고성능 콘크리트 공학
High Performance Concrete Engineering

<Admixture, Aggregate, Water>

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Progress

HPCE_0_Intro

HPCE_1_Cement Chemistry

HPCE_2_Admixture, Aggregate, Water

HPCE_3_Fresh and Hardened Properties

HPCE_4_Durability

HPCE_5_UHPC

HPCE_6_Time Dependent Behavior

Contents in HPCE_2_Admixture, Aggregate, Water:

- Water
- Porosity
- Pore solution
- Mineral admixture
- Chemical admixture
- Aggregate

Water, Pore structure, Pore solution

Water

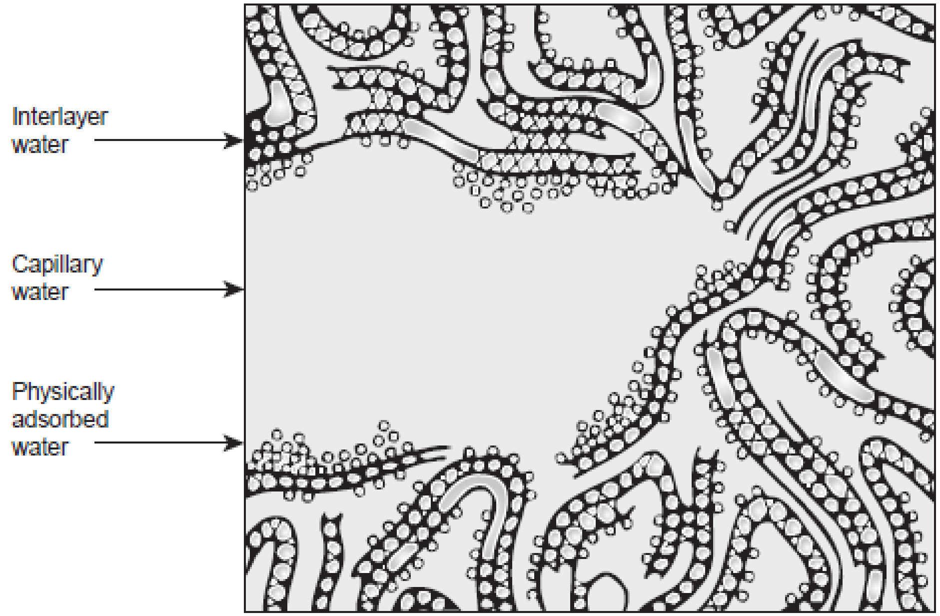
- A key ingredient, plays a significant role

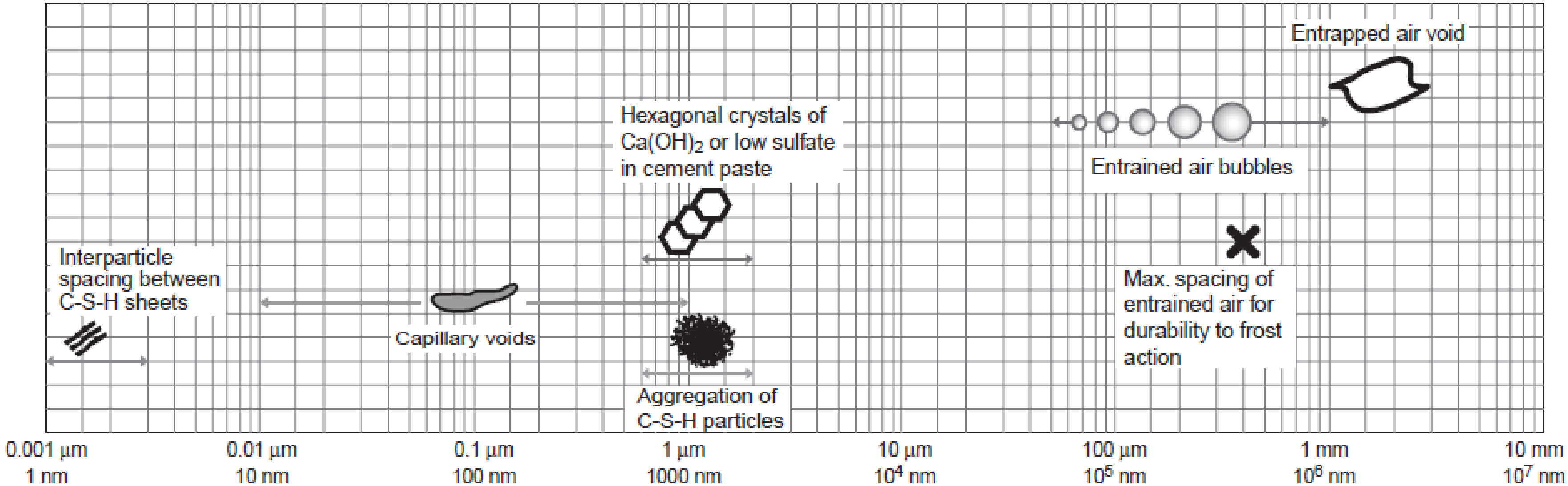
- Water quality
  - Rule of thumb: if you can drink it, you can make concrete with it

- Impurities in mixing water may
  - Interfere setting of cement
  - Adversely affect concrete strength
  - Causes stain of concrete surface
  - Lead to corrosion of reinforcement.

Porosity

Pore structure hierarchy





(Metha and Monteiro 2006)

Porosity (pore classification)

- **Capillary pores** – remnants of water filled space that exists between the partially hydrated cement grains
- **Gel pores** – regarded as an intrinsic part of the C-S-H
- Capillary pore system is the interconnected network of pores through which bulk water flow & ion diffusion occur easily

TABLE 4.6 Classification of Pore Sizes in Hydrated Cement Pastes (Mindess 2003)

Designation	*Diameter*	*Description*
Capillary Pores	10,000–50 nm (10–0.05 μm)	large capillaries (macropores)
	50–10 nm	medium capillaries (large mesopores)
Gel Pores	10–2.5 nm	small isolated capillaries (small mesopores)
	2.5–0.5 nm	micropores
	≤ 0.5 nm	interlayer spaces

Porosity (pore connectivity)

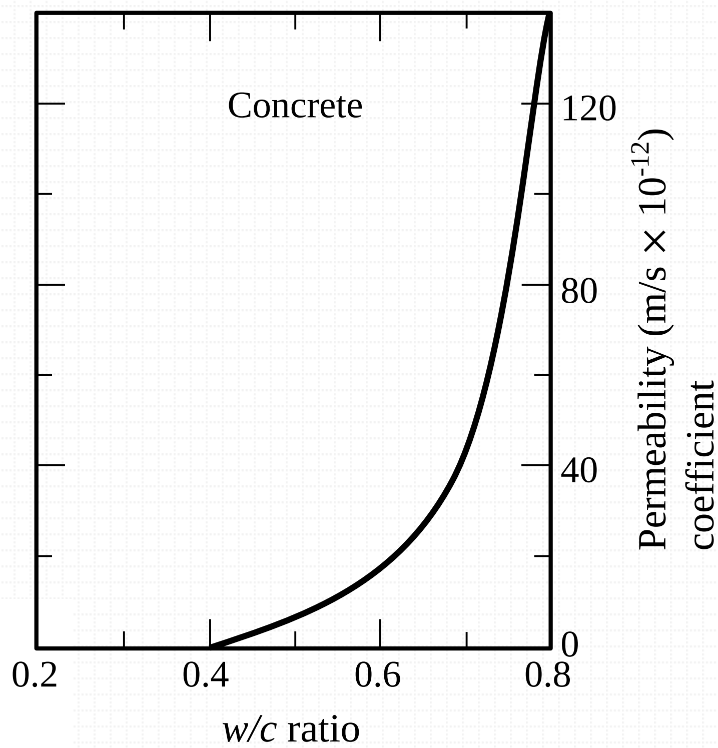
TABLE 18.2 Effect of Age of Cement Paste on Its Permeability Coefficient (*w/c* = 0.51)

Age (days)	K_p *(m/s)*	
Fresh paste	10^{-5}	Independent of *w/c*
1	10^{-8}	Capillary pores interconnected
3	10^{-9}	
4	10^{-10}	
7	10^{-11}	
14	10^{-12}	
28	10^{-13}	
100	10^{-16}	Capillary pores discontinuous
240 (maximum hydration)	10^{-18}	

TABLE 18.3 Curing Time Required to Produce a Discontinuous System of Capillaries (Assuming Continuous Moist Curing)

w/c Ratio	*Curing Time (days)*
0.40	3
0.45	7
0.50	28
0.60	180 (6 months)
0.70	365 (1 year)
> 0.70	Not possible

(Mindess 2003)

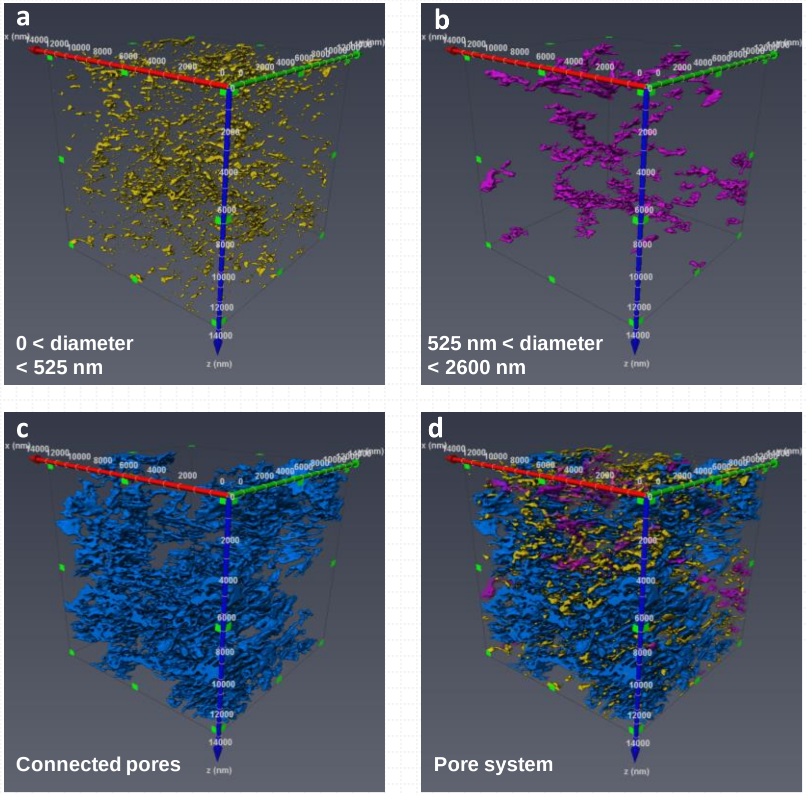


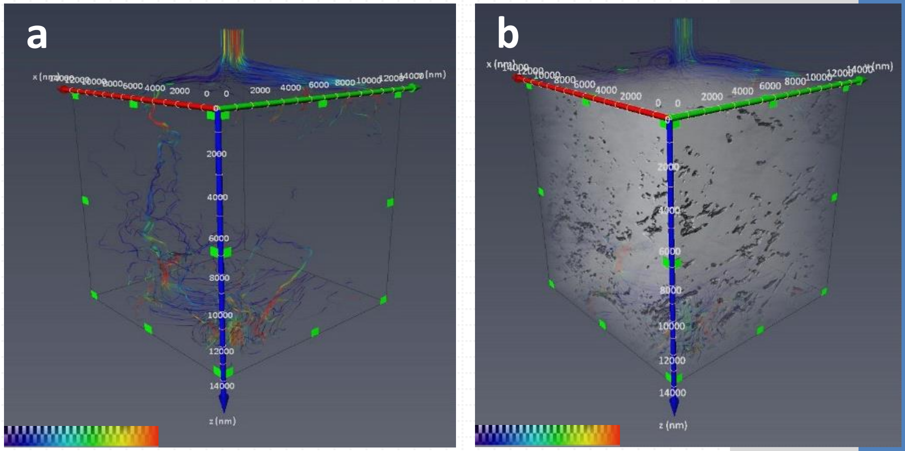
Admx, Agg

Porosity (pore connectivity)

Can we really see the interconnected pore structure?

Synchrotron based nano-resolution X-ray tomography at Advanced Photon Source (Chicago, USA)



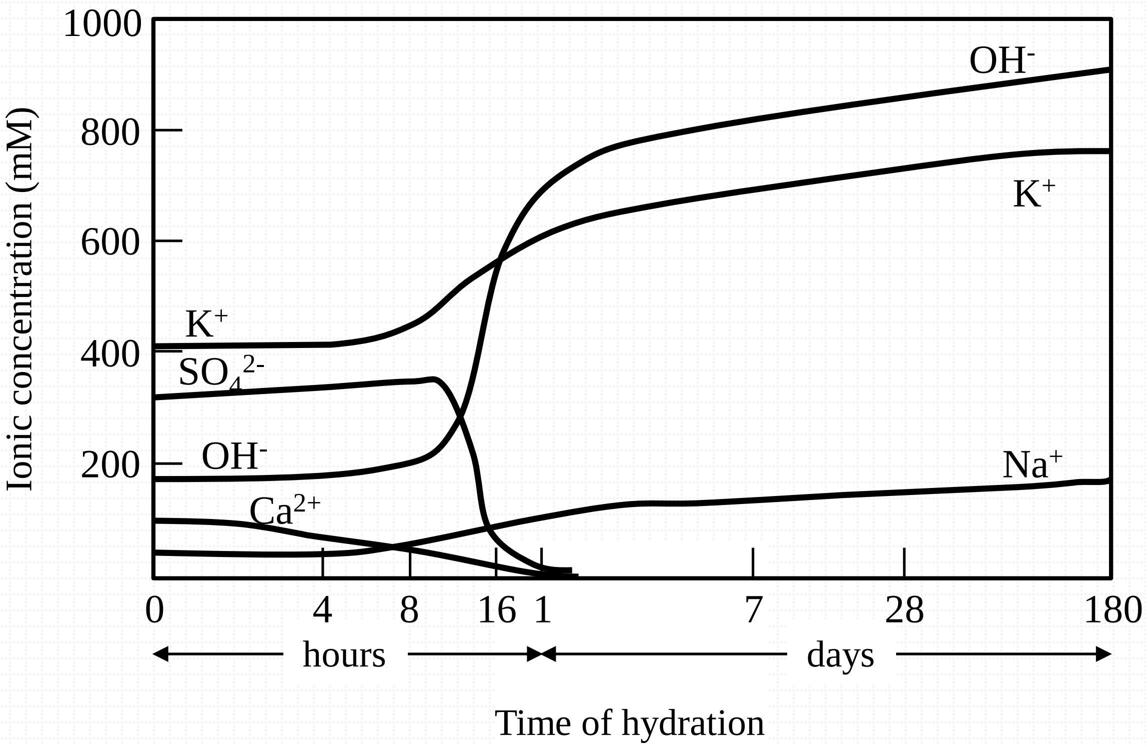


(Unpublished data)

Pore Solution

Fluid contained in capillary pores is not pure water, but an ionic solution that is in equilibrium with hydrated paste

In low alkali cement, pH ~ 13
In high alkali cements, pH > 13.5



Mineral Admixture

Mineral admixture

- **Supplementary Cementitious Materials, SCM**
- Primary purposes of adding mineral admixtures or supplementary cementing materials in concrete
    - To replace cement (economical & technical reasons, and environmental consideration)
    - To improve the workability of fresh concrete
    - To reduce heat and early temperature rise
    - To enhance the durability of hardened concrete
- Current practice
    - Blended cements
    - Added in concrete mixers as supplementary cementing materials

Mineral admixture

- **Supplementary Cementitious Materials, SCM**
- **Pozzolanic Materials**
- Alumino-silicate materials of either natural or industrial origins
- By-product materials
    - Fly ash – inorganic, non combustible residue of powdered coal after burning in power plants
        - **Class F fly ash**
            - Procuded from bituminous and sub-bituminous coals
            - $(SiO_2+Al_2O_3+Fe_2O_3) > 70\%$
        - **Class C fly ash**
            - Produced from lignitic coals
            - $(SiO_2+Al_2O_3+Fe_2O_3) > 50\%$
    - **Silica fume** – a by-product in the manufacture of silicon metal and allows (extremely fine size ~ 0.1μm)

Mineral admixture

- **Supplementary Cementitious Materials, SCM**
- **Pozzolanic Materials**
- **Primary reaction**: amorphous silica reacts with CH from cement hydration

$$SiO_2 + Ca(OH)_2 + H_2O \rightarrow C\text{-}S\text{-}H$$

- It can reduce early heat evolution and early strength, but not long-term strength
- Reduce porosity and permeability, increase durability

Mineral admixture

- Supplementary Cementitious Materials, SCM
- Typical bulk analysis of pozzolans (weight%)

TABLE 5.3 Typical Bulk Analyses of Pozzolans (weight %) (Mindess et al 2003)

Material	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	K_2O	*Carbon*
Volcanic Glass	50–70	15–20	1–6	2–10	2–4	2–10	—
Volcanic Tuffs	45–75	10–20	1–10	1–10	<2	2–7	—
Diatomaceous Earth	~85	~2	~2	<1	—	—	
Fly Ash - Class F	>50	20–30	<20	<5	Variable		<5
- Class C	>30	15–25	<10	20–30	Variable		<1
Silica Fume	85–98	<2	<10	—	Variable, low		<2
Rice Husk Ash	85	—	—	<1	1–4	3–10	3–18
Calcined clay	~55	35–45	<10	—	<1	<1	—
OPC	~20	6	3	~65			

(Mindess et al 2003)

Mineral admixture

- Supplementary Cementitious Materials, SCM
- Physical characteristics of selected pozzolans

TABLE 5.4 Physical Characteristics of Selected Pozzolans (Mindess et al 2003)

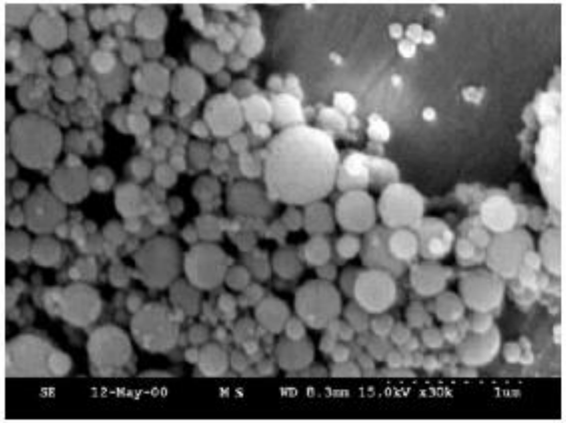
Material	*Mean Size (μm)*	*Surface Area (m^2/g)*	*Particle Shape Gravity*	*Specific Gravity*
Portland Cement	10–15	<1	angular, irregular	~3.2
Natural Pozzolans	10–15**	<1	angular, irregular	variable
Fly Ash (F and C)	10–15	1–2	mostly spherical	2.2–2.4
Silica Fume	0.1–0.3	15–25	spherical	2.2
Rice Husk Ash	10–20**	50–100	cellular, irregular	<2.0
Calcined Clay (metakaolin)	1–2	~15	platey	2.4

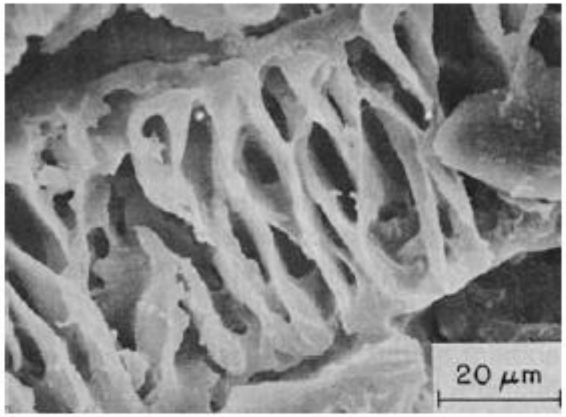
** After grinding.

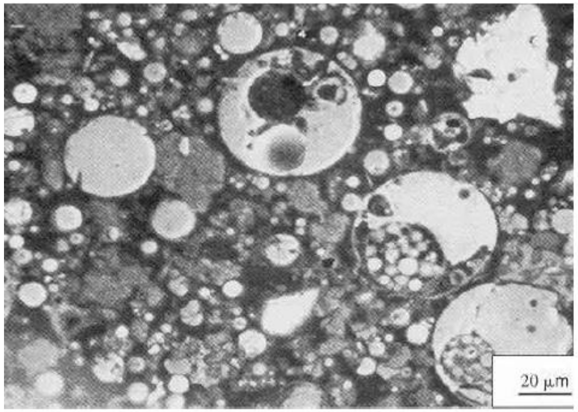
(Mindess et al 2003)

Mineral admixture

- **Supplementary Cementitious Materials, SCM**
- **Microscopic images**







Silica fume
Small size -> packing effect, reduce bleeding reduce the size of capillary pores

Rice husk ash
Silicate porous material

Fly ash
Aluminosilicate hollow particle

(Mindess et al 2003)
(Metha and Monteiro 2006)

Mineral admixture

- **Cementitious Materials**
- **Ground Granulated Blast-Furnace Slag (GGBFS)**

- Typical composition

  CaO = 35-45%, SiO_2 = 32-38%, Al_2O_3 = 8-16%, MgO = 5-15%, Fe_2O_3 < 2%, sulfur = 1-2%

- BFS used in concrete is obtained by rapid cooling (quenching) the molten slag using water to form calcium aluminosilicate glass. Ground the granulated BFS to fine particles -> mineral admixture (GGBFS)

- GGBFS reacts slowly with water, strength development too slow
- Slags can be activated by Portland cement
- In slag-cement blends, slag also shows pozzolanic behavior
- Products of slag hydration
  - A mixture of C-S-H and AFm (monosulphoalumiante) and/or AFt (ettringite)

Mineral admixture

Effects of Mineral admixture on Properties of Fresh & Hardening Concrete

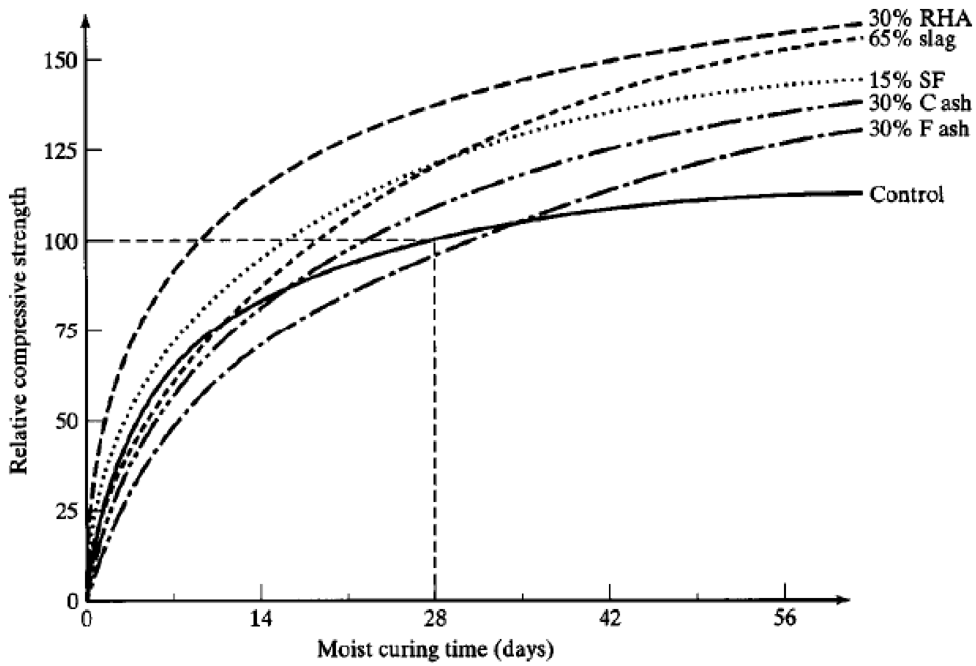
- **Heat of hydration (fly ash and slag)**
  - Reduce the overall heat of hydration
  - Reduce the rate of heat liberation
  - Reduce temperature rise in concrete

- **Workability**
  - Improve cohesiveness
  - Fly ash and silica fume are particularly beneficial due to their spherical shape
  - Addition of fly ash allow ratio of water/(cement + mineral admixture) (w/cm) to be reduced while maintaining slump
  - Silica fume is more beneficial provided that a water reducing admixture is used.

Mineral admixture

Effects of Strength Development

- Develop very good strength over time
- May reduce early-age strength, can be offset by reducing w/cm
- More reactive pozzolanic materials such as silica fume will reduce setting time and contribute to early strength



(Mindess et al 2003)

Mineral admixture

Effects of Durability

- Increase C-S-H & reduce CH leads to more homogenous microstructure

$$SiO_2 + Ca(OH)_2 + H_2O \rightarrow C\text{-}S\text{-}H$$

- Improve pore structure, reduce overall porosity & pore size
- Used extensively for improving the durability of concrete
- Improvements in durability result from the **reduction in CH**, **changes in pore structure**, and **reduction in water/cementitious material ratio (w/cm)**
  - Increase sulfate resistance
  - Reduce chloride diffusion

Mineral admixture

Comparison of ASTM and BS-EN Standards

	ASTM	BS-EN
Portland cement	C 150 – Spec for Portland cements	197-1: 2000 CEM I – Portland cement
Blended cements	C 595 – Spec for blended hydraulic cements	197-1: 2000 CEM II – Portland comp. cem CEM III – blastfurnace cem CEM IV – pozzolanic cem CEM V – composite cem
	C 1157 – Performance Spec for blended hydraulic cements	
Mineral admixtures	C 618 – Spec for coal fly ash and raw or calcined natural pozzolans for use in concrete	450-1: 2005 Fly ash for concrete – Definition, spec, and conformity criteria
	C 989 – Spec for GGBFS for use in concrete and mortars	15167-1: 2006 Ground granulated blast furnace slag for use in concrete, mortars, and grouts
	C 1240 – Spec for silica fume used in cementitious mixtures	13263-1: 2005 Silica fume for concrete

Mineral admixture

Mechanical and Physical Requirements (BS-EN 197-1)

Table 2 — Mechanical and physical requirements given as characteristic values

Strength class	Compressive strength MPa				Initial setting time	Soundness (expansion)
	Early strength		Standard strength			
	2 days	7 days	28 days		min	mm
32,5 N	–	≥ 16,0	≥ 32,5	≤ 52,5	≥ 75	≤ 10
32,5 R	≥ 10,0	–				
42,5 N	≥ 10,0	–	≥ 42,5	≤ 62,5	≥ 60	
42,5 R	≥ 20,0	–				
52,5 N	≥ 20,0	–	≥ 52,5	–	≥ 45	
52,5 R	≥ 30,0	–				

N – ordinary early strength

R – high early strength

Mineral admixture

Chemical Requirements (BS-EN 197-1)

Table 3 — Chemical requirements given as characteristic values

1	2	3	4	5
Property	**Test reference**	**Cement type**	**Strength class**	**Requirements [a]**
Loss on ignition	EN 196-2	CEM I CEM III	all	≤ 5,0 %
Insoluble residue	EN 196-2 [b]	CEM I CEM III	all	≤ 5,0 %
Sulfate content (as SO_3)	EN 196-2	CEM I CEM II [c] CEM IV CEM V	32,5 N 32,5 R 42,5 N	≤ 3,5 %
			42,5 R 52,5 N 52,5 R	≤ 4,0 %
		CEM III [d]	all	
Chloride content	EN 196-21	all [e]	all	≤ 0,10 % [f]
Pozzolanicity	EN 196-5	CEM IV	all	Satisfies the test

[a] Requirements are given as percentage by mass of the final cement.
[b] Determination of residue insoluble in hydrochloric acid and sodium carbonate.
[c] Cement type CEM II/B-T may contain up to 4,5 % sulfate for all strength classes.
[d] Cement type CEM III/C may contain up to 4,5 % sulfate.
[e] Cement type CEM III may contain more than 0,10 % chloride but in that case the maximum chloride content shall be stated on the packaging and/or the delivery note.
[f] For pre-stressing applications cements may be produced according to a lower requirement. If so, the value of 0,10 % shall be replaced by this lower value which shall be stated in the delivery note.