

Chapter 2

Silica Fume

2.1 Introduction

Silica fume (SF) is a byproduct of the smelting process in the silicon and ferro-silicon industry. The reduction of high-purity quartz to silicon at temperatures up to 2,000°C produces SiO₂ vapours, which oxidizes and condense in the low-temperature zone to tiny particles consisting of non-crystalline silica. By-products of the production of *silicon metal* and the *ferrosilicon alloys* having silicon contents of 75% or more contain 85–95% non-crystalline silica. The by-product of the production of ferrosilicon alloy having 50% silicon has much lower silica content and is less pozzolanic. Therefore, SiO₂ content of the silica fume is related to the type of alloy being produced (Table 2.1).

Silica fume is also known as micro silica, condensed silica fume, volatilized silica or silica dust.

The American concrete institute (ACI) defines silica fume as a “very fine non-crystalline silica produced in electric arc furnaces as a by product of production of elemental silicon or alloys containing silicon”. It is usually a grey colored powder, somewhat similar to Portland cement or some fly ashes. It can exhibit both pozzolanic and cementitious properties.

Silica fume has been recognized as a *pozzolanic admixture* that is effective in enhancing the *mechanical properties* to a great extent. By using silica fume along with superplasticizers, it is relatively easier to obtain compressive strengths of order of 100–150 MPa in laboratory. Addition of silica fume to concrete improves the durability of concrete through reduction in the permeability, refined pore structure, leading to a reduction in the diffusion of harmful ions, reduces calcium hydroxide content which results in a higher resistance to sulfate attack. Improvement in durability will also improve the ability of silica fume concrete in protecting the embedded steel from corrosion.

Figure 2.1 shows the schematic diagram of silica fume production. The silica fume is collected in very large filters in the baghouse and then made available for use in concrete.

Table 2.1 SiO₂ content of silica fume produced from different alloy sources [4]

Alloy type	SiO ₂ content SF (%)
50% ferrosilicon	61–84
75% ferrosilicon	84–91
Silicon metal	87–98

2.1.1 Availability and Handling

Silica fume is available in two conditions: dry and wet. Dry silica can be provided as produced or densified with or without dry admixtures and can be stored in silos and hoppers. Silica Fume slurry with low or high dosages of chemical admixtures are available. Slurried products are stored in tanks.

2.2 Properties of Silica Fume

2.2.1 Physical Properties

Silica fume particles are extremely small, with more than 95% of the particles finer than 1 µm. Its typical physical properties are given in Table 2.2. Silica fume colour is either premium white or grey (Fig. 2.2).

2.2.2 Chemical Composition

Silica fume is composed primarily of pure silica in *non-crystalline form*. X-ray diffraction analysis of different silica fumes reveals that material is essentially

Fig. 2.1 Schematic diagram of silica fume production

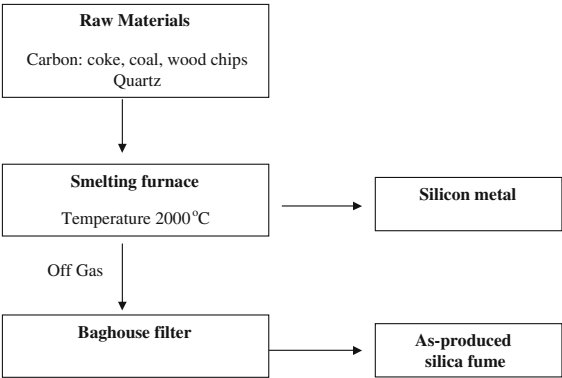


Table 2.2 Typical physical properties of silica fume [82]

Property	Value
Particle size (typical)	<1 μm
Bulk density	
As-produced	130–430 kg/m^3
Slurry	1,320–1,440 kg/m^3
Densified	480–720 kg/m^3
Specific gravity	2.22
Surface area (BET)	13,000–30,000 m^2/kg

Fig. 2.2 Silica fume

vitreous silica, mainly of *cristobalite form*. Silica fume has a very high content of amorphous silicon dioxide and consists of very fine *spherical particles*. Silica fume generally contains more than 90% SiO_2 . Small amounts of iron, magnesium, and alkali oxides are also found. Oxides analyses of silica fume as reported by some authors are given in Table 2.3.

2.3 Reaction Mechanism

Because of its extreme fineness and very high amorphous silicon dioxide content, silica fume is a very reactive *pozzolanic material*. As the Portland cement in concrete begins to react chemically, it releases calcium hydroxide. The silica fume reacts with this calcium hydroxide to form additional binder material called calcium silicate hydrate which is very similar to the calcium silicate hydrate formed

Table 2.3 Chemical composition of silica fume samples

Oxides	Sandvik and Gjrv [75]	Hooton and Titherington [39]	Yazici [98]
SiO_2	92.1	96.65	92.26
Al_2O_3	0.5	0.23	0.89
Fe_2O_3	1.4	0.07	1.97
CaO	0.5	0.31	0.49
MgO	0.3	0.04	0.96
K_2O	0.7	0.56	1.31
Na_2O	0.3	0.15	0.42
SO_3	–	0.17	0.33
LOI	2.8	2.27	–

from Portland cement. It is an additional binder that gives silica-fume concrete its improved properties. Mechanism of silica fume in concrete can be studied basically under three roles:

(i) *Pore-size Refinement* and Matrix Densification:

The presence of silica fume in the Portland cement concrete mixes causes considerable reduction in the volume of large pores at all ages. It basically acts as *filler* due to its *fineness* and because of which it fits into spaces between grains in the same way that sand fills the spaces between particles of coarse aggregates and cement grains fill the spaces between fine aggregates grains.

(ii) Reaction with Free-Lime (From Hydration of Cement)

CH crystals in Portland cement pastes are a source of weakness because cracks can easily propagate through or within these crystals without any significant resistance affecting the strength, durability and other properties of concrete. Silica fume which is siliceous and aluminous material reacts with CH resulting reduction in CH content in addition to forming strength contributing cementitious products which in other words can be termed as “Pozzolanic Reaction”.

(iii) Cement Paste–Aggregate Interfacial Refinement

In concrete the characteristics of the *transition zone* between the aggregate particles and cement paste plays a significant role in the *cement-aggregate bond*. Silica fume addition influences the thickness of transition phase in mortars and the degree of the orientation of the CH crystals in it. The thickness compared with mortar containing only ordinary Portland cement decreases and reduction in degree of orientation of CH crystals in transition phase with the addition of silica fume. Hence mechanical properties and *durability* is improved because of the enhancement in interfacial or bond strength. Mechanism behind is not only connected to chemical formation of C–S–H (i.e. pozzolanic reaction) at interface, but also to the microstructure modification (i.e. CH) orientation, porosity and transition zone thickness) as well.

2.4 Heat of Hydration

Silica fume is amorphous in nature and may contain some crystalline silica in the form of quartz or cristobalite. The higher surface area and amorphous nature of silica fume make it highly reactive. The hydration of C_3S , C_2S , and C_4AF are accelerated in the presence of silica fume [55, 94]. Grutzeck et al. [34] concluded that silica fume experiences rapid dissolution in the presence of $Ca(OH)_2$ and a supersaturation of silica with respect to a silica-rich phase. This unstable silica-rich phase forms a layer on the surface of the silica fume particles. The layer is then partly dissolved and the remainder acts as a substitute on which conventional C–S–H is formed.

Uchikawa and Uchida [94] reported that addition of silica fume accelerates the hydration of ordinary Portland cement at all stages of hydration. Immediately after mixing, the saturation factor of $\text{Ca}(\text{OH})_2$ indicative of the concentrations of Ca^{2+} and OH^- ions, in the paste containing silica fume was reduced compared to that made of ordinary Portland cement. However, the saturation factor sharply increased to its maximum earlier than for ordinary Portland cement paste. During the course of hydration, the cumulative heat evolved due to hydration of ordinary Portland cement containing silica fume was always higher than from ordinary Portland cement paste. However, this trend may be reversed if water-reducing admixture is added to the mixing water. In the presence of melamine based water-reducer, the major hydration peak was accelerated in a silica fume cement paste. The cumulative heat evolved also increased in the presence of silica fume in the paste, and the higher the amount of silica fume in the paste, the greater the heat evolved and the shorter the hydration time [40].

Meland [63] observed that cumulative heat evolved is lower when paste containing silica fume and *lignosulfonate*. In addition, the higher the amount of silica fume, the smaller the amount of heat evolved. In the presence of lignosulfonate, the *hydration reaction* was retarded and less heat was evolved from paste containing silica fume.

Uchikawa [93] mentioned that use of excessive superplasticizer may cause substantial delays in setting times of cement paste containing silica fume.

Lohtia and Joshi [58] concluded that partial replacement of cement by silica fume results in reduction of *heat of hydration* without any reduction in strength. For a high strength concrete having 540 kg/m^3 cement and 10% cement replacement with silica fume, heat was 9% less compared to the mix without silica fume. Addition of silica fume may accelerate the temperature rise during the first 2–3 days, but a net decrease in temperature rise of silica fume concrete was observed at later stages (7–28 days) when compared to corresponding plain concrete. At early age, due to fast pozzolanic reaction of silica fume, a greater amount of heat is liberated compared to Portland cement. Ratio of heat liberated by pozzolanic activities of silica fume during the first 2–3 days per gram of silica fume to that of Portland cement is reported to be of the order of 1–2.

Langan et al. [56] studied the effect of silica fume on the heat of hydration of Portland cement. Silica fume was added as a partial replacement of cement at 10% by weight of the total *cementitious material*. Calorimeter tests were performed on these mixtures at water/cementitious ratios (w/cm) of 0.35, 0.40 and 0.50, up to a period of 24 h. However, several were carried on for 72 h to observe any later reactions. Effect of silica fume on the accumulative heat of hydration is shown in Table 2.4. It is evident that the presence of silica fume increased heat evolution during the first 30 min of hydration, and during the period from 8 to 24 h regardless of the w/cm ratio. Heat evolved during the dormant period remained almost constant for all mixtures, while the heat during the period from 2 to 8 h was reduced. Total heat evolved at 1 and 3 days was not changed by the presence of silica fume at w/c ratio of 0.35. Total heat at 1 day does increase with an increase in w/cm.

Table 2.4 Effect of silica fume on heat evolution of Portland cement hydration [56]

Mix type	Heat of hydration (Kcal/kg)						
	w/cm	0.0–0.5 h	0.5–2.0 h	2.0–8.0 h	8.0–24 h	Total at 1 day	Total at 3 days
0% SF	0.35	2.6	0.4	11.7	31.3	45.9	56.9
10% SF	0.35	3.1	0.4	8.7	34.5	46.6	56.1
0% SF	0.40	2.6	0.5	11.8	31.8	46.7	–
10% SF	0.40	3.2	0.4	10.3	33.6	47.4	–
0% SF	0.50	2.6	0.4	10.2	33.3	46.4	–
10% SF	0.50	3.2	0.5	9.7	35.3	48.7	–

Kadri and Duval [45] investigated the influence of silica fume on the hydration heat of concrete. Portland cement was replaced by *silica fume* (10–30% by mass) in concrete with $w/(c + sf)$ ratios varying between 0.25 and 0.45. The heat of hydration was monitored continuously by a semi-adiabatic calorimetric method for 10 days at 20°C. They concluded that (i) hydration rate of silica fume concretes mainly depends on two parameters: the $w/(c + sf)$ ratio and the silica fume content. Regardless of silica fume in concrete, it is evident that hydration rate decreased with an increase in $w/(c + sf)$ ratio. The reduction in the hydration rate for the lower $w/(c + sf)$ ratios is due to the lack of water available for cement hydration, whereas increased superplasticizer addition may be accounted for extension for the dormant period. On the contrary, for the 0.45 $w/(c + sf)$ ratio, the amount of water is enough to fill the voids and coat the cement grains which enable a greater hydration of cement; (ii) addition of silica fume altered the hydration process at very early ages. For three lower $w/(c + sf)$ ratios, the hydration heat increased with silica fume in the first hour; (iii) difference in the rate of heat evolution between a 30% silica fume concrete and the plain concrete exceeds 50% for the 0.25 and 0.35 $w/(c + sf)$ ratios. On the contrary for the 0.45 ratio, the heat evolution rate of the reference concrete is higher than that of the silica fume concrete; and (iv) total heat of hydration (Fig. 2.3) in the ten first days depends on the silica fume content. With the increase in silica fume content, quantity of cement reduces. The reduction in the cement content tends to diminish the total heat released, while the pozzolanic reaction tends to increase it. A 10% substitution of Portland cement increased the cumulative heat of hydration as compared to control concrete (0% silica fume) due to the pozzolanic effect. At 30% silica fume content, total heat of hydration decreased since at a later stage the hydration rate of cement slows down and forms less $Ca(OH)_2$. The pozzolanic reaction is controlled by the $Ca(OH)_2$ formation and depends on the available amount of $Ca(OH)_2$.

2.5 Silica Fume Efficiency

Silica fume efficiency [8] in concrete is not constant at all percentages of replacement. The “overall efficiency factor” of silica fume can be assessed in two

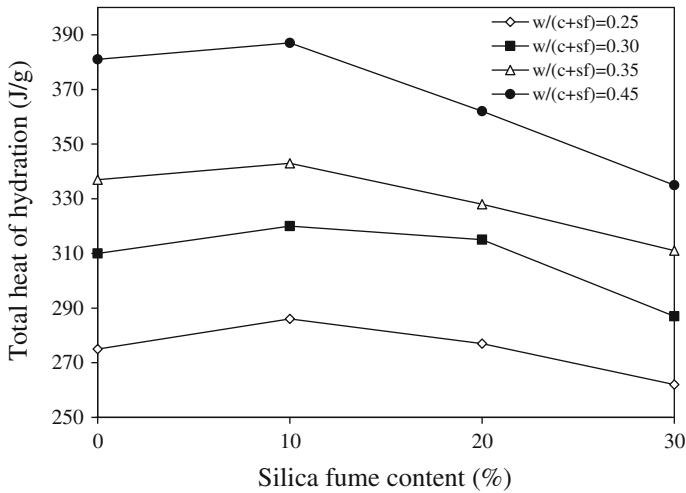


Fig. 2.3 Total heat of hydration over 10 days as a function of silica fume content [45]

separate parts; “general efficiency” which is constant at all percentages of replacement and the “percentage efficiency factor” which varies with the replacement percentage. The activity of silica fume in concrete is obtained in terms of the amount of cement replaced through its “cementing efficiency factor” (K). Efficiency factor for silica fume in concrete can be defined as the number of parts of cement that may be replaced by one part of the silica fume, without changing the property being investigated generally the compressive strength.

$$K = (K_e) \times K_p$$

K = Overall Efficiency Factor

K_p = Percentage Efficiency Factor ($K_p = 0.0015 \text{ pr}^2 - 0.3671 \text{ pr} + 2.8502$)

K_e = General Efficiency Factor (K_e). It is taken as 3, usually kept constant for all the percentages of replacement.

pr = the percentage of silica fume in the total cementitious materials

2.6 Advantages of Using Silica Fume

- High early *compressive strength*
- High tensile, *flexural strength*, and *modulus of elasticity*
- Very low *permeability* to chloride and water intrusion
- Enhanced *durability*
- Increased *toughness*
- Increased *abrasion resistance* on decks, floors, overlays and marine structures

- Superior resistance to chemical attack from chlorides, acids, nitrates and sulfates and life-cycle cost efficiencies.
- Higher *bond strength*
- High *electrical resistivity* and low permeability

2.7 Applications of Silica Fume

- *High Performance Concrete (HPC) containing silica fume*—for highway bridges, parking decks, marine structures and bridge deck overlays which are subjected to constant deterioration caused by rebar corrosion current, abrasion and chemical attack. Silica fume will protect concrete against deicing salts, seawater, road traffic and freeze/thaw cycles. Rebar corrosion activity and concrete deterioration are virtually eliminated, which minimizes maintenance expense.
- *High-strength concrete enhanced with silica fume*—provides architects and engineers with greater design flexibility. Traditionally used in high-rise buildings for the benefit of smaller columns (increasing the usable space) high-strength concrete containing silica fume is often used in precast and prestressed girders allowing longer spans in structural bridge designs.
- *Silica-fume Shotcrete*—delivers greater economy, greater time savings and more efficient use of *sprayed concrete*. Silica fume produces superior shotcrete for use in rock stabilization; mine tunnel linings, and rehabilitation of deteriorating bridge and marine columns and piles. Greater bonding strength assures outstanding performance of both wet and dry process shotcreting with less rebound loss and thicker applications with each pass of the shotcrete nozzle.
- *Oil Well Grouting*—whether used for primary (placement of grout as a hydraulic seal in the well-bore) or secondary applications (remedial operations including leak repairs, splits, closing of depleted zones); the addition of silica fume enables a well to achieve full production potential. Besides producing a blocking effect in the oil well grout that prevents gas migration, it provides these advantages such as (i) Improved flow, for easier, more effective application; (ii) dramatically decrease permeability, for better control of gas leakage; and (iii) lightweight
- *Repair Products*—silica fume is used in a variety of cementitious repair products. Mortars or grouts modified with silica fume can be tailored to perform in many different applications—overhead and vertical mortars benefit from silica fume's ability to increase surface adhesion. Silica fume significantly improves cohesiveness making it ideal for use in underwater grouts, decreases permeability in grouts used for post-tensioning applications and increases the resistance to aggressive chemicals.

- *Refractory and Ceramics*—the use of silica fume in refractory castables provides better particle packing. It allows for less water to be used while maintaining the same flow characteristics. It also promotes low temperature sintering and the formation of mullite in the matrix of the castable. This produces a castable that has a low permeability to avoid gas, slag and metal penetration. Castables incorporating silica fume are stronger than non-silica fume containing castables especially at high temperatures with higher density they attain lower porosity and are more volume stable.

2.8 Effect of Silica Fume on Fresh Properties of Cement/Mortar/Concrete

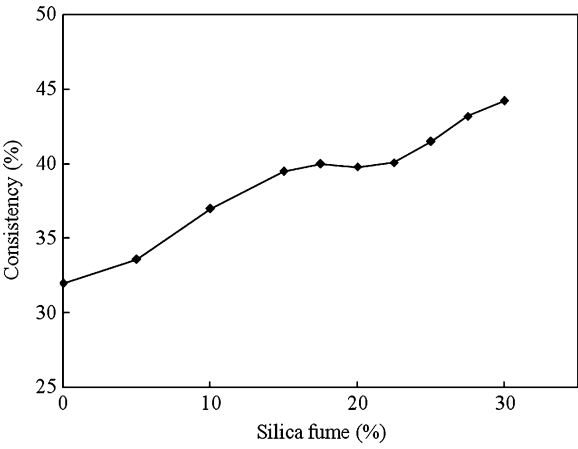
Rheological properties of a fresh cement paste play an important role in determining the *workability* of concrete. The water requirement for flow, hydration behaviour, and properties of the hardened state largely depends upon the degree of dispersion of cement in water. Properties such as fineness, particle size distribution, and mixing intensity are important in determining the rheological properties of cement paste. Due to the charges that develop on the surface, cement particles tend to agglomerate in the paste and form flocs that trap some of the mixing water. Factors such as water content, early hydration, water reducing admixtures and mineral admixtures like silica fume determine the degree of flocculation in a cement paste.

Fresh concrete containing silica fume is more cohesive and less prone to *segregation* than concrete without silica fume. Concrete containing silica fume shows substantial reduced *bleeding*. Additionally silica fume reduces bleeding by physically blocking the pores in the fresh concrete. Use of silica fume does not significantly change the unit weight of concrete.

2.8.1 Consistency

Rao [72] determined the influence of silica fume on the *consistency* of cement pastes and mortars. *Specific gravity* and *specific surface* of the silica fume were 2.05 and 16,000 m²/kg, respectively. Silica fume was varied from 0 to 30% at a constant increment of 2.5/5% by weight of cement. Since the SF is finer than the cement, the specific surface increased with increase in SF content. The standard consistency of pure cement paste was found out to be 31.50%; while at 30% SF, it was 44.25%. It was observed that the consistency of cement increased with the increase in SF content. As much as 40% of additional water requirement was observed for cement pastes containing 20–30% SF. Figure 2.4 shows the variation of consistency of cement at different silica fume contents.

Fig. 2.4 Variation of consistency of cement pastes containing different percentages of silica fume [72]



Qing et al. [71] examined the influence of nano-SiO₂ (NS) addition on consistency of cement paste incorporating NS or silica fume. The influence of NS or silica fume addition on consistency and setting time of fresh pastes is given in Table 2.5. It was found that with increasing the NS content, fresh pastes for sample A-series grew thicker gradually and their penetration depths (consistency value) decreased gently as compared with that of control sample CO. While with increasing the silica fume content, the pastes for sample B-series grew thinner and their depths increased. They concluded that silica fume makes cement paste thinner as compared with NS.

2.8.2 Setting Times

Alshamsi et al. [3] reported that addition of micro-silica lengthened the *setting time* of pastes. This was expected since micro-silica replaces part of the OPC, reducing the early stiffening potential. While the addition of *micro-silica* (10%)

Table 2.5 Mix proportions, consistency of pastes made of cement and NS and silica fume [71]

Sample	Mix proportion in mass					Consistency (mm)
	Cement	Nano silica	Silica fume	Water	SM	
CO	100	0	0	22	2.5	34
A1	99	1	0	22	2.5	34
A2	98	2	0	22	2.5	33
A3	97	3	0	22	2.5	33
A5	95	5	0	22	2.5	32
B2	98	0	2	22	2.5	35
B3	97	0	3	22	2.5	35
B5	95	0	5	22	2.5	36

had little effect on setting times, higher percentages produced significant influences. There was 6–20% increase in setting times when OPC was replaced with 20% micro-silica.

Lohtia and Joshi [58] concluded that the addition of silica fume to concrete in the absence of water-reducer or superplasticizer causes delay in setting time, compared to non-silica fume concrete of equal strength, especially when the silica fume content was high. The additions of 5–10% *silica fume* to either superplasticized or non-superplasticized concrete with $W/(C + SF)$ ratio of 0.40 did not exhibit any significant increase in setting time. However, when 15% silica fume was added with superplasticizer, both the initial and final setting times were delayed by approximately 1 and 2 h, respectively. The observed delay was attributed to the relatively high dose of superplasticizers needed for the high amount of silica fume added to concrete.

Rao [72] studied the influence of silica fume on the setting time of cement paste. Specific gravity and specific surface of the silica fume were 2.05 and 16,000 m²/kg, respectively. Figure 2.5 shows the variation of setting times with the addition of silica fume in cement pastes. It was observed that initial setting time decreased with the increase in silica fume content. At smaller contents, the setting time of cement paste did not affect much. However, at higher silica fume contents, the initial setting time was significantly decreased. At 30% silica fume, the initial setting time had been only 30 min. The final setting time seem to be not influenced by the silica fume. The pozzolanic action of silica fume seems to be very active at early hours of hydration. Therefore, he concluded that silica fume contents result in quick setting of cement.

Qing et al. [71] investigated the influence of nano-SiO₂ (NS) on the setting time of cement paste incorporating NS or silica fume. The influence of NS or silica fume addition on consistency and setting time of fresh pastes is presented in

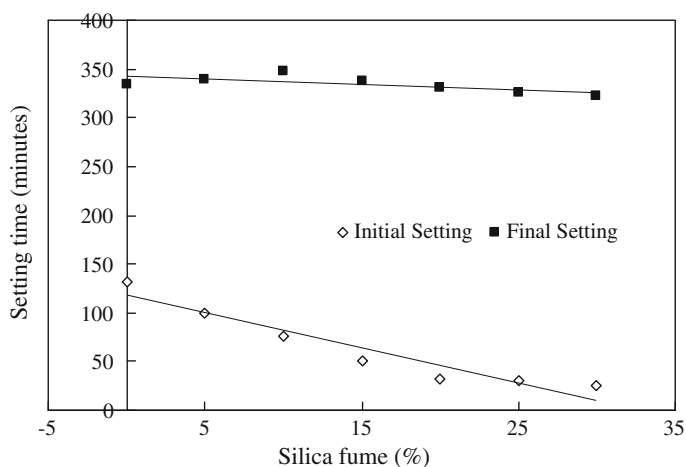


Fig. 2.5 Variation of setting time with different percentages of silica fume addition [72]

Table 2.6. It was observed that the setting of fresh pastes (sample A-series) was slightly accelerated but the difference between initial and final setting time decreased with increase in NS content. While the setting of fresh pastes (sample B-series) was obviously retarded and the difference was also decreased with increasing the silica fume content. They concluded that silica fume makes cement paste thinner and retards the cement setting process as compared with NS.

2.8.3 Workability

Sellevoid and Redjy [80] reported that there is net decrease in water requirements in concretes containing high concentration of silica fume and *water-reducer* or superplasticizers. The addition of water-reducer or a superplasticizer causes the dispersion of cement and silica fume particles and reduces the concentration of contact points between the different grains; resulting in less water requirement to achieve a given consistency.

Alshamsi et al. [3] highlighted that addition of micro-silica to cement pastes or concretes leads to lower *workability*. Such effect can result in higher water demand to maintain a constant slump. Hence water-reducing admixtures or superplasticizers should be dosaged by weight of micro-silica in order to keep water demand similar to that of control. Table 2.7 shows that higher the replacement level, the larger the water demand and larger the superplasticizer dosage required to maintain the standard *consistency*. The physical properties of micro-silica are known to reduce workability mainly due to small particle size that leads to higher water demand. The workability of concrete mix (9) containing mineral admixture is considerably improved by using chemical admixture. The combination of a superplasticizer and a mineral admixture (silica-fume) is desirable, since silica fume in the amount exceeding 5% from the mass of cement considerably increases the fine fraction volume and hence the water requirement of the binder.

Table 2.6 Mix proportions, setting time of pastes made out of cement and NS and silica fume [71]

Sample	Mix proportion in mass					Setting time	
	Cement	Nano silica	SF	Water	SM	Initial	Final
CO	100	0	0	22	2.5	2 h 57 m	4 h 23 m
A1	99	1	0	22	2.5	2 h 57 m	4 h 05 m
A2	98	2	0	22	2.5	2 h 55 m	3 h 50 m
A3	97	3	0	22	2.5	2 h 48 m	3 h 40 m
A5	95	5	0	22	2.5	2 h 16 m	3 h 06 m
B2	98	0	2	22	2.5	3 h 50 m	4 h 45 m
B3	97	0	3	22	2.5	4 h 35 m	5 h 20 m
B5	95	0	5	22	2.5	4 h 45 m	5 h 28 m

Table 2.7 Mix proportions for standard consistency [3]

Mix #	OPC	Micro-silica	Water	Admixture (ml)
1	100	0	27.5	0
2	95	5	30	0
3	90	10	32	0
4	85	15	37.5	0
5	80	20	43	0
6	95	4	27.5	3
7	90	10	27.5	5
8	85	15	27.5	6.5
9	80	20	27.5	8

Khayat and Aitcin [50] reported that addition of 10% silica fume in a lean concrete (100 kg/m^3) of cement reduced the water demand. However, it exhibited poor durability against *freeze–thaw attack*. In normal structure concrete, even with 5% silica fume addition, the water demand is increased to maintain constant *slump*. For producing very high strength and durable concrete, silica fume up to 10% is added as an admixture and use of superplasticizer to maintain specified slump is found necessary. When no plasticizers are used an additional 1 l/m^3 of water should be used for every 1 kg/m^3 of silica fume addition to maintain constant level of fluidity.

Wong and Razak [97] studied the *cementing efficiency factor* (k) of silica fume. Specific gravity of silica fume was 2.22. Three water-to-cementitious material ratios (w/cm) of 0.27, 0.30 and 0.33 were used in concrete mixtures. At each w/c ratio, cement was replaced with 0, 5, 10, and 15% silica fume. Slump and *Vebe time* results are shown in Table 2.8. It could be seen from this table that mixtures achieved slump values ranging from 30 to 260 mm, while *Vebe time* was in the range of 1–15 s. The large variation of workability across mixtures was due to the constant superplasticizer dosage used for mixtures with the same w/cm ratio.

Mazloom et al. [62] made *high-performance concrete* containing silica fume. The silica fume content was 0, 6, 10, and 15%, and water–cementitious ratio being 0.35. The water/cement ratio and the slump of control high-strength concrete were 0.35 and $100 \pm 10 \text{ mm}$, respectively. The same water/binder ratio of 0.35 was used for the other concrete mixes with the same slump. Consequently, the dosage of superplasticizer changed due to the effect of the different levels of silica fume. Details of mix proportions for concrete containing different levels of silica fume

Table 2.8 Workability characteristics [97]

Mixture	w/cm	Slump (mm)	Vebe (s)	w/cm	Slump (mm)	Vebe (s)	w/cm	Slump (mm)	Vebe (s)
C	0.27	165	8	0.30	225	3	0.33	240	1
SF 5		100	8		215	3		180	3
SF 10		50	12		117	5		100	6
SF 15		35	15		30	16		35	16

Table 2.9 Mix proportions of concrete containing different levels of silica fume [62]

Mix components	Concrete mixes			
	OPC	SF 6	SF 10	SF 15
Cement (kg/m ³)	500	470	450	425
Silica fume (kg/m ³)	–	30	50	75
Superplasticizer (kg/m ³)	8.17	9.78	11.71	13.34

Gravel: 1,203 kg/m³, sand: 647 kg/m³, water: 175 kg/m³, w/cm = 0.35

are given in Table 2.9. It was observed that mixes incorporating higher silica fume content tended to require higher dosages of superplasticizer. The higher demand of superplasticizer with the concrete containing silica fume was attributed to the very fine particle size of silica fume that causes some of the superplasticizer being adsorbed on its surface. Also mixes incorporating more silica fume were more cohesive, which is in agreement with the findings of Khatri et al. [47].

Rao [72] studied the influence of silica fume on the workability (*flow table test*) of mortars. Specific gravity and specific surface of the silica fume were 2.05 and 16,000 m²/kg, respectively. The *specific gravity* and the *bulk density* of sand were 2.68 and 1,584 kg/m³, respectively. The cement–sand ratio in the mortars was 1:3, and w/b ratios were 0.45 and 0.50. Figure 2.6 demonstrates the variation of workability as percentage flow at w/cm ratios 0.45 and 0.50 with different silica fume contents. It is evident from these results that workability of mortar slightly decreased as the silica fume content increased. This has been due to the higher specific surface of silica fume, which needs more water for complete hydration and for workability. When very fine particles of silica fume are added to the mortar, the size of flow channels further reduced because these fine particles are able to adjust

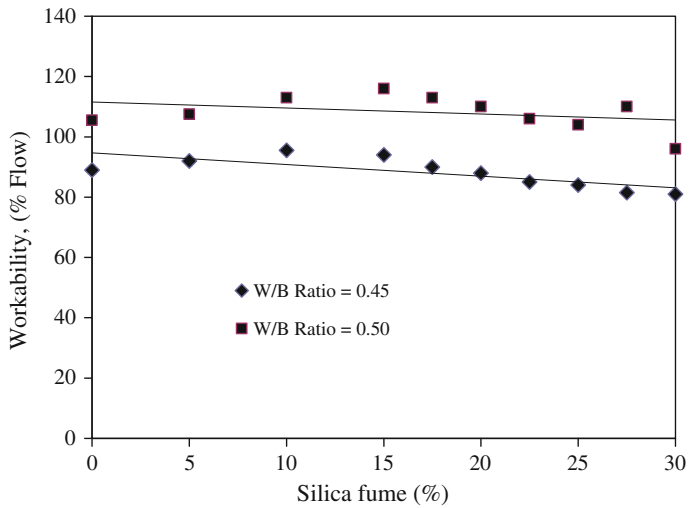


Fig. 2.6 Variation of workability of cement mortars with silica fume at different contents [72]

their positions to occupy the empty spaces between cement particles. Due to increase in the number of contact points between solid particles, the cohesiveness of mortar mixture greatly improves when silica fume is present. In fact, the presence of too much silica fume in mortar ($>10\%$ by weight of cement) tends to make the mixture stiff. The addition of small amounts of silica fume does not require the use of extra water or super plasticizers. However, with higher dosages of silica fume, the workability of mortar was found to be reduced.

2.9 Effect of Silica Fume on the Hardened Properties of Cement/Mortar/Concrete

2.9.1 Compressive Strength

When silica fume is added to concrete, it results in a significant change in the *compressive strength* of the mix. This is mainly due to the aggregate-paste bond improvement and enhanced *microstructure*.

2.9.1.1 Compressive Strength of Cement Paste/Mortar

Huang and Feldman [41] found that mortar without silica fume has lower strength than cement paste with the same water–cement ratio, while mortar with 30% of cement replaced with silica fume has a higher strength than cement–silica fume paste with the same water–cementitious ratio. They concluded that the addition of silica fume to mortar resulted in an improved bond between the hydrated cement matrix and sand in the mix, hence increasing strength. This improved bond is due to the conversion of the calcium hydroxide, which tends to form on the surface of aggregate particles, into calcium silicate hydrate due to the presence of reactive silica.

Cong et al. [20] observed that the replacement of cement by silica fume (up to 18%) and the addition of superplasticizer increased the strength of cement paste. Concrete containing silica fume as a partial replacement of cement exhibited an increased compressive strength largely because of the improved strength of cement paste matrix. But, changes in paste aggregate interface caused by the incorporation of silica fume had little effect on the compressive strength of concrete.

Gleize et al. [30] determined *compressive strength* of *silica fume* mortar having proportion 1:1:6 (Cement + silica fume: lime: sand). The results are given in Table 2.10. They concluded that in Portland cement mortars, silica fume acts mainly at the interface paste-aggregate, where there is a higher concentration of calcium hydroxide and greater porosity than in paste. In Portland cement mortars with silica fume, lime is better suited in the paste and there is no evidence of concentration of silica fume at the interface paste aggregate.

Table 2.10 Mortar compressive strength [30]

Age (days)	0% Silica fume	10% Silica fume
7	3.26 ± 0.12	2.93 ± 0.13
28	6.58 ± 0.19	7.11 ± 0.25

Gutiérrez et al. [36] studied the effect of silica fume on the compressive strength of *fibre reinforced mortar*. Different types of natural and synthetic fibres were also used. These were embedded in the blended cement mortars in the proportion of 2.5% by weight of the cement. The effect of addition of silica fume in plain mortar is shown in Fig. 2.7. Incorporation of silica fume increased the average compressive strength by 23%. But fibres in the plain mortar caused a reduction in its compressive strength. However this loss was compensated by addition of silica fume into the matrix. The compressive strength of the matrix reinforced with glass fibres gained an increment of up to 68% when silica fume was included as a part of the cementitious material.

2.9.1.2 Compressive Strength of Normal Strength/High-Performance Concrete

Bentur et al. [11] reported that the strength of *silica fume concrete* is greater than that of silica fume paste which they attributed to the change in the role of the aggregate in concrete. In cement concrete, the aggregate functions as inert filler but due to the presence of weak *interfacial zone*, composite concrete is weaker than cement paste. But, in silica fume concrete, the presence of silica fume eliminates this weak link by strengthening the cement paste aggregate bond and forming a less porous and more homogenous microstructure in the interfacial

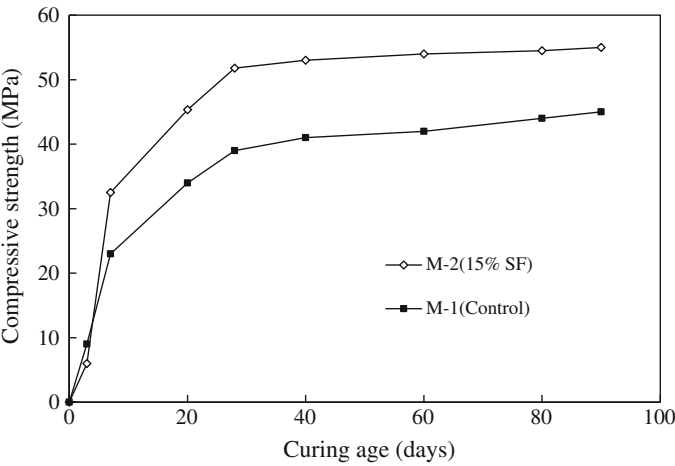


Fig. 2.7 Effects of addition of silica fume in plain mortar [36]

Table 2.11 Development of compressive strength with age (MPa) [62]

Concrete mixes	Silica fume (%)	Compressive strengths (MPa)						
		7 days	14 days	28 days	42 days	90 days	365 days	400 days
OPC	0	46	52	58	62	64	73	74
SF 6	6	50.5	58	65	69	71	73	73
SF 10	10	52	61	67.5	71	74	73	73
SF 15	15	53	63	70	73	76	75	76

region. Thus, silica fume concrete is stronger than silica fume cement paste, taking into account that the strength of aggregate exceeds the strength of cement paste.

Mazloom et al. [62] investigated the compressive strength of high performance concrete containing silica fume. The silica fume content was 0, 6, 10, and 15%, and water–cementitious ratio being 0.35. The results are given in Table 2.11. From the results it can be seen that (i) at the age of 28 days, the silica fume concrete was 21% stronger than control concrete; (ii) *compressive strength* development of concrete mixtures containing silica fume was negligible after the age of 90 days; however, there was 26% and 14% strength increase in the control concrete after 1 year compared to its 28 and 90 days strength, respectively. Also the tests showed that at the age of 400 days, the compressive strength of control concrete and concrete mixes containing different proportions of silica fume were the same. According to Wild et al. [96], this difference in strength development in OPC concrete and silica fume concrete can be attributed to the rapid formation of an inhibiting layer of reaction product preventing further reaction of silica fume with calcium hydroxide beyond 90 days.

Sobolev [84] studied the compressive strength of high performance concretes. The compressive results of HPC mixture are shown in Table 2.12. It was observed that (i) increase in superplasticizer dosage from 8 to 18% led to a reduction of w/c from 0.31 to 0.26 and improved the concrete compressive strength from 86 to 97 MPa; (ii) maximum compressive strength of 91 MPa was obtained at 15% silica fume.; (iii) lower strength value of 90 MPa occurred at 10 and 20% silica fume; and (iii) reduction of w/c 0.32–0.19 increased the compressive strength of cement concrete and resulted in super high strength concrete having strength up to 135 MPa.

Table 2.12 Details of HPC mixtures [84]

Proportions (kg/m ³)	SF (5%)	SF (10%)	SF (15%)	SF (20%)
Cement	426	449	468	478
Silica fume	22	50	83	120
Age	Compressive strength (MPa)			
1 day	16.8	24.1	34.4	45.1
3 days	28.6	42.2	63.0	84.9
7 days	50.1	67.2	84.8	102.5
28 days	60.0	80.0	100.0	120.0

Wong and Razak [97] studied the compressive strength of concrete containing silica fume. Concrete mixtures with w/cm ratios of 0.27, 0.30 and 0.33 were prepared. At each w/c ratio, cement was replaced with 0, 5, 10, and 15% silica fume. The results are given in Table 2.13. They observed that (i) silica fume did not produce an immediate strength enhancement; instead, the blended mixtures only achieved higher strength than the control from 7 days onwards. Strength loss in the early ages, which was proportional to the cement replacement level, was probably due to the dilution effect of the *pozzolan* and as well as the slow nature of pozzolanic reaction; and (ii) after 90 days of curing, the average strength enhancement with 10% silica fume achieved 17% increment. It was also found that reducing the w/c ratio from 0.30 to 0.27 did not trigger a significant strength enhancement as anticipated.

Poon et al. [69] reported the results of *compressive strength* of *high-performance concrete* with silica fume. Two series of concrete mixes were prepared at the w/b ratios of 0.30 and 0.50. Each series included 5 and 10% silica fume. Compressive strength results are given in Table 2.14. It is clear from the results that the incorporation of silica fume did not result in any strength increase for the concrete at 3 days, although it increased the strength at the ages of or after 7 days.

Behnood and Ziari [10] designed concrete mixtures to evaluate the effect of silica fume on the compressive strength of the *heated and unheated concrete* specimens. Three mixtures were made with a constant water-to-cement ratio (w/c) 0.30. The dosages of replacing cement by silica fume were 0% (W30OPC), 6% (W30SF6) and 10% (W30SF10). One mixture was prepared with w/c of 0.40 without silica fume (W40OPC), whereas other concrete was produced with w/c of 0.35 containing 6% silica fume (W35SF6). The results of the *compressive strength* are given in Table 2.15. As was expected, the replacement of cement by 6 and 10% silica fume increased the 28-day compressive strength approximately by 19

Table 2.13 Cube compressive strength [97]

Mixture	Compressive strength (MPa)						
	1 day	3 days	7 days	28 days	56 days	90 days	180 days
w/cm 0.27	39	68	72.5	84	86.5	87.5	90
SF 5	35	63	75.5	88.5	93	96.5	97.5
SF 10	25	61	79	95.5	100	104	107
SF 15	24.5	59.5	76.5	101	103.5	106	109
w/cm 0.30	48	63.5	72	83.5	84.5	85.5	87.5
SF 5	46	62	81	91	95.5	95.5	97
SF 10	42	61.5	78.5	95	97	99	103
SF 15	38	57.5	74.5	98.5	101.5	104	106.5
w/cm 0.33	41.0	58.0	62.5	75	78	79	81.5
SF 5	35.0	55.0	69.5	83.0	85.0	90.0	90.0
SF 10	32.0	53.0	70.5	89.5	90.5	92.0	93.5
SF 15	31.0	47.5	70.5	88.5	93.0	95.5	100.5

Table 2.14 Compressive strength of control and blended concrete [69]

Series	w/b	Mix	Compressive strength			
			3 days	7 days	28 days	90 days
1	0.30	Control	68.5	81.1	96.5	102.5
		5% SF	67.0	79.3	106.5	110.2
		10% SF	63.2	76.9	107.9	115.6
2	0.50	Control	28.6	41.2	52.1	60.4
		5% SF	27.4	47.0	54.3	67.5
		10% SF	25.8	47.4	58.4	69.1

Table 2.15 Results of compressive strength at different temperatures [10]

Mixture name	SF (%)	w/c	Compressive strength (MPa)					
			20°C		100°C	200°C	300°C	600°C
			7-day	28-day				
W40OPC	0	0.40	48.3	61.8	53.3	55.5	46.5	20.6
W35SF6	6	0.35	61.5	73.9	62.8	64.7	56.5	21.8
W30OPC	0	0.30	55.3	67.4	57.6	59.7	49.0	21.0
W30SF6	6	0.30	69.1	80.3	68.0	69.0	56.5	23.4
W30SF10	10	0.30	74.1	84.2	70.8	71.7	57.9	22.6

and 25% respectively. This was due to the reaction of silica fume with calcium hydroxide formed during the hydration of cement that caused the formation of *calcium silicate hydrate* (C–S–H). It was also due to the filler role of very fine particles of silica fume. Furthermore, concretes containing different levels of silica fume showed lower rates of compressive strength gain in early ages. They concluded that (i) Concrete containing silica fume had significantly higher strength than that of OPC concrete at room temperature. After exposure to 100°C, significant reductions occurred in the compressive strength of concrete with and without silica fume; (ii) In the range 300–600°C, severe strength losses occurred in all three concretes, which were 68.8, 70.9 and 73.2% of the initial values for W30OPC, W30SF6 and W30SF10 concretes respectively. This was because during exposure to high temperatures, cement paste contracts, whereas aggregates expand. Thus, the transition zone and bonding between aggregates and paste are weakened. As a result, this process as well as chemical decomposition of hydration products causes severe deteriorations and strength losses in concrete after subjecting to high temperatures; and (iii) After heating to 600°C, the residual compressive strength of all three concretes were approximately same, whereas the relative residual compressive strengths of concretes containing 6 and 10% silica fume were 6.7 and 14.1% lower than those of the OPC concretes, respectively, after exposure to 600°C. Therefore, the rate of strength loss was significantly higher in silica fume concretes. This was attributed to the presence and amount of silica fume in concretes that produced very dense transition zone between aggregate and paste due to ultra fine particles as filler.

Köksal et al. [53] studied the compressive strength of *steel fibre reinforced concrete* with silica fume. Cold drawn steel fibres with hooked ends were used. Aspect ratios (l/d) of fibres were 65 and 80 and volume fractions (V_f) of steel fibres were 0.5 and 1%. Silica fume content was 0, 5, 10, and 15% weight of cement. The test results are given in Table 2.16. They observed that (i) a considerable increase in the compressive strength of the concretes without steel fibres by increasing the *silica fume* content. The increases were 12, 73.4 and 85.5% for 5, 10 and 15% silica fume, respectively. These result were clearly dependant on increasing *bond strength* of *cement paste–aggregate interface* by means of filling effect of silica fume; and (ii) compressive strengths of concretes produced by additions of both steel fibre and silica fume had higher than the ones containing silica fume only.

2.9.1.3 Effect of Curing on the Compressive Strength of Concrete

Bentur and Goldman [12] studied the effect of water and *air-curing* in mild environmental conditions on the compressive strength at the age of 90 days. The air curing resulted in a somewhat lower strength compared to continuous water curing. This was attributed to the observations that the strengthening influence of the silica fume takes place quite early during the period 1–28 days and possibly slower rate of drying from within the silica fume concrete, which apparently developed a tight micro-structure after 7 days of water curing. Similar trends were

Table 2.16 Test results of concrete steel fibre concrete [53]

Series	Silica fume (%)	Steel fibre content (%)	Compressive strength (N/mm ²)
A	0	0	32.4
		0.5	33.4
		1.0	37.4
		0.5	34.1
		1.0	38.5
B	5	0	36.4
		0.5	38.3
		1.0	48.1
		0.5	41.4
		1.0	45.7
C	10	0	56.2
		0.5	60.4
		1.0	66.9
		0.5	59.7
		1.0	63.7
D	15	0	60.1
		0.5	66.5
		1.0	69.3
		0.5	63.2
		1.0	70.5

observed for 28 days except that the strength values were usually lower by about 10%.

Hooton [38] determined the compressive strengths of concretes containing 0, 10, 15, and 20% silica fume up to the age of 5 years. Results are presented in Table 2.17. While strengths of the concretes containing silica fume were higher at ages between 7 and 91 days, the Portland cement concrete continued to gain strength at later ages; with a 55% increase between 28 days and 5 years. In contrast, the long-term strength gain of silica fume concretes were very low and 5-year strengths were $\pm 12\%$ of the day strengths. Reductions in strengths were noted to be within the normal variation of strengths observed in long-term studies with Portland cement concretes.

2.9.1.4 Compressive Strength of Recycled Aggregate Silica Fume Concrete

González-Fonteboa and Martínez-Abella [32] studied the properties of concrete using *recycled aggregates* from Spanish demolition debris (RC mixes) and the impact of the addition of silica fume on the properties of recycled concrete (RCS mixes). A comparison was made between both these materials and standard conventional concrete (CC mixes), which was also modified by adding silica fume (CCS mixes). It also aimed to study the effect of addition of silica fume on the basic properties of recycled concrete. For the test four series (10 CC, 7CCS, 10 RC and 6 RCS) of mixes were made. Compressive strength results are shown in Fig. 2.8. They reported that (i) *Pozzolanic effect* of silica fume was seen between 7 and 21 days which tends to increase the compressive strength of the concrete; and (ii) concrete containing 8% silica fume displayed greater compressive strength than concretes that did not contain this admixture, at all ages.

Almusallam et al. [6] investigated the effects of silica fume on the compressive strength of concrete made with *low-quality coarse aggregates*. Four types of low quality coarse aggregates, namely calcareous, dolomitic, and quartzitic limestone

Table 2.17 Moist-cured concrete compressive strength development [38]

Testing age	Concrete mixture details				
	Control	10% SF	15% SF	20% SF	10% SF in slurried product
1 day	25.6	25.2	28.0	27.2	33.2
7 days	44.6	59.8	63.2	64.5	69.9
28 days	55.6	70.7	75.2	74.2	85.0
56 days	63.5	74.0	76.4	72.9	82.6
91 days	63.4	77.6	72.9	74.0	83.7
182 days	72.5	73.2	71.4	77.8	82.7
365 days	79.0	76.7	70.0	80.3	80.2
2 years	86.1	81.5	71.4	82.0	—
3 years	88.2	89.7	85.1	88.3	—
5 years	86.0	79.6	68.6	70.3	—

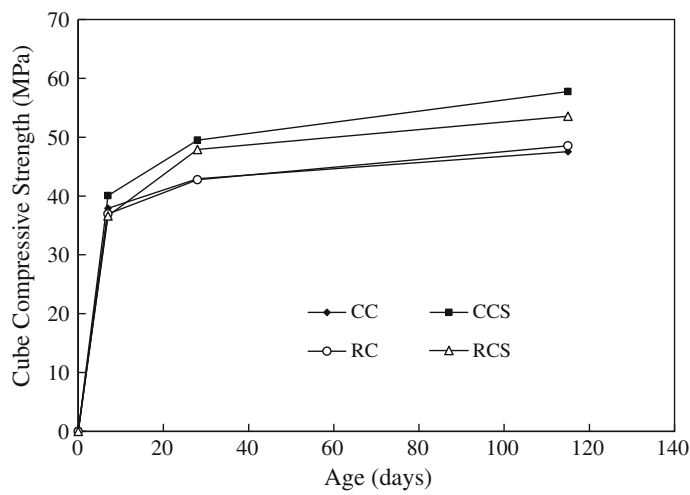


Fig. 2.8 Development of cube compressive strength [32]

and steel slag were used, and silica fume content was 10 and 15% as partial replacement of cement. The concrete specimens had a w/c ratio of 0.35 and a coarse aggregate to fine aggregate ratio of 1.63. The influence of aggregate quality on the compressive strength of 15% silica fume cement concretes is shown in Fig. 2.9. They observed that compressive strength increased with age in all the concrete specimens. After 180 days of curing, highest compressive strength was noted in the 15% silica fume cement concrete specimens (54 MPa) followed by

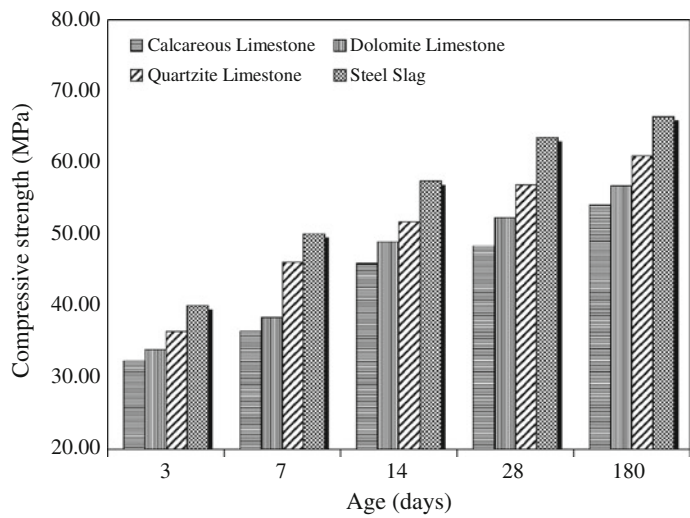


Fig. 2.9 Effect of aggregate type on the compressive strength of 15% silica fume cement concrete [6]

those prepared with 10% silica fume (52 MPa), and plain cement concrete (49 MPa). The higher compressive strength noted in the silica fume cement concrete, compared to plain cement concrete, may be attributed to the reaction of the silica fume with calcium hydroxide liberated during the hydration of cement. Khatri et al. [47] stated that it results in formation of secondary calcium silicate hydrate that fills up the pores due to the hydration of the initial calcium silicate hydrate.

Babu and Babu [9] studied the use of *expanded polystyrene* (EPS) beads as *lightweight aggregate* both in concrete and mortars containing silica fume as a supplementary cementitious material. Three percentages of silica fume—3, 5 and 9% (by weight of the total cementitious materials) were used. They concluded that the rate of strength development was greater initially and decreased as the age increased. A comparison of strengths at 7 days reveals that concretes with 3% silica fume developed almost 75% of its 28-day strength, while that with 5 and 9% silica fume developed almost 85 and 95% of the corresponding 28-day strength. They concluded that rate of strength gain was increasing with an increasing percentage of silica fume.

2.9.2 Tensile Strength

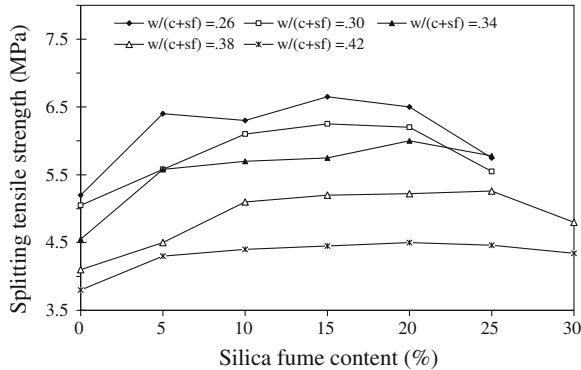
Hooton [38] reported the *splitting tensile strength* of silica fume concretes up to the age of 182 days (Table 2.18). It can be seen that except at 28 days, the splitting tensile strength was not improved for silica fume concrete mixes. Also it was observed that with increasing replacement of silica fume split tensile strength decreased.

Bhanja and Sengupta [14] studied the isolated contribution of silica fume on the tensile strengths of *high-performance concrete*. Five concrete mixes, at w/cm ratios of 0.26, 0.30, 0.34, 0.38 and 0.42 were prepared by partial replacement of cement by equal weight of silica fume. The dosage of silica fumes were 0% (control mix), 5, 10, 15, 20 and 25% of the total cementitious materials. For all the mixes, tensile strengths were determined at the end of 28 days. Studies clearly exhibited that very high percentages of silica fume did not significantly increase the splitting tensile strength and increase was insignificant beyond 15% (Fig. 2.10).

Table 2.18 Splitting tensile strength of concrete [38]

Test age (days)	Concrete mixes			
	Control	10% SF	15% SF	20% SF
28	5.2	6.3	6.2	4.6
91	6.8	6.7	6.2	5.6
182	7.1	6.2	6.5	5.6

Fig. 2.10 Relationship between 28-day split tensile strength and percentage replacement of silica fume [14]



Yazıcı [98] conducted tests on *self-compacting concrete* investigating various properties like *freezing and thawing resistance*, *chloride penetration resistance* along with mechanical properties. He also found that silica fume addition improves the tensile strength at all fly ash replacement levels.

Almusallam et al. [6] investigated the effects of silica fume on the splitting tensile strength of concrete made with low-quality coarse aggregates. Four types of low quality coarse aggregates, namely calcareous, dolomitic, and quartzitic limestone and steel slag were used, and silica fume content was 10 and 15% as partial replacement of cement. The concrete specimens had a w/c ratio of 0.35 and a coarse aggregate to fine aggregate ratio of 1.63. The influence of aggregate quality on the compressive strength of 15% silica fume cement concretes is shown Fig. 2.11. The tests showed that the splitting tensile strength increased with age in

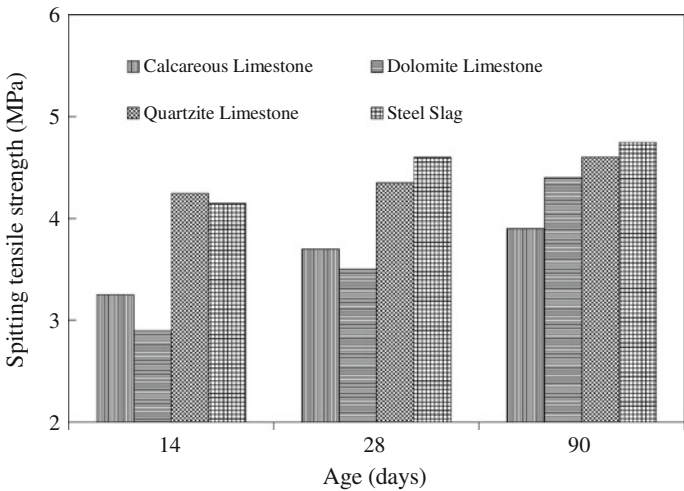


Fig. 2.11 Effect of aggregate type on split tensile strength of 15% silica fume cement concrete [6]

all the concrete specimens. The highest splitting tensile strength was observed in 15% silica fume cement concrete specimens followed by those prepared with 10% silica fume. They found that the splitting tensile strength of the silica fume cement concrete was more than that of plain concrete. After 90 days of curing, the splitting tensile strength of 15% silica fume concrete was maximum being 4.39 MPa. Also, after 90 days, the split tensile strength of 10 and 15% silica fume cement concrete specimens was nearly the same, being 4.54 and 4.59 MPa, respectively.

Tanyildizi and Coskun [88] studied the effect of silica fume on tensile strength of lightweight concrete exposed to *high temperature*. In mixtures containing silica fume, 0, 10, 20 and 30% of Portland cement by weight was replaced with silica fume. They reported that the tensile strength started to drop with temperature starting from 200°C. The reduction in splitting tensile strength of lightweight concrete containing 10% silica fume was 3.11, 11.46 and 80.15% at the 200, 400 and 800°C, respectively. The reduction in splitting tensile strength of lightweight concrete containing 20% silica fume was 4.69, 12.91 and 78.87% at the 200, 400 and 800°C, respectively. And the reduction in splitting tensile strength of lightweight concrete containing 30% silica fume was 5.8, 40.62 and 75.08% at the 200, 400 and 800°C, respectively. They concluded that addition of admixture silica fume prevented the decrease in the tensile strength of concrete.

González-Fontebao and Martínez-Abella [32] studied the properties of concrete using recycled aggregates from Spanish demolition debris (RC mixes) and the impact of the addition of silica fume on the properties of recycled concrete (RCS mixes). A comparison was made between both these materials and standard conventional concrete (CC mixes), which was also modified by adding silica fume (CCS mixes). For the test, they made 10 CC, 7CCS, 10RC and 6RCS mixes. The results of *splitting tensile strength* are shown in Table 2.19. They stated that neither the addition of recycled aggregates nor the addition of silica fume had any particular impact on the tensile strength of the concrete types. The reason behind this was that silica fume mainly affected mechanical properties like compressive strength of high strength concretes.

Köksal et al. [53] studied the splitting tensile of *steel fibre reinforced concrete* with silica fume. Cold drawn steel fibres with hooked ends were used. Aspect ratios (l/d) of fibres were 65 and 80 and volume fractions (V_f) of steel fibres were 0.5 and 1%. Silica fume content was 0, 5, 10, and 15% weight of cement. The test results are given in Table 2.20. They found that increasing the silica fume and steel fibre contents, a considerable increase in the splitting tensile strength of the

Table 2.19 Average tensile splitting tensile strength (MPa) for the various test ages [32]

Cube	Average splitting tensile strength (MPa)		
	7 days	28 days	115 days
CC	3.12	3.15	3.32
CCS	3.04	3.15	3.31
RC	3.17	3.00	3.37
RCS	3.24	3.36	3.35

Table 2.20 Test results of concrete mechanical properties [53]

Series	Silica fume (%)	Steel fibre content (%)	Splitting tensile strength (N/mm ²)
A	0	0	3.48
		0.5	3.75
		1.0	4.59
		0.5	3.7
		1.0	6.6
B	5	0	3.82
		0.5	4.05
		1.0	8.98
		0.5	4.4
		1.0	6.9
C	10	0	5.36
		0.5	6.91
		1.0	9.56
		0.5	7.3
		1.0	9.7
D	15	0	6.54
		0.5	8.4
		1.0	10.01
		0.5	7.5
		1.0	10.0

concrete occurred. The increases in the splitting tensile strengths of the concretes without steel fibres were determined as 9.7, 54 and 87.9% for the 5, 10 and 15% silica fume, respectively.

Babu and Babu [9] studied the use of *expanded polystyrene* (EPS) beads as lightweight aggregate both in concrete and mortars containing silica fume as a supplementary cementitious material. Three percentages of silica fume 3, 5 and 9% (by weight of the total cementitious materials) were used. Split tensile strength test was conducted at 28 days. It was found that tensile strength increased with an increase in compressive strength. And failure observed was more gradual and the specimens did no separate into two, as was earlier reported for plastic shredded aggregate concretes [5].

Sata et al. [76] also observed that tensile strength of concrete slightly increased with the increase in the compressive strength.

2.9.3 Flexural Tensile Strength

Bhanja and Sengupta [14] studied the contribution of silica fume on the *flexural strength* of high performance concrete (HPC). Five series of concrete mixes, at w/cm ratios of 0.26, 0.30, 0.34, 0.38 and 0.42 were made with partial replacement of cement by equal weight of silica fume. The dosages of silica fumes were 0, 5, 10, 15, 20 and 25% of the total cementitious materials. The variations of flexural

tensile strength with silica fume replacement percentage at different w/cm ratios in shown in Fig. 2.12. They stated that silica fume seemed to have a pronounced effect on flexural strength in comparison with splitting tensile strength. For flexural strengths, even very high percentages of silica fume significantly improve the strengths. Also it was found that there was a steady increase in the flexural strength with increase in the silica fume replacement percentage.

Köksal et al. [53] evaluated the flexural strength of concrete incorporating hooked steel fibres and silica fume. Aspect ratios (l/d) of fibres were 65 and 80 and volume fractions (V_f) of steel fibres were 0.5 and 1%. Silica fume was added to concrete directly as the percentages of 0, 5, 10 and 15% by weight of cement. Table 2.21 gives the flexural strength results. Significant increases in the flexural strengths of the concretes were observed by adding silica fume and steel fibres. The increases in the flexural strengths of the concretes without steel fibres were 7, 42.1 and 64.9% for the 5, 10 and 15% silica fume, respectively. Also they found that the flexural strengths of concretes containing 1% steel fibre were found to be greater than that of the concrete with 0.5% steel fibre for each of the silica fume content.

Kılıç et al. [52] examined the influence of aggregate type on the flexural strength characteristics of high-strength silica fume concrete. Five different aggregate types (gabbro, basalt, quartzite, limestone and sandstone) were used to produce high strength concrete containing silica fume. Silica fume replacement ratio with cement was 15% on a mass basis. Water-binder ratio was 0.35. The amount of hyperplasticizer was 4% of the binder content by mass. The flexural tensile strengths of concretes were measured at 3, 7, 28 days, and 3 months. The results are given in Table 2.22. They showed that (i) flexural tensile strength increased with the increase in curing time; and (ii) sandstone concrete showed the

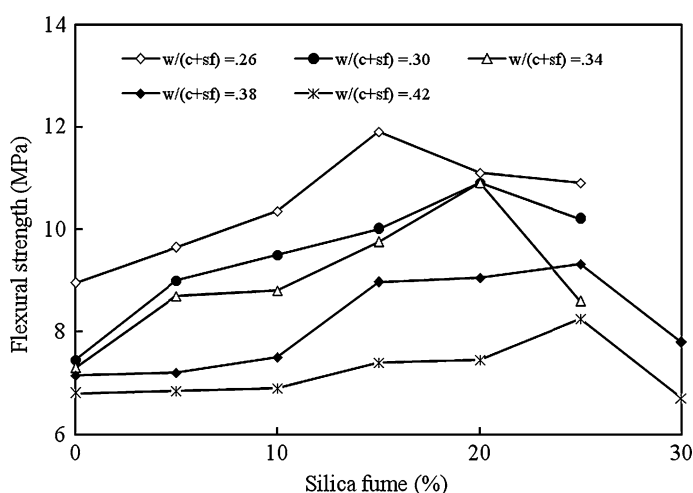


Fig. 2.12 Relationship between 28-day flexural strength and percentage replacement of silica fume [14]

Table 2.21 Test results of concrete mechanical properties [53]

Series	Silica fume (%)	Steel fibre content (%)	Flexural tensile strength (N/mm ²)
A	0	0	5.7
		0.5	5.9
		1.0	6.69
		0.5	6.10
		1.0	10.10
B	5	0	6.1
		0.5	7.2
		1.0	8.7
		0.5	7.6
		1.0	10.3
C	10	0	8.08
		0.5	8.5
		1.0	9.6
		0.5	8.98
		1.0	11.3
D	15	0	9.35
		0.5	9.52
		1.0	10.28
		0.5	9.58
		1.0	12.8

lowest flexural tensile strength, while Gabbro concrete showed the highest flexural tensile strength.

2.9.4 Modulus of Elasticity

Hooton [38] reported the *modulus of elasticity* of silica fume concretes up to the age of 365 days (Table 2.23). It can be seen that elastic modulus of the Portland cement concrete was approximately equal to silica fume concretes at 28 days but continued to increase at later ages.

Mazloom et al. [62] investigated the effect of silica fume on the *secant modulus of elasticity* of high performance concrete. The percentages of silica fume were: 0,

Table 2.22 Flexural strengths of concrete at different curing times [52]

Curing time (days)	Flexural tensile strength (MPa)				
	Gabbro (247)	Basalt (132)	Quartsite (160)	Limestone (110)	Sandstone (52)
3	12.6	11.4	12.9	7.9	3.2
7	16.1	15.4	14.9	12.5	4.5
28	17.3	16.7	16.2	12.8	5.2
90	18.4	17.9	16.9	13.9	5.6

Table 2.23 Modulus of elasticity of silica fume concrete [38]

Testing age (days)	Concrete mix			
	Control	10% SF	15% SF	20% SF
28	43.2	43.7	42.8	43.4
91	48.0	46.2	45.0	45.7
182	49.2	46.7	46.1	46.1
385	51.8	48.4	48.1	48.1

6, 10 and 15%. The results of secant modulus of elasticity of concrete specimens containing different levels of silica fume are given in Table 2.24. From the results it was observed that increasing the silica fume replacement level increased the secant modulus of concrete.

Almusallam et al. [6] determined the elastic modulus of concretes prepared with four types of low quality coarse aggregates, namely calcareous, dolomitic, and quartzitic limestone and steel slag, and 10 and 15% silica fume. The results are given in Table 2.25. The type of coarse aggregate had a significant effect on the modulus of elasticity of concrete. After 28 days of curing, the modulus of elasticity of plain cement concrete prepared with calcareous, dolomitic, and quartzitic limestone and steel-slag aggregates was 22.0, 25.0, 29.0 and 30.0 GPa, respectively. The modulus of elasticity of steel-slag aggregate concrete was the highest while the modulus of elasticity of calcareous limestone aggregate concrete was the lowest. On average, the increase in the modulus of elasticity was 16 and 32% due to the incorporation of 10 and 15% silica fume, respectively. Moreover, the modulus of elasticity of concrete specimens prepared with steel-slag aggregate was more than that of concrete specimens prepared with limestone aggregate.

González-Fonteboa and Martínez-Abella [32] concluded by saying that addition of silica fume did not improve the elastic modulus of concrete made from demolition waste.

Table 2.24 Compressive strength and secant modulus of elasticity [62]

Kind and age of concrete	Compressive strength (MPa)	Measured modulus (GPa)
OPC		
7 days	46	28.8
28 days	58	34.4
SF 6		
7 days	50.5	31
28 days	65	35.5
SF 10		
7 days	52	31.1
28 days	67.5	37
SF 15		
7 days	53	31.5
28 days	70	38.1

Table 2.25 Modulus of elasticity of concrete after 28 days of curing [6]

Aggregate	Modulus of elasticity (GPa)		
	0% SF	10% SF	15% SF
Calcareous limestone	21.6	26	29.3
Dolomitic limestone	24.5	25.9	32.8
Quartzitic limestone	28.8	36.2	38
Steel slag aggregates	29.6	32.9	40.4

Güneyisi et al. [35] studied the modulus of elasticity of *rubberized concretes* with and without silica fume. Two types of *tire rubber*, *crumb rubber* and *tire chips*, were used as fine and coarse aggregate, respectively. Two control mixtures were designed at w/cm ratios of 0.60 and 0.40, and silica fume content varied between 5 and 20%. The results showed that the moduli of elasticity of the plain concretes were about 33 and 46 GPa at 0.60 and 0.40 w/cm ratios, respectively. However, the silica fume concretes had slightly greater elastic modulus values which were about 36 and 47 GPa for high and low w/cm ratios, respectively, irrespective of the amount of silica fume used.

2.9.5 Toughness

Köksal et al. [53] studied the effect of silica fume (0, 5, 10, and 15%) on the *steel fibre reinforced concrete*. Steel fibres with hooked ends were used. Aspect ratios (l/d) of fibres were 65 and 80 and volume fractions (V_f) of steel fibres were 0.5 and 1%. Figure 2.13 shows the relations between toughness of concrete, evaluated up to a 10 mm deflection, and silica fume content for each aspect ratio. It was concluded that steel fibres in matrixes with a high strength can exhibit a broken fracture down behavior without being pulled-out from matrix due to since strong bond between fibres and matrix. However, for low silica fume content or low matrix strength, the common failure type at the fracture plane appeared as the pulling-out of fibres from matrix, demonstrating the adverse effect of relatively resulting in a weaker bond.

2.9.6 Absorption

Demirboğa and Gül [25] studied high strength concretes using *blast furnace slag aggregates* (BFSA). Silica fume and a superplasticizer were used to improve BFSA concretes. They concluded that water absorption values were somewhat less than those of control specimens. Silica fume and BFSA were considered responsible for this behavior.

Gonen and Yazicioglu [31] studied the *capillary absorption* performance of concrete by adding *mineral admixtures*, silica fume and fly ash in the concrete

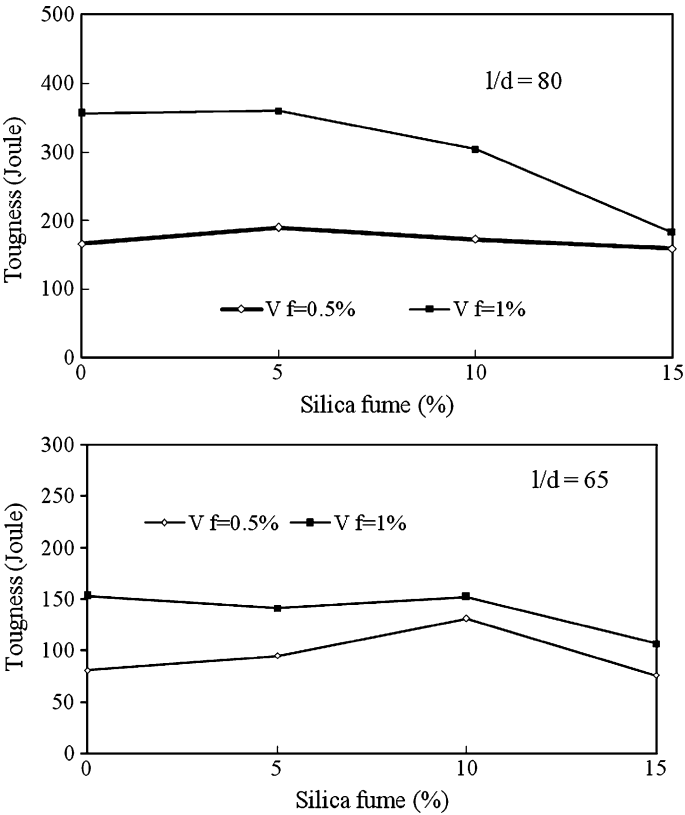


Fig. 2.13 Toughness versus silica fume content for different aspect ratios [53]

mixes, the replacement of fly ash and silica fume were kept at the level of 15 and 10% as the weight of cement, respectively. Test results are given in Table 2.26. It can be seen that the capillary absorption of concrete sample with FA was increased by as much as 47%; however, this increasing trend was reversed in specimens with fly ash and silica fume (double adding). Since silica fume is very fine, pores in the bulk paste or in the interfaces between aggregate and cement paste is filled by these mineral admixtures, hence, the Capillary pores are reduced.

Table 2.26 Mix proportions [31]

Mixes		Composite of binder pastes (%)			Capillary absorption coefficient (cm/s ^{1/2})
		Cement	Fly ash	Silica fume	
I	NC	100	–	–	0.66
II	SFC	90	–	10	0.41
III	FAC	85	15	–	0.97
IV	SFAC	70	20	10	0.46
V	SSFC	90	–	10	0.41

González-Fontebao and Martínez-Abella [32] indicated that recycled concretes showed higher water absorption ratios than conventional concretes. Babu and Babu [9] studied the use of expanded polystyrene (EPS) beads as *lightweight aggregate* both in concrete and mortars containing silica fume as a supplementary cementitious material. Three percentages of silica fume—3, 5 and 9% (by weight of the total cementitious materials) were used. The total *absorption* values of EPS concretes, ranging from 3 to 6%, decreased as the silica fume percentage increased. This could be attributed to the effect of silica fume and the advantage of the nonabsorbent nature of the EPS aggregate.

Gutiérrez et al. [36] found that the steel fibre reinforced material with the inclusion of silica fume showed the lowest percentage of water absorption. The incorporation of silica fume improved the *water absorption* of the material because of the reduction of permeable voids.

Krishnamoorthy et al. [54] did investigations on the cementitious *grouts* containing *supplementary cementitious materials* (SCM), in which he found that water absorption of the specimens having SCM's (like SF, FA, GGBS) was lower than that of control specimens having neat cement.

2.9.7 Porosity

Gleize et al. [30] investigated the effect of silica fume on the porosity of mortar. 10% of Portland cement was replaced with silica fume in a 1:1:16(cement/lime/sand mix proportion by volume) masonry mortar. The *porosity* results are given in Table 2.27. They found that the silica fume lowered the porosity only at 28 days and the pore structure of mortar with silica fume was found to be finer than that of non-silica fume mortar. But this refinement in pore size was more pronounced at 28 days than 2 days due to silica fume pozzolanic reaction.

Igarashi et al. [42] evaluated the capillary porosity and *pore size distribution* in *high-strength concrete* containing 10% silica fume at early ages. They concluded that silica-fume-containing concretes were found to have fewer coarse pores than the ordinary concretes, even at early ages of 12 and 24 h. The threshold diameter at which porosity starts to steeply increase with decreasing pore diameter was smaller in silica-fume-containing concretes than in ordinary concretes at 12 h.

Table 2.27 Total porosity of mortars [30]

Silica fume content (%)	Age (days)	Total porosity (%)
0	7	30.57
10	7	32.31
0	28	28.53
10	28	27.92

This smaller threshold diameter in silica-fume-containing concretes indicated higher packing density of binder grains in these concretes.

Khan [49] observed that the inclusion of silica fume (0–15% as partial replacement of cement) resulted in more significant reductions in porosity in mixtures. However, the reduction in the porosity was greater when silica fume was incorporated at up to 10% replacement level, beyond which the reduction was marginal or reversed.

Gonen and Yazicioglu [31] studied the performance of concrete by adding mineral admixtures, silica fume and fly ash. In the concrete mixes, the replacement of fly ash and silica fume were kept at the level of 15 and 10% as the weight of cement, respectively. The porosity results are given in Table 2.28. Porosity of mixtures varied between 6 and 16%. The porosity values indicated the effect of mineral admixtures on the porosity of concrete. When FA as a single mineral admixture was used in mix, porosity value was higher compared to NC. However, the porosity of concrete improved when two types of mineral admixtures (fly ash and silica fume) were added at the same time (double approach). Their results showed that the porosity of concrete with double mineral admixtures is smaller than the other series.

Poon et al. [69] examined the *porosity* of concrete mixtures using MIP. Two series of concrete mixes were prepared at the w/b ratios of 0.3 and 0.5. Each mixture included two silica fume contents (10 and 15%). Porosity results are given in Table 2.29. The results showed the decrease in porosity in with age due to addition of silica fume .

Cwirzen and Penttala [22] did investigations on eight non-air-entrained concretes having water-to-binder (w/b) ratios of 0.3, 0.35 and 0.42 and different additions of condensed silica fume. Their results from the MIP investigation showed that the concrete having a w/b ratio of 0.3 showed decrease in capillary porosity with silica fume. However for w/b ratios of 0.35 and 0.42, capillary and total porosities appeared to be quite similar.

Rossignolo [74] wrote a paper which deals with the effect of silica fume and styrene-butadiene latex (SBR) on the microstructure of the interfacial transition zone (ITZ) between Portland cement pastes and aggregates (basalt). It was observed that the usage of 10% of silica fume, in relation to the cement paste, caused a reduction of 36% in the thickness of the matrix-aggregate ITZ, in relation to the reference concrete.

Table 2.28 Mix Proportions [31]

Mixes	Composite of binder pastes (%)			Porosity (%)
	Cement	Fly ash	Silica fume	
NC	100	–	–	10.47
SFC	90	–	10	6.82
FAC	85	15	–	15.82
SFAC	70	20	10	6.41
SSFC	90	–	10	8.37

Table 2.29 MIP measured total porosity of series 1 concrete (w/b = 0.3) [69]

Mix	MIP measured total porosity (% v/v)			
	3 days	7 days	28 days	90 days
Control	8.69 ± 0.11	8.44 ± 0.13	7.92 ± 0.12	6.97 ± 0.28
5% SF	7.53 ± 0.16	7.24 ± 0.14	6.31 ± 0.11	5.85 ± 0.02
10% SF	7.64 ± 0.15	6.14 ± 0.13	5.66 ± 0.12	5.11 ± 0.41

2.9.8 Thermal Properties

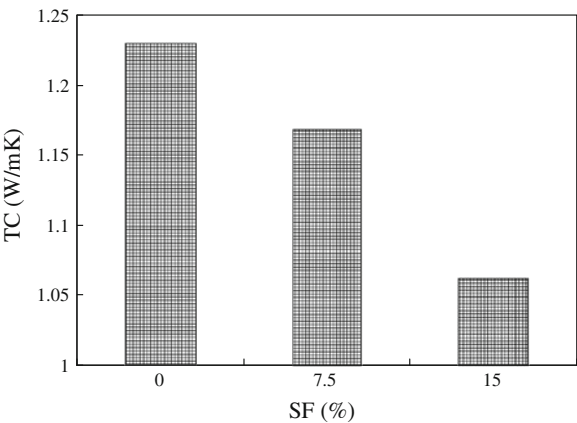
Demirboğa [24] studied the effect of silica fume on *thermal conductivity* (TC) of concrete. *Density* decreased with the replacement of silica fume. The variation of TC of concrete is shown in Fig. 2.14. It can be seen that the highest value of TC of concrete was obtained for specimens produced with 100% PC. Further, the graph declines largely with increasing silica fume replacement for PC. For 7.5 and 15% silica fume replacement, keeping other conditions constant, the reductions were 5 and 14%, respectively, compared to the corresponding control specimens.

Demirboğa [23] reported that silica fume decreased thermal conductivity of mortar up to 40 and 33% at 30% replacement of PC, respectively. Chen and Chung [19] and Postacioğlu and Maddeler [70] had reasoned that the reduction in thermal conductivity was primarily due to the low density of LWAC (*Lightweight Aggregate concrete*) with silica fume and fly ash content, and may be partly due to the amorphous silica content of silica fume and fly ash

2.9.9 Creep

According to Mindess and Young [64], there are number of factors that determine the amount of creep a concrete will undergo. First, *creep* is approximately

Fig. 2.14 Relationship between thermal conductivity and silica fume [24]



proportional to the level of applied stress as a percent of ultimate strength of the concrete within the normal range of long-term loading (up to 50% of ultimate strength). In fact, this relationship is only a gross estimate because the concrete continues to hydrate and gain strength and stiffness over time. The compressive strength of the concrete is inversely related to the specific creep.

Khatri et al. [47] studied the behaviour of concretes containing silica fume having a constant water/solids ratio of 0.35 and a total cementitious materials content of 430 kg/m³. They observed that silica fume reduced the strain due to creep compared with Portland cement concrete. Adding silica fume to concrete containing 65% slag did not affect the creep. Ternary mixes containing 15 or 25% fly ash and 10% silica fume experienced greater creep than control concrete.

Mazloom et al. [62] studied the *creep* of high performance concrete having silica fume. The control mix was made with OPC, while the other mixes were prepared by replacing part of the cement with silica fume at four different (0, 6, 10 and 15%) replacement levels by mass. The w/c ratio was 0.35. It was found that silica fume had a significant influence on the long-term creep. As the proportion of silica fume increased to 15%, the creep of concrete decreased by 20–30% (Table 2.30).

Tao and Weizu [89] carried out an experimental study on the early-age *tensile creep behavior* of *high-strength* concrete (HSC) comprising of silica fume concrete under uniaxial restraining stresses. The experiments were performed with three 0.35 w/b mixtures, including plain concrete OPC, double-blended concrete silica fume (6% replacement of OPC by silica fume). The compressive creep strain for silica fume and OPC concretes during the temperature rising period is shown in Fig. 2.15. It was found that about 70% of free expansion deformation was compensated by compressive creep within the first day. After this period, the compressive creep was replaced by tensile creep due to high tensile stress development in specimens.

2.9.10 Shrinkage

Taylor [92] identified four effects contributing to *drying shrinkage*; *capillary stress*, surface free energy, disjoining pressure, and movement of interlayer water. Capillary stress describes the phenomenon of transfer of the tension from the

Table 2.30 Values of creep of 80 × 270 mm high specimens on completion of the tests (microstrain) [62]

Age of loading (days)	Concrete mixes			
	OPC	SF 6	SF 10	SF 15
7	595	510	459	417
28	413	407	381	328

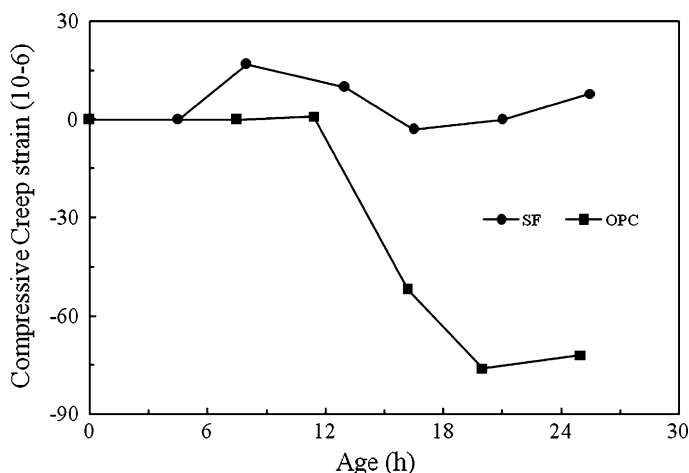


Fig. 2.15 Compressive creep strain under semi-adiabatic condition [89]

meniscus of capillary pore water to the walls of the pore as water evaporates. The pore shrinks and may even collapse, in which case it will not expand on rehydration. The surface tension of solid particles is reduced by the adsorption of molecules. When they are removed, the particles tend to contract. Disjoining pressure is analogous to the phenomenon that occurs in the swelling of clays as water is drawn between adjacent particles forcing them apart. As the water is removed, the particles come back together

Tazawa et al. [90] investigated the effects of silica fume addition on the drying shrinkage of mortar. They observed that magnitude of drying shrinkage is determined by the balancing of two factors; the shrinkage stress due to capillary tension in the pores, and rigidity of the structure as determined by compressive strength.

Mazloom et al. [62] conducted tests for total, autogenous and drying shrinkage of high performance concrete having silica fume. The percentages of silica fume were: 0, 6, 10 and 15% with w/c ratio being 0.35. The results showed that (i) silica fume did not have much effect on drying specimens (total shrinkage); (ii) silica fume considerably affected the shrinkage of sealed specimens. It is clear that the general effect of increasing the silica fume inclusion is to increase autogenous shrinkage; and (iii) there was significant increase in autogenous shrinkage at high levels of silica fume. In fact, inclusion of 10 and 15% silica fume increased the autogenous shrinkage of concrete by 33 and 50%, respectively. The effect of silica fume on autogenous shrinkage was explained by its influence on the pore structure and pore size distribution of concrete as well as its pozzolanic reaction.

According to Sellevold [78] the inclusion of silica fume at high replacement levels significantly increased the *autogenous shrinkage* of concrete due to the refinement of pore size distribution that leads to a further increase in capillary tension and more contraction of the cement paste.

Table 2.31 Maximum plastic shrinkage strain in plain and blended cement concretes, exposed to a wind velocity of 15 km/h, temperature of 45°C and RH of 35% [2]

Silica fume type	Replacement (%)	Maximum plastic shrinkage strain (μm)
1	5	1,322
	7.5	1,645
	10	2,348
2	5	1,724
	7.5	2,794
	10	2,924
3	5	1,038
	7.5	1,370
	10	1,656
4	5	1,122
	7.5	1,183
	10	1,224
5	5	783
	7.5	939
	10	1,119
Plain cement	0	716

Al-Amoudi et al. [1] found that the maximum *plastic shrinkage strain* was observed in silica fume (undensified) cement concrete. This was attributed to the undensified nature of this silica fume. On the other hand, the lowest plastic shrinkage strain was noted in the plain cement concrete.

Al-Amoudi et al. [2] varied the dosage of silica fume to investigate its effect on the plastic shrinkage of concrete exposed to *hot-weather conditions*. A summary of the maximum plastic shrinkage strains attained during the 24-h exposure is presented in Table 2.31. The plastic shrinkage strain increased with increasing dosage of silica fume in the parent cement. This trend was noted in all the concrete specimens prepared with the selected silica fume cements.

Zhang et al. [99] did an experimental study on the *autogenous shrinkage* of Portland cement concrete (OPC) and concrete incorporating silica fume. The water-to-cementitious materials (w/c) ratios of the concrete were in the range of 0.26–0.35, and silica fume content was between 0 and 10% by weight of cement. Autogenous shrinkage up to 98 days is presented in Table 2.32. It appeared that both the w/c ratio and the incorporation of silica fume had significant effect on the autogenous shrinkage strain of the concrete. The autogenous shrinkage increased with decreasing w/c ratio and with increasing silica fume content. This is in agreement with those reported by Tazawa and Miyazawa [91], Brooks et al. [16], Mak et al. [60], and Persson [68]. The results indicated that the concrete with low w/c ratio and with silica fume induce autogenous shrinkage rapidly even at early ages. Particularly at w/c ratio of 0.26, the autogenous shrinkage strains of the silica fume concrete at the age of 2 days were more than 100 micro strain.

2.10 Effect of Silica Fume on the Durability Properties of Concrete

2.10.1 Permeability

Perraton et al. [67] studied the effect of silica fume on the *chloride permeability* of concretes. Concretes were made with water–cementitious ratios of 0.4 and 0.5. Silica fume dosage varied from 5 to 20% by weight of cement. Concretes were moist cured for 7 days before drying in air at normal and low temperatures for 6 month. They observed significant reduction in the chloride-ion diffusion in silica fume concretes which further decreased with increasing addition of silica fume as shown in Fig. 2.16. Main reason that could be attributed to reduced permeability is that addition of *silica fume* cause considerable pore refinement i.e. transformation of bigger pores into smaller one due to their pozzolanic reaction concurrent with cement hydration. By this process the permeability of hydrated cement paste as well as porosity of the transition zone between cement paste and aggregate are reduced.

Gjrov [29] illustrated that silica fume can greatly reduce the *water permeability* in a lean concrete, but it can have a small influence on the permeability of rich mixture. It was found that water permeability co-efficient of a concrete containing 100 kg/m^3 of cement can decrease from 1.6×10^{-7} to 4×10^{-10} m/s when 10 kg/m^3 of silica fume is used. The latter permeability value was comparable to that obtained from non-silica fume concrete containing 250 kg/m^3 of cement.

Hooton [38] studied the permeability of silica fume concretes and stated that permeability decreased with addition of silica fume. Water-permeability of control mix was 1.8×10^{-14} m/s; whereas it was less than 1×10^{-17} m/s for concrete mix made with 10% silica fume. Permeability of silica fume concretes with higher dosage of silica fume could not be measured.

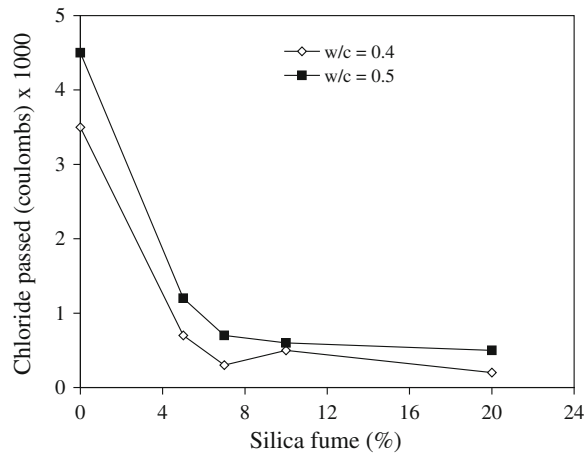
Ozyildirim and Halstead [66] found that ternary mixes containing fly ash and silica fume performed better in chloride resistance than comparable concretes containing only Portland cement.

Kayali and Zhu [46] concluded that reinforced concrete slabs whose concrete included silica fume as 10% by mass of cement and whose strength was around 70 MPa, showed extremely low value of corrosion current density and half-cell

Table 2.32 Autogenous shrinkage of concrete [99]

w/c	Autogenous shrinkage (micro strain)/% of 98-day shrinkage											
	SF 0%				SF 5%				SF 10%			
	2 days	7 days	14 days	98 days	2 days	7 days	14 days	98 days	2 days	7 days	14 days	98 days
0.26	49/25	100/51	129/65	197	101/38	170/64	194/73	266	101/36	174/62	221/78	282
0.30	36/20	87/48	115/64	180	77/35	149/68	174/80	218	74/27	161/59	213/64	251
0.35	25/63	34/85	40/100	40	49/22	101/47	128/60	215	41/16	115/46	160/64	251

Fig. 2.16 Changes in chloride ion permeability of concrete with amount of silica fume replacement [67]



potentials. These values remained very low even after long exposure to chloride ion solution.

Song et al. [85] presented a procedure for predicting the *diffusivity* of high strength silica fume concrete, developed by considering water-to-binder ratio, silica fume replacement ratio, and degree of hydration as major influencing factors. Relative diffusivity of bulk paste and ITZ decreases as silica fume replacement ratio increases; however, if silica fume replacement is about 10%, it would be marginal (Figs. 2.17 and 2.18).

Gutiérrez et al. [36] determined the effect of incorporation of various *supplementary cementitious materials* on various properties of Portland cement fibre-reinforced

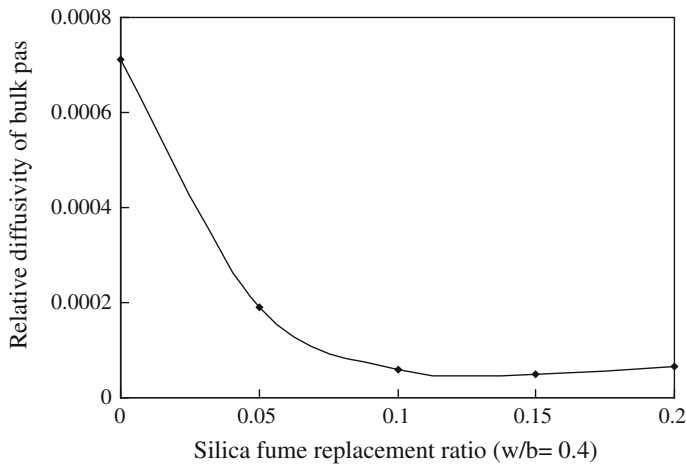


Fig. 2.17 Relative diffusivity of ITZ versus silica fume replacement ratio [85]

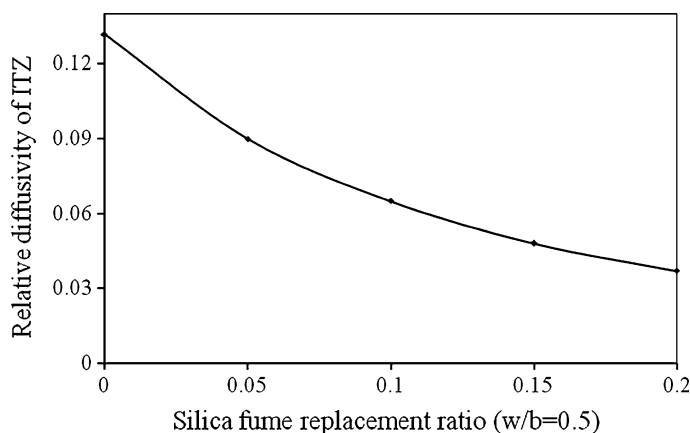


Fig. 2.18 Relative diffusivity of ITZ vs. silica fume replacement ratio [85]

mortars. It was found that the pozzolanic materials and the slag were effective in reducing the permeation of chloride ion. The greatest effect on the plain matrix was produced by the silica fume addition followed by the additions of MK, GGBS, and FA. It was also noted that the fibre inclusion negatively affects the penetration of chlorides because of the increase in capillary porosity. This was observed for both synthetic and natural fibre reinforced specimens.

Soroushian et al. [87] reported a 75% reduction in the permeability to chloride ions when polypropylene fibres were used along with silica fume in a Portland cement matrix. The decrease in the coefficient of chloride diffusion was 98% when silica fume was added to the glass fibre reinforced mortar. The positive effects of silica fume additions were attributed to the increase in density and reduction in capillary porosity caused by reaction products such as calcium silicates and calcium aluminates, which change the material microstructure.

Babu and Babu [9] studied chloride resistance of concrete and mortar made with expanded polystyrene (EPS) beads as lightweight aggregate. It also contained silica fume as a supplementary cementitious material. Three percentages of silica fume were 3, 5 and 9% (by weight of the total cementitious materials). They concluded that as per the assessment criteria, all the EPS concretes containing silica fume showed a low chloride permeability of <1,000 C. These concretes also exhibited much lower corrosion rates compared to the normal concrete.

2.10.2 Freezing and Thawing

Sørensen [86] studied the effect of silica fume on *salt-scaling* of concrete. He found that drying-rewetting history of concrete prior to *freezing and thawing* has a significant effect on conventional concrete, whereas silica fume concrete is

relatively unaffected. *Air entrainment* has a beneficial effect on both types of concrete, but frost-resistant silica fume concretes can be made with out entrained air.

Feldman [27] investigated the effect of silica fume and sand/cement ratio on pore structure and frost resistance of Portland cement mortars. Silica fume-Portland cement blend mortars fabricated with 0, 10 and 30% silica fume at a water/binder ratio of 0.60 and a sand/cement ratio of 2.25 were monitored by mercury porosimetry while being cured for 1–180 days. The threshold value for pore intrusion increased with pore size and becomes less abrupt with silica fume addition; it was in the 0.5 to 20×10^3 nm regions. Mortars were also made with and without 10% silica fume at a water/cement ratio of 0.60 and sand/cement ratios of 0, 1.0, 1.5, 1.8, 2.0, 2.25 and 3.0. Mercury intrusion measurements were carried out after 14 days of curing. In the presence of silica fume pore volume in the 0.5 to 20×10^3 nm pore diameter range increased with sand/cement ratio. Mortar prisms were subjected to freezing and thawing cycles (two cycles in 24 h) according to ASTM standard test method C 666, Procedure B. Results indicated that if the sand/cement ratio was 2.25 or over, expansion was less than 0.02% after 500 cycles. At lower sand/cement ratios 10% silica fume gives little protection.

Hooton [38] investigated the *frost resistance* of concretes containing 0, 10, 15, and 20% silica fume by mass of cement. Water–cementitious materials ratio of concretes was between 0.360 and 0.369. Concretes contained 1% air. Test results showed that Portland cement concrete failed ASTM C 666 (Procedure A), after 58 cycles, while all silica fume concretes had durability factor in excess of 90% after 300 cycles. Concretes with 10, 15 and 20% silica fume had durability factor of 97.5, 93.4, and 92.8, respectively. He attributed this excellent performance to a low degree of saturation due to self-desiccation during hydration.

Johnston [44] observed that concretes containing 10 and 15% silica fume and having the maximum permissible water–cementitious materials ratio of 0.45 had barely acceptable resistance to salt-scaling. Resistance to salt scaling correlated well with the water/cement ratio (not water–cementitious material ratio)

Cwirzen and Penttala [22] studied the influence of the cement paste–aggregate *interfacial transition zone* (ITZ) on the frost durability of high-performance silica fume concrete (HPSFC). Investigation was carried out on eight non-air-entrained concretes having water-to-binder (w/b) ratios of 0.3, 0.35 and 0.42 and different additions of condensed silica fume. Results of the freeze–thaw tests are presented in Fig. 2.19. It was found that none of the concretes having w/b ratio of 0.35 and 0.42 had surface scaling results under $1,500 \text{ g/m}^2$ and the dynamic modulus of elasticity was less than 60% after 56 cycles. Scaling decreased with increasing silica fume amount and decreasing w/b. The weakest concrete with respect to surface scaling appeared to be concrete having w/b ratio of 0.42 without any silica fume addition. Internal damage was in line with the surface scaling except for the mix 0.42-3SF (w/b ratio 0.42 and 3% silica fume of cement weight). They said that neither internal damage nor surface scaling was observed for mixes having a w/b ratio of 0.3. The results also showed that the transition zone initiates and accelerates damaging mechanisms by enhancing movement of the pore solution within

the concrete during freezing and thawing cycles. They concluded that moderate additions of silica fume seemed to densify the microstructure of the ITZ.

Yazıcı [98] conducted tests on *compressive strength* and *splitting tensile strength* of self-compacting concrete after freezing and thawing cycles. Test results shown in Fig. 2.20 indicated that, the residual compressive strength ratio of control mixture after 90 freeze–thaw cycles was 93%. It was also found that the compressive strength of control mixture had been exceeded by both H (without silica fume) and HS (with silica fume) series at all FA replacement level after freezing and thawing. For H series, the residual strength of H30 was 108%, which meant that freeze–thaw cycling caused increase in compressive strength. For HS series, at 30 and 40% fly ash content, gain in compressive strength was clear.

2.10.3 Corrosion

Berke [13] used electrochemical tests on concrete samples monitored for 2 years, and found that using silica fume (up to 15% addition to cement) improved the long-term *corrosion resistance*. Rasheeduzzafar and Al-Gahtani [73] reported that blending of plain cements with 10 or 20% silica fume significantly improved the corrosion resistance. They found hardly any tangible advantage in corrosion-initiation time by increasing the silica-fume content from 10 to 20%.

Khayat and Aitcin [50] observed that iron oxide layer on conventional steel reinforcing bars becomes unstable when the pH of surrounding concrete dropped to approximately 10–11 or when this layer comes in contact with chloride ions. When silica fume was used as cement replacement, the pH of concrete decreased

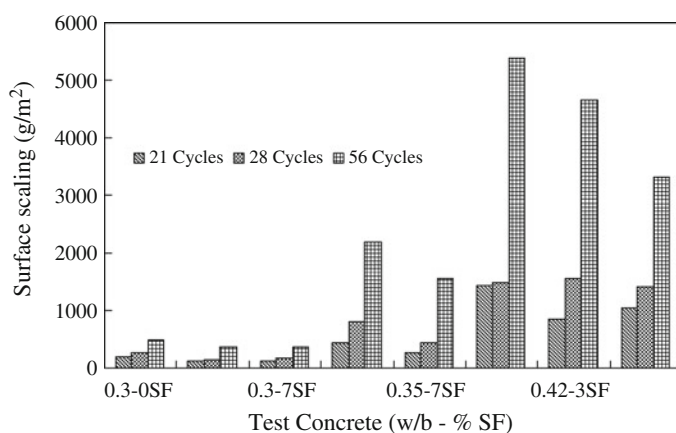


Fig. 2.19 Surface scaling of the test concretes in the CDF-test after 21, 28 and 56 freeze–thaw cycles [22]

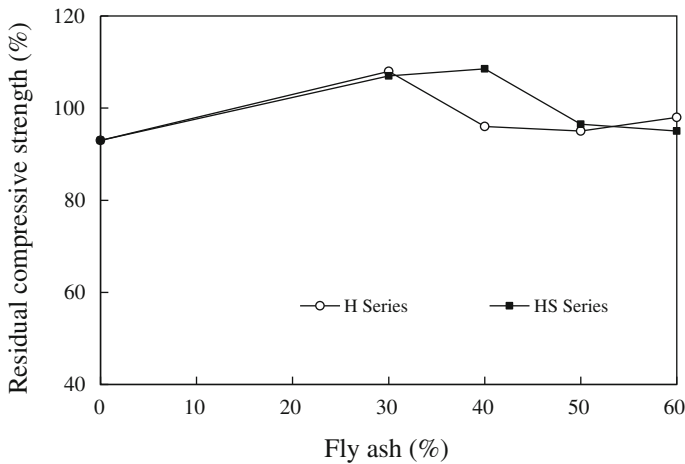


Fig. 2.20 Residual compressive strength after 90 freeze–thaw cycles [98]

because cement content is less. Also decrease in $\text{Ca}(\text{OH})_2$ content due to pozzolanic reaction of silica fume and reduction in alkali-pore water concentration further reduces the pH. But these factors have small effects in destabilizing the passive iron oxide layer since pH of concrete does not fall below 12 even when 30% silica fume was used. Diffusion coefficient of chloride and chlorides content in concrete are reduced significantly in presence of silica fume. Also the use of silica fume substantially increased the electrical resistivity of concrete hence slowing the rate of corrosion.

Khedr and Idriss [51] studied the effectiveness of silica fume concrete in resisting damage caused by corrosion of embedded steel using an accelerated impressed voltage-testing setup. Silica fume concrete included 0, 10, 15, 20, and 25% silica as equal replacement of ordinary Portland cement. Concrete samples were treated in either fresh water or 4% NaCl saline water for 7 and 28 days. STC (Susceptibility to corrosion) was used as an index of resistance of concrete to corrosion-related damage. Blending of plain concrete with 10–20% silica fume significantly improved the corrosion resistance. At 7 days of curing, STC index of control concrete (0% silica fume) was $16.61 \times 10^{-4}/\text{W h}^2$ with fresh water and $29.32 \times 10^{-4}/\text{W h}^2$ with saline water. STC index was almost constant (same as with 0% silica fume) up to 15% silica fume content, but, at higher dosages of silica fume (20–25%) significantly reduced the STC index ($2.5\text{--}9.8 \times 10^{-4}/\text{W h}^2$). At 28 days curing, control concrete (0% silica fume) achieved STC index of $6 \times 10^{-4}/\text{W h}^2$ with fresh water and $8.1 \times 10^{-4}/\text{W h}^2$ with saline water. An optimal effect at silica fume replacement dosage of 15% was observed. STC was always lower for longer curing periods. For control mix the STC values of 28-day samples were 28–36% of those of 7-day samples. This percentage was significantly lower (0.8–17%) for Silica Fume concrete.

Dotto et al. [26] studied the influence of silica fume on the *corrosion behaviour* of reinforcement bars. Concretes with different water–binder ratio (cement + silica fume) 0.50, 0.65 and 0.80 were used. Silica fume additions were 0, 6 and 12% by weight of cement. Tests were conducted for electrical resistivity, and polarization curves. The results showed that the addition of 6% silica fume increases the electrical resistivity of concrete by 2.5 times and 12% silica fume increases it by 5 times. This suggests that the addition of silica fume can be effectively used in protecting steel reinforcement against corrosion.

Kayali and Zhu [46] did tests on high-strength reinforced silica fume–cement concrete slabs with a compressive strength of 70 MPa for chloride diffusion and corrosion activity after partial immersion in a 2% chloride solution. It was found that high-strength concrete containing 10% silica fume possessed exceedingly high corrosion resistance.

Civjan et al. [18] carried a long-term corrosion study was conducted to determine the effectiveness of calcium nitrite, silica fume, fly ash, ground granulated blast furnace slag, and disodium tetrapropenyl succinate (DSS) in reducing corrosion of reinforcing steel in concrete. Mixture proportions included single, double, and triple combinations of these admixtures. They concluded that for optimal protection against corrosion in structural concrete, a triple combination of CN, SF, and FA (or a double combination of CN and BFS), all at moderate dosages, was recommended.

2.10.4 Sulfate Resistance

According to ACI Committee 234 [4], the effect of silica fume on *sulfate resistance* is due more to the reduction in permeability than to dilution of the C_3A content because of the relatively low doses of silica fume used in practice.

Selleveold and Nilsen [79] reported field studies of concretes with and with out 15% silica fume. After 20 years' exposure to ground water containing 4 g/L sulfate and 2.5–7.0 pH, the performance of the silica fume concrete was found equal to that of the concretes made with sulfate-resisting Portland cement, even though the water/cementitious materials ratio was higher for silica fume concrete (0.62) than for control (0.50).

Cohen and Bentur [21] studied the effect of 15% silica fume replacement of Types I and V Portland cement on the resistance to sulfate attack in magnesium and sodium sulfate solutions. The water–cementitious materials ratio was 0.3. In the sodium sulfate solutions, the silica fume concrete specimens were resistant to sulfate attack. In the magnesium sulfate solutions, all the specimens expanded, with the Type I cement specimens (with or without silica fume) expanding more than Type V cement specimens (with or without silica fume). Since specimens were thin (6 mm), the authors attributed the effect of silica fume on sulfate resistance more to chemical effects than to reduced permeability.

Hooton [38] used a 10.7% C_3A cement for *mortar bars* tested according to ASTM C 1012 [7]. Cement was replaced with 0, 10, and 20% of silica fume by mass. 10% silica fume bars were made both with and without superplasticizer to maintain constant water content at constant slump. The 20% silica fume bars were made only with superplasticizer. A control mortar bars were made using Type V cement. After 1-year, results indicated that all of the silica fume mortar had less expansion than Type V mortar, and all of the mixes except the Type I cement easily passed the proposed ASTM failure criterion of 0.10% expansion. The Type V cement mortar exceeded the 0.10% expansion limit after 1.7 years, while none of the silica fume mortars had exceeded the expansion limit after 5 years.

Mangat and Khatib [61] investigated the influence of silica fume (0, 5, 9, and 15%) on the sulfate resistance of concrete containing under different *curing conditions* (initial air curing at 45°C and 55% RH; initial wt/air curing at 45°C and 25% RH; initial air curing at 20°C and 25% RH) up to the age of 512 days. They concluded that (i) replacement level between 5 and 15% of cement with silica fume increased considerably the sulfate resistance of concrete; (ii) under initial air-curing at 45°C, 25% RH, an expansion of 0.275% was obtained for the control mix (0% silica fume), compared with only 0.04% for the 9% silica fume after 502 days of exposure to sulfate solution; (ii) under initial wet/air-curing at 45°C, 25% RH, the control mix disintegrated before 207 days in sulfate solution where as silica fume concrete did not disintegrated until after 502 days; and (iii) air-curing at 20°C, 55% RH did not show large expansions and was effective in improving the sulfate resistance of normal concrete as with replacement of cement by Silica Fume in optimum quantity. Reasons that could be attributed to the increase in sulfate resistance was probably to refined pore structure of silica fume incorporated mixes or to the reduction in calcium hydroxide cement in the presence of silica fume which reduces the extent of gypsum formation and hence, increase sulfate resistance.

Irassar et al. [43] investigated the sulfate resistance of concrete made with *silica fume*. Concrete specimens were half-buried in sulfate soil for 5 years. Mineral admixtures were used as a partial replacement for ordinary Portland cement ($C_3A = 8.5\%$), and the progress of sulfate attack was evaluated by several methods (visual rating, loss in mass, dynamic modulus, strength, X-ray analysis). Results showed that silica fume improved the sulfate resistance when the concrete was buried in the soil. However, concretes with high content of silica fume exhibited a greater surface scaling over soil level due to the sulfate salt crystallization.

Hekal et al. [37] reported that partial replacement of Portland cement by silica fume (10–15%) did not show a significant improvement in sulfate resistance of hardened cement pastes.

Ganjian and Pouya [28] studied the effect of silica fume on deterioration resistance to sulfate attack in *seawater* within tidal zone and simulated wetting–drying conditions. The performance of pastes and concrete specimens with silica fume exposed to simulation ponds and site tidal zone were inferior to those without silica fume replacement.

Lee et al. [57] studied the effectiveness of silica fume in controlling the damage arising from sulfate attack. The water/cementitious materials ratios (w/cm) of the mortar mixtures were 0.35, 0.45 and 0.55. Under this sulfate environment, the incorporation of 10% silica fume in OPC matrix showed no evidence of spalling and cracking up to about 1 year of exposure, and strength loss (Fig. 2.21) increased as the w/cm ratio increased; and the total strength loss as well as that between different w/cm ratio levels was greater in mortar specimens without silica fume compared to those with silica fume.

Wee et al. [95] also showed that silica fume, at replacement levels of 5 and 10% by mass of OPC plays a key role in resisting sodium sulfate attack, indicating no signs of *spalling* after about 1 year of exposure in 5% sodium sulfate solution.

Shannag and Shaia [81] prepared high-performance concrete mixes containing various proportions of natural pozzolan and silica fume (up to 15% by weight of cement). They were stored in sodium and magnesium sulfate solutions, in Dead Sea and Red Sea waters. After 1 year immersion in sulfate solution and sea water, the concrete mix containing a combination of 15% silica fume, and 15% natural pozzolan (by weight of cement) showed a maximum protection against sulfate attack compared to those investigated in the study. This mix retained more than 65% of its strength after 1 year of storage in sulfates solutions and sea waters. The superior resistance of that mix against sulfate attack was attributed to the pore refinement process and further densification of the transition zone occurring due to the conversion of lime forming from the hydration of cement into additional binding material through lime-pozzolan reaction. The results also showed that magnesium sulfates had a more damaging effect than sodium sulfates; which was consistent with the data available in the literature [65]

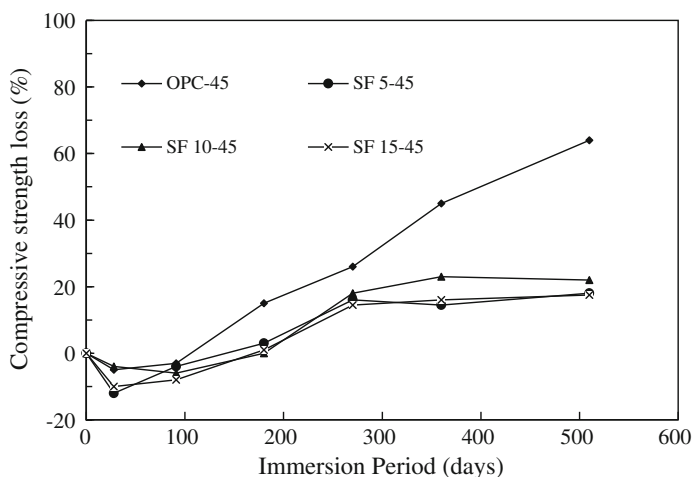


Fig. 2.21 Compressive strength loss of mortars subjected to sulfate attack in 5% sodium sulfate solution (w/cm/40.45) [57]

2.10.5 Carbonation

Skjolsvold [83] investigated *carbonation* depths of field concrete with or without silica fume. The results were normalized to correct the differences in compressive strength and length exposure to the atmosphere. The mean carbonation depth was greater for silica fume concretes under these conditions, but the variation was quite high. Laboratory study showed that for a given compressive strength, silica fume concrete had greater carbonation rates than concretes without silica fume. Schubert [77] believed that the consumption of $\text{Ca}(\text{OH})_2$ in the pozzolanic reaction acts to increase the rate of carbonation, while the blocking of capillary pores acts to decrease it. Grimaldi et al. [33] found that the carbonation depth was greater in mortars containing silica fume than in controls. They attributed this result to the reduction of pH caused by the pozzolanic reaction.

Khan and Lynsdale [48] did investigations which aimed at developing high-performance concrete. Binary and ternary blended cementitious systems based on ordinary Portland cement, pulverised fuel ash and silica fume were investigated. PFA up to 40% was used, and to these blends, 0, 5, 10 and 15% silica fume were incorporated as partial cement replacements. Carbonation measurements were carried out for concrete cubes of 100 mm after 2 years of exposure in a constant temperature room at $20 \pm 3^\circ\text{C}$ and $65 \pm 5\%$ RH in normal atmospheric conditions. The carbonation study was limited to concrete prepared with w/b ratio of 0.27. The samples (100 mm cubes) were broken into two halves at the age of 2 years. The results (Fig. 2.22) clearly demonstrated that there was an increase in carbonation with an increase in PFA content, whilst silica fume inclusion of its own did not exhibit significant influence on the carbonation; this was in good agreement with earlier findings [17, 59].

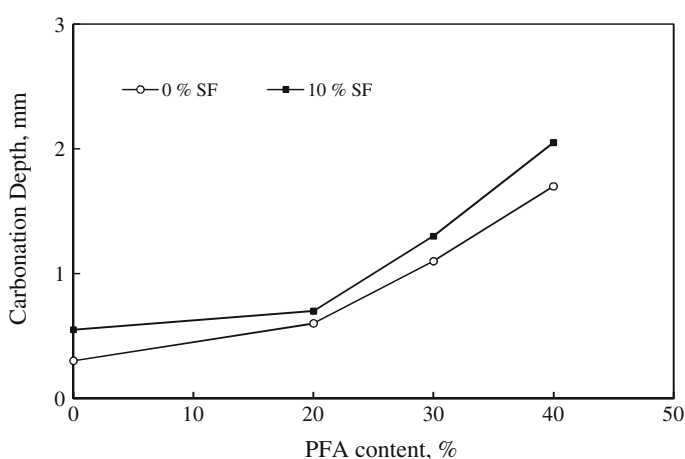


Fig. 2.22 Carbonation depth of concrete at the age of 2 years, w/b ratio of 0.27 [48]

Byfors [17] investigated the *carbonation* of silica fume and pulverized fuel ash blended cement concrete (compared on equal w/b ratio) and found that the incorporation of 10–20% silica fume has no effect on carbonation as compared to OPC control, whilst 15–40% PFA exhibited higher rate of carbonation. So Khan and Lynsdale [48] concluded that still silica fume inclusion slightly increases *carbonation depth* as compared to the OPC control and PFA added mix.

Gonen and Yazicioglu [31] studied the performance of concrete by adding *mineral admixtures*, silica fume and fly ash. In the concrete mixes, the replacement of fly ash and silica fume were kept at the level of 15 and 10% as the weight of cement, respectively. They concluded that the depth of carbonation in concrete mixtures containing FA was slightly higher than that of control concrete. In concrete mixtures containing silica fume and fly ash at the same time, depth of carbonation was lower compared to the results of other concrete mixtures, where silica fume had little effect on carbonation. The lower depth of carbonation in SFAC was attributed to the lower porosity.

2.10.6 Alkali–Silica Reaction

Concrete prepared with sand or aggregates containing amorphous silica or siliceous aggregates (gneiss, schist) can deteriorate by the formation of expansive alkali silicate gels. The alkalis (Na_2O and K_2O) from the cement and other sources, with hydroxyl ions and certain siliceous constituents leading to formation of distinctive gelatinous hydrates which expand as water is imbibed and exert pressure on surrounding matrix. Pressure generated by the swelling gel ruptures the aggregate particles and causes cracks to extend into the surrounding concrete. Typically, alkali–silica reaction results in the formation of map-pattern cracking of the concrete.

The optimum method for minimizing the potential for expansion due to *alkali–silica reaction* in concrete is to replace a portion of the Portland cement with a supplementary cementing material. Low-lime fly ash, ground granulated blast furnace slag, silica fume, metakaolin and natural pozzolans used in the appropriate quantities have been found to be an effective antidote for alkali–silica reaction. Mixtures of two supplementary cementing materials with Portland cement (so-called ternary mixtures) are also very effective in preventing deterioration due to alkali–silica reaction.

Hooton [38] studied the influence of silica fume on the *expansion of mortars* made with *high-alkali cement* up to the age of 365 days. Expansions were reduced with increasing replacement of silica fume. It was concluded that mortars made with 10, 15 and 20% silica fume met the ASTM expansion limit of 0.020% at the age of 14 days.

Boddy et al. [15] investigated the possible use and effectiveness of “lower grade” silica fume with SiO_2 contents less than 85% as such materials do not meet current ASTM standards for silica fume. The performance of two silica fumes with

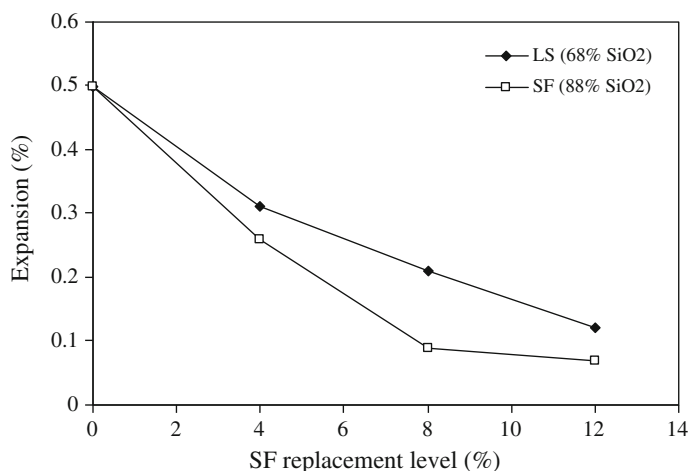


Fig. 2.23 Effect of silica fume level of replacement and SiO₂ content on mortar bar expansion at 14 days [15]

different silica contents; LS (68% SiO₂) and silica fume (88% SiO₂) were compared by examining the effect of the materials on the expansion due to alkali-silica reaction (ASR) and the composition of the pore solution. The concrete mixtures included 0, 4, 8, and 12% silica fume replacement by mass of cement. The accelerated mortar bar test was used for determining alkali-silica reactivity. Test results are shown in Fig. 2.23. Mortar bar mixtures containing LS (68% SiO₂) silica fume at levels of replacement up to 12% failed to control ASR expansion of Spratt aggregate. An NS (88% SiO₂) silica fume was effective at 12% replacement, and just below the 0.10% expansion limit criterion at 8% replacement.

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