash are used in the construction industry as SCMs to improve the fresh and hardened concrete properties. These are class C and class F fly ash. The main difference between the two types is that class F fly ash is a pozzolan; thus, it needs to react with the calcium hydroxide resulting from the cement hydration process to form the binding material. While class C fly ash is a cementitious material, it can produce binder directly once it reacts with water (direct hydration process).

The use of fly ash in concrete mixing provides fresh concrete with workability advantages. Fly ash particles are spherical in shape, which provides the concrete powder (cement, SCMs, and aggregates) with a higher tendency to flow. In addition to the lubricant effect provided, fly ash reduces the shear capacity of fresh concrete. Hence, the fly ash concrete mix has a higher tendency to flow, being pumped, and has a better hardened surface after formwork is removed.

Recent research shows that fly ash can partially replace up to 30% of the cement weight of conventional mixes. More than 30% fly ash could be used when mass concrete is poured [10]. The replacement of 20% of cement with an equivalent amount of fly ash results in improving the mix workability and/or maintaining similar workability while reducing 10% of mixing water.

In hardened concrete, class C fly ash provides improved mechanical properties due to its ability to form the additional binder. Class C and F fly ash results in reduced voids and lowered permeability in hardened concrete. Reduced concrete

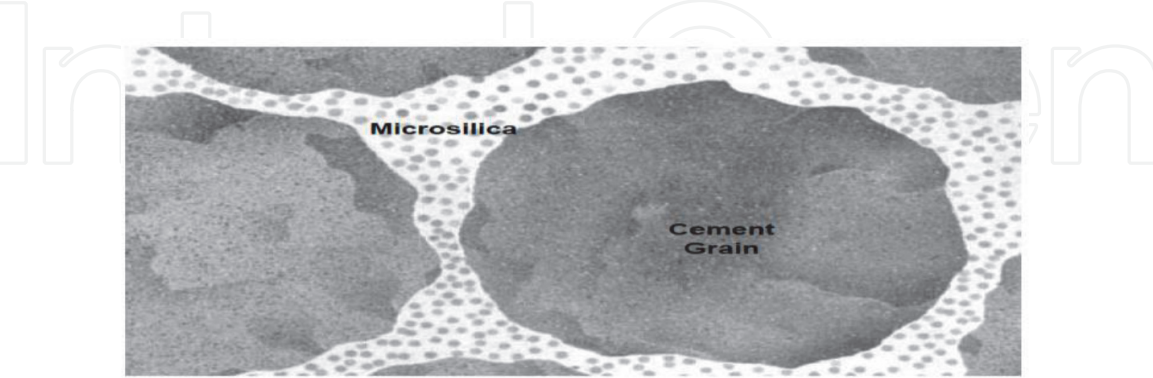


Figure 4.
Micro-silica concrete packing improved packing order [9].

Composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	SO ₃
Percentage %	49	24.6	7.3	1.6	9.1	0.2	0.6	0.4

Table 2.
Chemical composition of fly ash.

voids play a major role in improving durability and blocking moisture dissipation to the hardened concrete, which improves its alkali-silica resistivity.

3.3 Quartz flour

Quartz flour, also referred to as crystalline silica, is a mineral used in UHPC and HPC mix development. Quartz flour is found in sand, granite, rocks, and some soil types. When these materials are cut, chipped, or drilled, dust evolves that contains the quartz flour particles. The diameter of quartz flour particles enables quartz flour to fill the voids within cement particles, which reduces the mix permeability and improves the resistivity of concrete to adverse environmental conditions. Quartz flour is used as a supplementary cementitious component in proprietary UHPC mixes produced by Lafarge and is commercially available in global markets under the name Ductal. Proprietary UHPC mix composition including quartz flour is shown in **Table 3**.

3.4 Blast furnace slag

Blast furnace slag is produced by grinding the glassy granular by-product of the steel industry. The fine ground blast furnace by-product is highly cementitious and contains calcium silicate hydrate (C-S-H), which enhances the strength of the hardened concrete, and improves its durability and appearance. Coarse and ground slag particles are shown in **Figure 5**.

Material	Ib./yd ³	Kg/m ³	Percent (by weight)
Portland cement	1200	712	28.5
Fine sand	1720	1.020	40.8
Silica fume	390	231	9.3
Quartz flour	355	211	8.4
HRWR	51.8	30.7	1.2
Accelerator	50.5	30.0	1.2
Steel fibers	263	156	6.2
Water	184	109	4.4

Table 3.
Typical composition of Ductal [11].

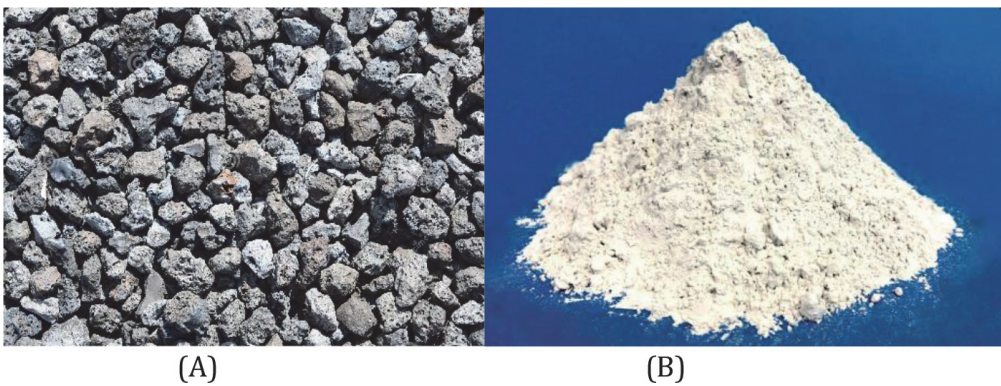


Figure 5.
(A) Granular slag particles and (B) ground slag particles.

4. Mix proportioning, mixing, and curing procedures

Mix proportioning of concrete mixes containing one or more SCMs targets the optimization of mix packing order to minimize voids and increase strength, and durability without altering mix slump and/or flowing ability. Different proprietary UHPC mixes are available in the construction market. Examples of proprietary mixes are BSI “Beton Special Industrial,” developed by Eiffage, Cemtec developed by LCPC, and Ductal developed by Lafarge. Different non-proprietary, ultra-high performance and high-performance mixes are developed through research programs across the globe.

The primary difference between UHPC and HPC mixes is the reduced strength of HPC (UHPC mix compressive strength exceeds 21.7 ksi [12, 13], and contains a higher percentage of SCMs, and incorporates random steel fibers to increase concrete ductility and post-cracking stiffness).

Supplementary cementitious materials and different steel fibers increase the overall density of concrete mixes. Optimized mixing procedures for concrete with high percentages of SCMs are as follows [14]:

- I. Preblended the concrete mix granular ingredients for 2–3 minutes. The granular ingredients include cement, SCMs, fine sand, and coarse aggregates (if present).
- II. Mixing water is added to the preblended powder. Mixing water may include 50% of the high-range water reducers (HRWR) included in the mix design. Wet mixing should continue for 8–10 minutes.
- III. The remaining HRWR is added to the mix during the wet mixing process.
- IV. Steel fibers included in UHPC are added before wet mixing is ended.

Due to the high packing order of granular materials and the possible inclusion of random steel fibers, high-energy paddle mixers are required to produce mixes with sufficient rheology. Examples of high-energy mixers are shown in **Figure 6**.

Concrete mixes with incorporated SCMs can be cured using regular moisture curing techniques. When very high early strength is required (as in precast/prestressed concrete industry), thermal curing could be applied. Thermal curing should be gradually applied to avoid developing hair cracks within hardened concrete [14].



Figure 6.
High-energy paddle mixers—Used for UHPC and HPC mixing.

4.1 SCMs in UHPC concrete

Silica fume and quartz flour are used in proprietary UHPC mixes to increase mix strength and durability. Current proprietary mixes, commercially available in the US and EU markets, have a high content of SCMs. In addition to their strength and durability advantages, SCMs partially reduce the cement consumption and hence reduce the carbon footprint [15–17]. Mix design and SCM content in major proprietary mixes are shown in **Table 4**.

The compressive strength of proprietary UHPC mixes ranges from 160 to 200 MPa. The strength is significantly increased due to the incorporation of SCMs and steel fibers. Steel fibers result in improved tensile capacity and higher values for the modulus of elasticity (MOE) and modulus of rupture (MOR). Detailed mechanical properties of proprietary UHPC mixes are shown in **Table 5**.

The high strength of girders produced using UHPC and HPC concrete mixes enables design engineers to fabricate shallow girders with a very high span-to-depth ratio. A comparison of sections with similar capacity produced by different materials including proprietary UHPC mixes is shown in **Figure 7** [29].

	Ductal	Cemtec	Cor-Tuf	CRC
Portland cement	712	1050	790	861
Silica fume	231	268	308	215
Quartz flour	211	—	216	215
Total cementitious materials	1154	1318	1314	1291
Percentage of SCMs to C. materials	38%	20%	40%	33%
Sand	1020	514	765	792
Water	109	188	166	220
HRWR	30.7	44	14	9.45
Accelerator	30	—	—	—
Fibers	156	180	166	218
W/CM	0.21	0.17	0.14	0.18

Table 4.
Proprietary UHPC mix designs in global construction markets [18–20].

	Value	ASTM Standard [22–28]
Design compressive strength	Greater than 150 MPa	ASTM C39/C39 M
Flexural strength	Greater than 20 MPa	ASTM C78/C78M-18
First cracking strength	Greater than 4 MPa	ASTM C1018–97
Creep coefficient	0.2	ASTM C512/512 M-15
Linear expansion coefficient	12×10^{-6}	ASTM C531–18
Elastic modulus	45 GPa	ASTM C469/C469M-14
Spread (flowing ability)	55 to 75 cm	ASTM C1611M-18

Table 5.
Average mechanical properties of proprietary UHPC mixes [21].

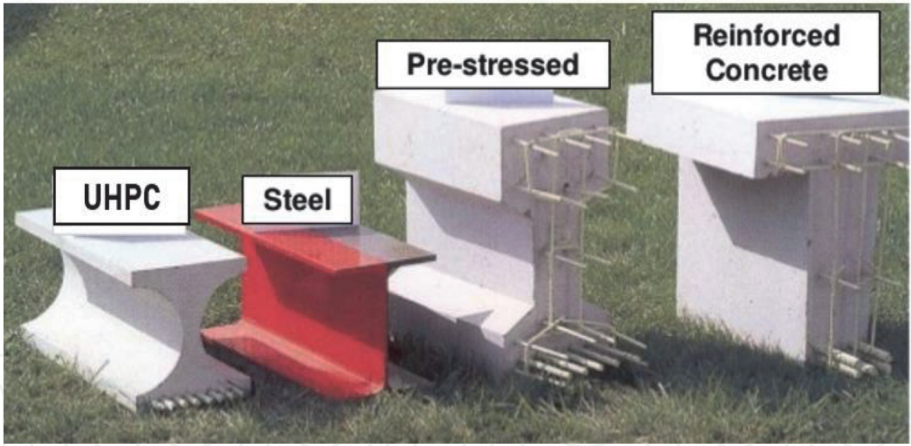


Figure 7.
Different girder sizes providing similar flexure capacity [29].

4.2 SCMs in HPC mixes

HPC mixes incorporates different SCMs with variable ratios according to the mix design purpose. Silica fume is used to increase the binder content and improve mix mechanical properties, whereas fly ash is primarily used to increase flowing ability. HPC mixes are produced using similar batching, mixing, and curing procedures as compared to UHPC. Steel fibers are eliminated due to their high cost, while chemicals for increased flowing ability are used to maintain high flowing ability using a low water-to-powder ratio. Different HPC mixes are shown in **Table 6**.

The aforementioned non-proprietary mixes had an average 24-h compressive strength of 80 MPa, and a final 28-day compressive strength of 110 MPa. Detailed compressive strength testing results are shown in **Figure 8**.

Current codes and standard specifications provide equations to estimate concrete mechanical properties as a function of its compressive strength. The American Concrete Institute (ACI) 318 calculates the modulus of elasticity of concrete (MOE) according to the following equation:

$$E_c = 0.043 w_c^{1.5} \sqrt{f'_c} \quad (\text{MPa}) \tag{3}$$

	Mix #1	Mix #2	Mix #3	Mix #4	Mix #5
Portland cement	630	625	630	670	630
Silica fume	90	80	90	145	90
Class C fly ash	180	80	180	145	180
Total cementitious materials	900	785	900	960	900
Percentage of SCMs to C. Materials	30%	20%	30%	32%	30%
Sand	1350	1450	950	1350	950
Water	135	155	145	145	140
HRWR	37	21	37	43	43
Fibers	—	—	—	—	—
W/CM	0.18	0.22	0.20	0.19	0.19

Table 6.
Non-proprietary HPC mixes using local materials in the US market.

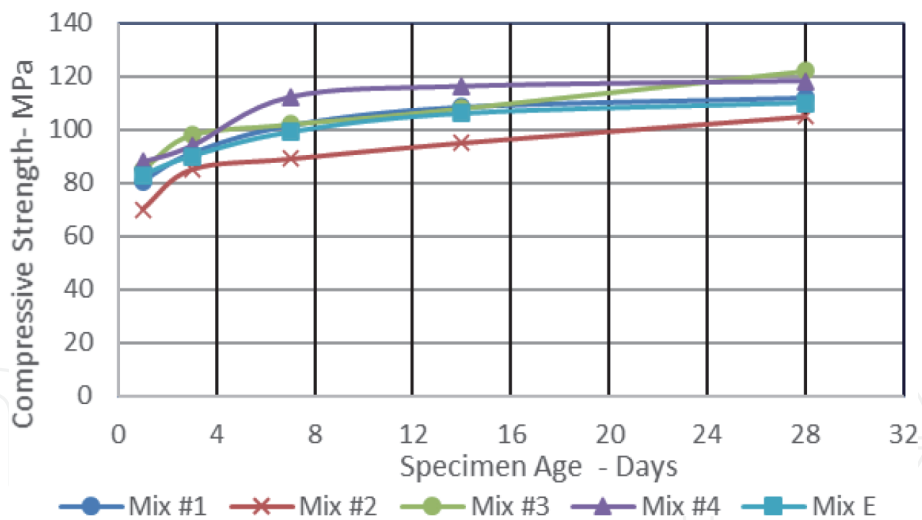


Figure 8.
Compressive strength test results for non-proprietary HPC mixes.

Similarly, ACI 318 and AASHTO LRFD specifications use the following equation to estimate the modulus of rupture (MOR) of concrete as

$$f_r = 0.62\sqrt{f'_c} \quad (\text{MPa}) \quad (4)$$

Eqs. (1) and (2) show that the MOE and MOR of concrete, denoted as E_c and f_r respectively, and are correlated with the concrete compressive strength, denoted as f'_c . Thus, the increase in concrete strength associated with the use of SCMs in mix development results in a significant increase in concrete MOE and MOR.

5. Applications of concrete incorporating SCMs

Concrete mixes, with different SCMs, are currently used in different applications that requires high early strength, superior mechanical properties, and increased durability. The following represents main applications in residential and heavy construction applications:

5.1 High-rise residential construction

HPC, including SCMs, mixes are currently used in the construction of structural members in high-rise buildings. The use of HPC in high-rise construction started in the 1970s in the metropolitan areas within the United States including New York, Los Angeles, and Chicago. Recently HPC mixes with the high flowing ability (SCC characteristics) are used in pumping concrete floors in the City of Jeddah's Kingdom Tower and the Iconic Tower in Egypt's New Administrative Capital (shown in Figure 9).

5.2 Precast/prestressed bridge construction

Prefabricated prestressed girders with spans up to 60 meters are increasingly used in bridge construction, including accelerated bridge construction projects [30]. In order to increase the productivity of prestressing facilities, very high early strength is required before strands are released. Some prestressing facilities require



Figure 9.
Iconic tower—Egypt’s new administrative capital.



Figure 10.
UHPC bridge construction projects in the United States [32].

24-h compressive strength in excess of 70 MPa to release larger strands of 15- and 18-mm. diameter. Thus, SCMs, mainly silica fume, are incorporated in the concrete mix to ensure high early strength due to increased binder content and avoid girder cracking upon strand release [31]. UHPC is increasingly used in the construction industry, especially in heavy construction applications, with emphasis on long-span precast/prestressed girder bridges construction. In early 2000s, the first UHPC bridge was built in the United States using Ductal concrete (with 38% SCMs content) and steel fibers incorporated in the mix. The first UHPC bridge—known as Mars Hill Bridge—was constructed in the state of Iowa using FHWA funding. The successful construction of the Mars Hill bridge and the attained advantages resulted in the construction of a large number of UHPC bridges, mainly on the east coast of the United States, are shown in **Figure 10**.

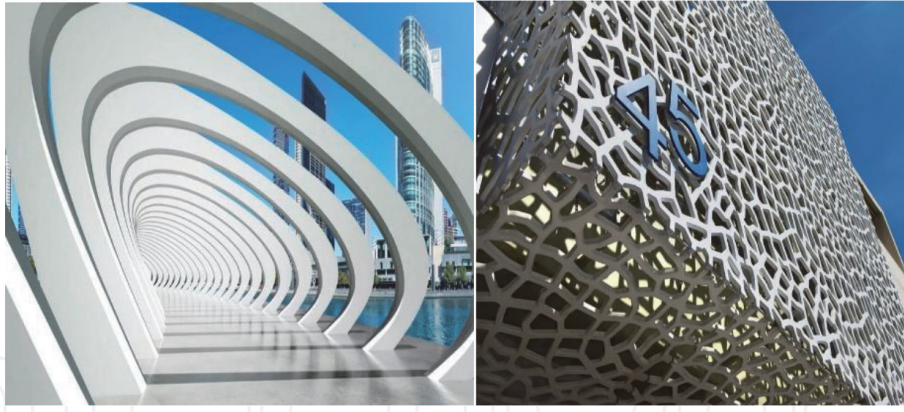


Figure 11.
UHPC architectural pours.

5.3 Architecture applications

SCMs are used in producing mixes with very high flowing ability and early high strength for architecture construction. The high flowing ability allows for the pour of complicated shapes and limited thicknesses. Architectural UHPC pours are shown in **Figure 11**.

6. Challenges of SCMs in concrete industry

The use of SCMs in concrete mix development is faced by several challenges that limit their use in construction projects. Major impediments to the widespread of SCMs incorporation in concrete mix design include the following:

- I. Material costs for specific SCMs are significantly higher than conventional concrete mix constituents. The average cost of micro-silica is \$900 per ton in the United States market. In addition, micro-silica availability production is limited to few states, which may result in increased shipping cost and extended lead time.
- II. Special mixers and mixing regimen are required, which necessitate modernization of batch plants and precast facilities to include SCMs in concrete mixing including changes in storage, batching techniques, and the type/size of mixers used.
- III. Impact on fresh concrete mix properties due to the different sizes of SCMs and different chemical composition as compared to conventional mix constituents as cement and sand. Additional SCMs result in lowering average particle size for the mix and increase the density, while significantly reducing voids and permeability. These chemical and volumetric changes may require additional provisions to avoid the development of concrete lumps within the mixer. Provisions include the use of high-range water reducers (superplasticizers) and extend mixing time, and use special types of high-energy mixers.
- IV. Health and safety restrictions should be followed when SCMs are used to avoid inhaling fine particles. Continuous exposure to certain types of SCMs as micro-silica might result in serious injuries or illnesses as silicosis. Thus, special PPEs are required when SCMs are used in mix development.

7. Conclusion

Supplementary cementitious materials (SCMs) are increasingly used in the construction industry to develop mixes with superior mechanical properties and improved long-term performance (durability). Different types of SCMs are available in the global market including micro-silica, class C fly ash, class F fly ash, quartz flour, and blast furnace slag. SCMs are incorporated in mix designs in partial replacement of Portland cement, with percentages ranging from 10% up to 40%. SCMs are used in proprietary UHPC mixes as Ductal, Cemtec, CRC, and Cor-Tuf, with percentages ranging from 20–40%. In non-proprietary HPC mixes, SCMs would have similar percentages; however, final strength is reduced due to the absence of steel fibers. SCMs improves the concrete properties through three techniques: 1) increase the amount of binder resulting from the hydration process, which increases the concrete final strength, 2) react with calcium hydroxide, which stops the efflorescence phenomenon, and 3) increase the packing order (density) of the cement matrix, which reduces concrete permeability, and its susceptibility to environmental attacks, de-icing salt effect, and protect reinforcing steel against corrosion. The reduction of cement consumption, being partially replaced by SCMs, reduces the carbon footprint of the construction industry.

The advantages of SCMs are partially offset with challenges including the scarcity of specific types of SCMs in some parts of the world. Specific types of SCMs are expensive compared to cement. Also, a special mixing regimen is required to avoid losing mix-flowing ability. Currently, SCMs are successfully used in concrete mix designs for high-rise residential construction, precast/prestressed girder bridge construction, and in architecture applications. The continuous research in concrete mix development using alternative SCMs will result in increased market share in global construction markets.

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Conflict of interest

The authors declare no conflict of interest.

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