Effects of Silica Fume on Ready Mixed Concrete

Ashley S. Carey[1]

Abstract

Silica fume is a pozzolanic byproduct of silicon metal/ferrosilicon alloy production. When silica fume is added to concrete physical and chemical properties of the mixture are altered. A literature review was conducted to find the effects of silica fume addition into concrete mixtures. Chemically silica fume reacts with free lime (COH) to create more calcium silicate hydrate (CSH). Physically silica fume increases compressive strength and resistivity due to its particle packing tendencies which decrease air voids. An experimental study was also completed to observe effects of increased silica fume amounts on fresh and hardened physical properties of concrete. Silica fume increased initial mixing temperature in 0.8 °C increments when silica fume was added as a 10% and 20% mass replacement for cement respectively. 7-day compressive strength and resistivity both decreased as silica fume content increased. This is contradictory to literature, but given the type of concrete mixture used these results are not surprising.

Keywords

silica fume supplementary cementitious material

[1] Graduate Research Assistant, Department of Mechanical Engineering, Mississippi State University. 501 Hardy Rd., Walker Engineering Room 105, Mississippi State, MS, 39762. Phone: (901) 826-3486 E-mail: asc296@msstate.edu

Introduction

Silica fume is a supplementary cementitious material (SCM) that interacts with free lime (COH) to form calcium silicate hydrate (CSH) which increases early and late age compressive strength of concrete and decreases permeability over time. These characteristics can be attributed to silica fume's size and chemical composition. Silica fume is a small spherical particle with an average diameter of 1 micron (Metha and Gjørv, 1982) and an average surface area of 20-25 m^2/g (Sharp, 1946). The small diameter increases particle packing which fills small voids between aggregates and cement grains, and creates nucleation sites which increase CSH production. Silica fume is a pozzolanic material made up of between 85-96% pure amorphous silica (SiO_2) with traces of iron oxide, alkalis, and carbon accounting for the remaining percentage. Since silica fume is pozzolanic it will not react with water alone, but will react during hydration when combined with cement. When silica fume is introduced into a system, SiO_2 reacts with COH to form CSH. This reaction that converts COH to CSH accounts for changes in fresh concrete properties, heat of hydration, corrosion resistance, and mechanical properties at both early and late ages.

Origin of Silica Fume Use in Concrete

In 1944, James Sharp filed his initial patent for a silica modified cement. Sharp (1946) claimed that silica fume mixed with portland cement could lead to concrete that was "impervious to water, strong in tension, elastic, and resistant to cracking over a wide range of climate and curing conditions". Previous to Sharp's claims, silica fume had not been used as a cement replacement. Since then silica fume has been slowly incorporated as a SCM that can be used to help decrease the total amount of ordinary portland cement (OPC) used in a concrete mixture. Currently ACI Committee 234 oversees silica fume's uses in concrete.

As environmental restrictions increased, silica fume began being used in applications such as cement replacement instead of being released freely into the atmosphere (ACI Committee 234, 2013). Silica fume is a byproduct in the production of silicon metals or ferrosilicon alloys for electronic components. Silicon metals and ferrosilicon alloys are products of a redox reaction between quartz (high in silica), iron ore, and carbon in which carbon acts as a reducing agent. When these reactants are placed in an electric arc furnace (EAF) and heated to temperatures of 2000 °C, quartz and carbon react to form silica. Silica then bonds with iron to form silicon metals, or ferrosilicon alloys depending on the reactant. Roughly 10-15% of the quartz/carbon reaction is lost as Si and O_2 vapor which becomes SiO_2. Once a reaction goes to completion and the EAF cools, SiO_2 vapor begins to condense as small amorphous silica particles (Metha and Gjørv, 1982; Sharp, 1946). Originally silica fume was released into the atmosphere, but as environmental restrictions increased, silica fume was collected using filters as it condensed. Depending on the type of alloy produced, SiO_2 content in silica fume can vary significantly as shown in Table 1.

Silica Fume's Effect on Fresh Concrete Properties

Silica fume's fine particles decrease workability of a concrete mixture by increasing particle packing. As silica fume content in a mixture increases, more water is needed to fully hydrate cement and increase workability due to a larger surface area created from silica fume. Workability can be increased while keeping the water to cementitious materials (w/cm) ratio constant by adding a high range water reducing admixture (HRWRA) (Metha and Gjørv, 1982). This decline in workability can decrease initial slump by up to two inches (ACI Committee 234, 2013). When silica fume is added to a mixture, air content typically decreases as well due to an increase in surface area from silica fume. Air-entraining admixture increases of 125 – 150% of typical values in traditional concrete without silica fume are common to help achieve target air content. Bleeding has been shown to decrease in silica fume mixtures due to the increase in surface area, drastically reducing free water available in a concrete matrix (Grutzeck et al., 1982). Since there is a reduction in bleeding, plastic shrinkage becomes a concern when using silica fume as a cement replacement. Mixtures that include silica fume should be protected in early stages to keep water in the concrete matrix (Aïtcin et al., 1981). Common techniques used to reduce plastic shrinkage include fog misting, wind breakers, evaporation retardants, and immediate curing (ACI Committee 234, 2013).

Silica Fume's Effect on Heat of Hydration

The rate of heat evolution in concrete can affect strength of specimen at both early and late ages. Addition of silica fume greatly changes total heat generated during hydration depending on cement replacement percentage. As silica fume replacement increases, the rate of heat generation also increases as illustrated in Figure 1 (Roy, 1989). W/cm ratio determines how silica fume will affect the hydration reaction. At a high w/cm ratio, water is able to disperse ultra-fine silica fume and increase possible nucleation sites for calcium to react and become CSH. As nucleation sites increase, hydration will occur at a faster rate. At a low w/cm ratio, nucleation sites still occur, but their effects are not as evident and hydration occurs slower (Cheng-yi and Feldman, 1985; Langan et al., 2002). As silica fume replacement increases, heat evolution curves begin to indicate sulfate imbalances. These imbalances do not seem to affect the overall heat of hydration but should be considered when deciding on a silica fume replacement percentage.

Silica Fume's Effect on Corrosion Resistance

Studies have shown that silica fume in a concrete mixture can effectively decrease permeability and calcium hydroxide content while also altering pore structure (Hooton, 1993). Silica fume also reacts with COH produced during hydration to create CSH. CSH increases concrete strength and decreases pores that will occur due to leaching of COH over time. In a study conducted by Khedr and Abou-Zeid (1994) mortar bar specimens with different replacement levels of silica fume were created to observe sulfate, salt, and acid attacks (Table 2). Against sulfates, mixes with silica fume had little to no disintegration and better resistance than control specimens. Ammonium nitrate and calcium chloride testing yielded similar results. The control disintegrated between 4 and 5 weeks while mortar with silica fume only lost between 5 and 13% of its total mass after an eight-week period. Both silica fume and control specimen performed better when exposed to nitric, sulfuric, and hydrochloric acids rather than sulfates, nitrates, and chlorates. A reason for increased chemical durability is removal of lime through its reaction with SiO_2. Lime often reacts with harmful chemicals such as sulfates, acids, and chlorides that can lead to structural failure. By removing COH to produce CSH a structure that is less prone to chemical attacks is produced. The concrete matrix is also optimized by fine silica fume particles filling concrete matrix voids.

Silica Fume's Effect on Mechanical Properties

The reaction of silica fume with free lime and an elevated curing temperature are key to high compressive and tensile strength in concrete. Lime removes harmful COH from a concrete matrix by reacting with SiO_2, forming more CSH which increases total bond strength. Pozzolanic reactions are temperature sensitive, and higher curing temperatures generally increase compressive and tensile strength (Maage, 1986). Mazloom et al. (2004) claims that silica fume addition mainly effects early strength gain in concrete. In the first 90 days, compressive strength of the mixes including silica fume were between 4.5 and 12 MPa stronger than a control mix. Results similar to this were found by Mehta and Gjørv (1982) with increases in compressive strength of 3%, 22%, 77% and 97% at 3, 7, 28, and 90 days respectively. At late ages, silica fume has been shown not to have a significant effect on compressive strength. Typically, after 90 days the pozzolanic reaction has run to completion. ACI committee 234 does not believe that silica fume addition causes a retrogression in strength after 90 days.

As silica fume replacement increases tensile strength in concrete also increases (Xie et al., 1995). This was verified using two different tests: 1) a splitting tensile test (ASTM C330) and 2) notched beams. In three mixes with increased amounts of silica fume, splitting tensile strength was recorded as 4.95 MPa, 6.36 MPa, and 7.44 MPa as silica fume replacement increased. This increase was also observed in fracture energy which was recorded for the same three mixes as 0.152 N/mm, 0.172 N/mm, and 0.191 N/mm.

COH byproduct during hydration causes swelling and shrinking in OPC. By increasing silica fume replacement, swelling has been noted to decrease, but autogenous shrinkage has been seen to increase. This is due to the pore structure created by silica fume. The smaller pore structure lead to an increase in capillary tension since water has a harder time penetrating concrete and assisting with hydration. Autogenous shrinkage can lead to cracking and a decrease in durability. Experts suggest limiting silica fume replacement to 10% to counter the effects of autogenous shrinkage (Mazloom et al., 2004). Mortar bar expansion testing was completed by Asgeirsson and Gudmundsson (1979) over the course of one year for mortar specimen at three different silica dust levels: 5%, 7.5%, and 10%. After one month, specimen with 5% silica dust expanded 0.14 centimeters (cm) while specimen with 7.5 and 10% replacement only expanded 0.002 cm. Specimen with 5% replacement was 54% larger after 3 months and 67% larger after 6 months than the 10% replacement, while specimen with 7.5% replacement was 34% larger after 3 months and 49% larger after 6 months than the 10% replacement. This trend continued through to yield expansion values after one year of 0.062 cm at 5% silica dust, 0.035 cm at 7.5% silica dust and 0.021 cm at 10% silica dust.

Experimental Program

An experimental program was developed to observe the effects of increasing the percentage of silica fume in a concrete mixture on its fresh and hardened properties. The concrete mixture contained ordinary portland cement (OPC) from Lehigh Cement, Elkem Microsilica ES 900-W silica fume, size 8 rounded pea gravel from Bacco Materials, and U.S. Silica F-50 whole grain silica sand with properties shown in Table 3. Three different mixes were made with a silica fume mass replacement percentage of 0%, 10%, and 20% respectively. Batches were produced by following general proportion ranges given in Table 1-12 in *Design and Control of Mixtures* (Kosmatka and Wilson, 2011) and were adjusted to account for small aggregates used in mixing. A target air content of 4% was chosen for volumetric batching. Remaining volumetric percentages are shown in Table 4. Three mixes were batched to produce three specimens apiece and were mixed with a 3 ft^3 Marshalltown drum mixer according to ASTM C192. After mixing, fresh concrete was tested for air content (ASTM C231), slump (ASTM C143), and initial temperature, then placed into 4 by 8-inch cylinder molds in two lifts. Once in cylinder molds, the tops of specimen were smoothed and a bag was placed over the specimen to keep moisture in. After 24 hours, specimens were removed from molds via air pressure and placed into a curing room kept at a nominal 23 °C ± 2°C and 100% humidity for 6 days. Specimens were then tested for density, resistivity, and compressive strength (ASTM C39).

Results and Discussion

Fresh mix properties for mixes 1, 2, and 3 were recorded and are shown in Table 5. Based on visual evaluation, 1 kilogram (kg) of water was added to mix 1 and 2 and 1.5 kg was added to mix 3 to improve workability. Initial temperature of the fresh mixes increased an average of 0.8 °C as silica fume replacement percentage was increased, which is consistent with literature. Air content was consistent between the three mixes. During air content testing of mix 1, air bubbles came out of the seal of the container which may account for a slightly higher air content. Additionally, no air entraining admixture was used during mixing which could account for a smaller volumetric air percentage than designed air volume. Slump for all three mixtures was 12.7 millimeters (mm) even with additional water to increase workability (Figure 2). No HRWRA was used during mixing which may account for a low slump, as the lack of HRWRA is uncommon with mixes containing silica fume. All three slump tests had areas where material had not fully condensed and air pockets were visible due to the low workability (Figure 3).

Density, resistivity, and compression testing was completed for specimen after removal from curing (Table 6). Average density for the three mixes decreased slightly with silica fume mass replacement. This is consistent with Holland (2005) who notes that adding silica fume will not “densify” a mixture because specific gravity of silica fume is less than OPC. Resistivity decreased by 10% at a silica fume replacement of 10% and 30% at a silica fume replacement of 20%. Since all three mixtures were tested at 7-day age, silica fume had not reacted completely with COH. At 28 days, resistivity values would be expected to be opposite of what was recorded for 7-day testing. Silica fume’s fineness allows for particle packing and as it reacts with COH, voids where chloride ions could enter the specimen will decrease. Seven-day compressive strength decreased as silica fume content increased. Early-age strength is gained through the formation of CSH during cement hydration. When cement is replaced with a pozzolanic material such as silica fume, early-age strength will decrease slightly since less cement produces less CSH. Additionally, only one size of gravel was used during mixing which produced a bad gradation. Optimizing gradation leads to a better particle packing and therefore better resistivity and compressive strength in a specimen. Curing temperature also affected seven-day compressive strengths, as silica fume is more reactive at higher temperatures. If specimen had been cured in hot water, pozzolanic reactions would have occurred at a faster rate. Yamato et al. (1986) observed this in a study on curing temperature effects on compressive strength. At seven days, compressive strength of silica fume mixtures was less than control mixtures, but at 28 and 91 days, compressive strength of silica fume mixtures were significantly higher when cured at lower temperatures.

Conclusions

Silica fume is a pozzolanic material that changes microstructure properties in a concrete matrix to produce higher early-age compressive strengths and decrease permeability. It is a byproduct produced during production of ferrosilicon/silicon technology that can be collected as one-micron diameter amorphous particles. Silica fume alters physical properties of concrete by decreasing the probability of bleeding, creating more nucleation sites to increase CSH production, and occupying space between large aggregates and cement grains to improve particle packing (ACI Committee 234, 2013). These three characteristics combine to greatly improve physical properties of silica fume concrete mixtures. Based on reviewed literature an experimental program was developed to observe the effects of increasing silica fume percentages on a concrete mixture's fresh and hardened properties. Fresh concrete properties were measured and were consistent with published literature. Slump was extremely low because no HRWRA was used in the three mixtures. Physical properties of specimens at seven days including density, resistivity, and compressive strength were measured. At seven days, mixtures with more silica fume were found to be weaker than a control mixture. This could be caused by a lower curing temperature (23 °C) and no HRWRA being used. Resistivity decreased as silica fume replacement percentages increased.

Applications to Transportation Infrastructure

Silica fume addition to conventional concrete mixes can increase compressive strength, decrease volume change, and decrease permeability to chemical corrosion of concrete-based transportation infrastructure. Decreased permeability allows for concrete placement where corrosion is common such as coastal and cold weather locations where structures are frequently in contact with salt and other harmful ions. Although silica fume addition increases initial costs, the increase in durability extends the lifespan of structures and time between repairs and maintenance, making up for initial costs (Shannag, 2000). Silica fume mixes have been used in bridges to increase the span of the bridge, reduce the number of girders for a given span, and reduce the section height for a given span due to increased early age compressive strength provided by silica fume (Holland, 2005).

Silica fume mixes can also be used in rehabilitation projects on aged infrastructure. Silica fume mixes are often used in shotcrete to repair infrastructure because of its high cohesion. This is ideal for repairing pre-existing structures where concrete is placed into cracks, often in places that are hard to reach with conventional concrete. The fineness of silica fume creates high cohesion between an existing structure and shotcrete which decreases rebound of shotcrete. A smaller rebound means layers of shotcrete with silica fume will generally be thicker than traditional concrete (Holland, 2005). Once placed, shotcrete with silica fume provides benefits identical to structures containing traditionally placed silica fume concrete.

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Table 1. SiO_2 content in Silica Fume for Different Alloys (ACI Committee 234, 2013)

Alloy Type	SiO_2 content in Silica Fume
50% Ferrosilicon	74 – 84%
75% Ferrosilicon	84 – 91%
98% Silicon Metal	87 – 98%

Table 2. Chemical Durability of Silica-Fume Mortar (Percent Weight Remaining after Chemical Aggression) (Khedr and Abou-Zeid, 1994)

	Week							
	1	2	3	4	5	6	7	8
Saturated Sulfates								
Sodium – control	100	100	99	99	98	98	97	96
Sodium - SFM[A]	100	100	100	100	100	100	100	100
Magnesium – control	100	99	98	97	97	96	95	94
Magnesiuim - SFM[A]	100	100	100	100	100	100	100	100
Saturated Ammonium Nitrate								
Control	100	98	96	95	81	---[B]	---	---
SFM[A]	100	98	96	95	95	95	95	95
Saturated Calcium Chloride								
Control	100	95	82	---[B]	---	---	---	---
SFM[A]	100	99	95	89	88	88	87	87[C]
Nitric Acid								
Concentrated – control	97	92	51	32	30	29	28	27
Concentrated - SFM[A]	99	99	89	68	64	61	58	55
20% - control	95	88	73	57	55	53	52	---[B]
20% - SFM[A]	97	92	92	92	92	91	91	91
Sulfuric Acid								
Concentrated – control	99	97	95	95	93	91	90	89
Concentrated - SFM[A]	99	98	96	96	94	93	92	91
20% - control	93	86	79	73	71	69	68	67
20% - SFM[A]	97	90	83	82	82	81	81	81
Hydrochorlic Acid								
50% - control	94	88	84	80	40	56	43	31
50% - SFM[A]	98	92	88	85	84	83	83	83

[A] SFM: Silica-Fume Mortar
[B] Disintegration
[C] Partial Rupture

Table 3. Constituent Properties

Constituent	γ	Description
Cement	3.15	Ordinary Portland Cement
Silica Fume	2.25	Elkem Microsilica ES 900-W
Pea Gravel	2.39	Size 8 Rounded Gravel
Silica Sand	2.65	F-50 Whole Grain Silica
Water	1.00	Laboratory Tap
Air	0.00	Air captured during mixing

Note: γ = specific gravity

Table 4. Volumetric Percentages for 0%, 10%, and 20% Silica Fume Mass Replacement

Mix	Cement (%)	Silica Fume (%)	Pea Gravel (%)	Silica Sand (%)	Water (%)	Air (%)
1	10.3	---	43.5	26.0	16.4	3.8
2	9.0	1.4	43.4	26.0	16.4	3.8
3	8.2	2.8	43.3	26.0	16.2	3.7

Table 5. Fresh Concrete Properties

Property	Mix		
	1	2	3
Initial Temperature (°C)	20.7	21.5	22.3
Air Content (%)	3.5	3.0	3.0
Slump (mm)	12.7	12.7	12.7

Table 6. Properties of Hardened Concrete

Mix	Specimen	Density (kg/cm^3)	Avg. Density (kg/cm^3)	Resistivity (kΩ/cm)	Avg. Resistivity (kΩ/cm)	fc (MPa)	Avg. fc (MPa)
1	1-A	2.23	2.24	6.2	6.4	24.9	23.4
	1-B	2.24		6.4		21.9	
	1-C	2.25		6.5		23.5	
2	2-A	2.23	2.23	5.8	5.8	20.6	20.4
	2-B	2.23		5.7		20.0	
	2-C	2.24		5.8		20.5	
3	3-A	2.21	2.22	4.7	4.9	18.7	18.3
	3-B	2.22		4.9		18.9	
	3-C	2.22		5.0		17.3	

Fig 1. Heat Evolution Curves of the Hydration of Cement with 0, 10, 20, and 30 % Silica Fume (SF) Replacement (Roy, 1989)

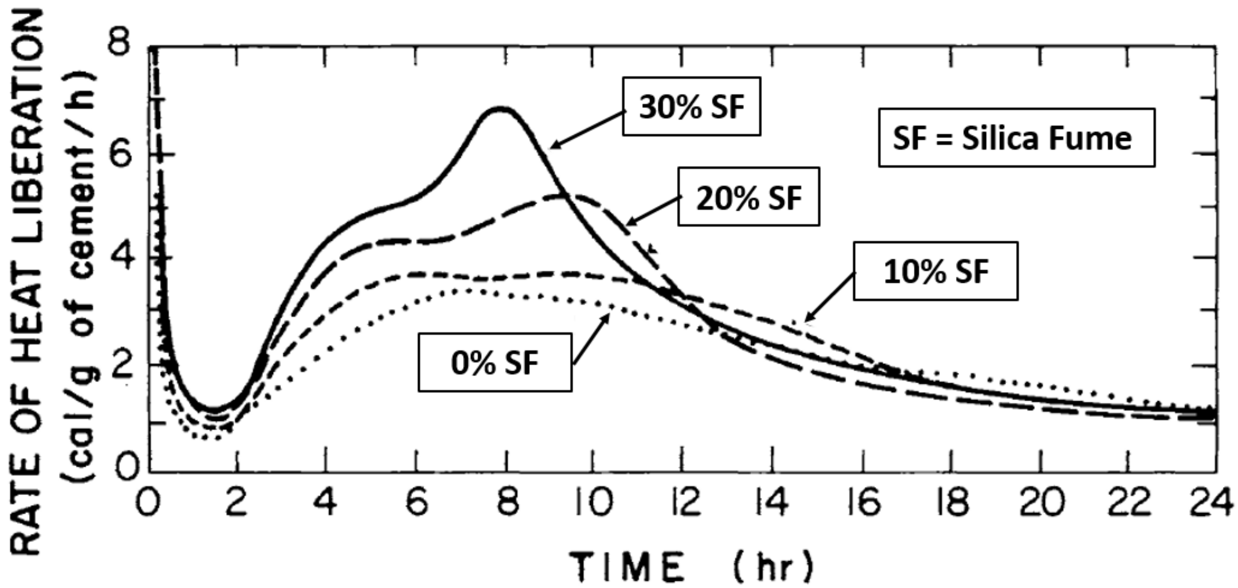

Fig 2. Slump for (a) Mix 1, (b) Mix 2, and (c) Mix 3

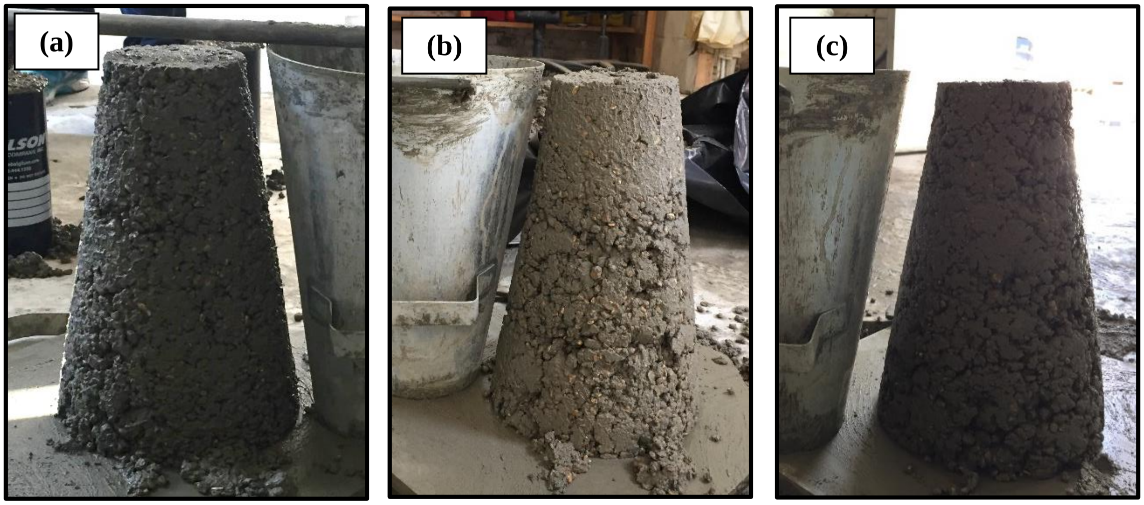

Fig 3. Air Pockets in Slump Specimens (Mix 3)