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# A new approach for application of silica fume in concrete: Wet granulation

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## HIGHLIGHTS

- Use of granulated silica fume in concrete.
- The incorporate of granulated silica fume demonstrated significant performance in concrete.
- The influence of granulated silica fume on transport properties of hardened concrete.

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## ABSTRACT

Silica fume as partial replacement in concrete for cement increases the durability of reinforced concrete and reduces cement usage. However, the low bulk density and high specific surface area of silica fume offer challenges in its application and transport. In this study, the density of silica fume was increased by producing silica fume granules mixed with a solid super plasticizer. The effects of silica fume granulation on durability and mechanical properties of concrete were tested. Results indicated an increase in strength and surface electrical resistivity, and a decrease in permeability for both slurry silica fume and granule, compared to the control sample.



## 1. Introduction

Silica fume is used to improve some properties of concrete, namely, an increase in bonding strength (aggregate-to-matrix / concrete-to-reinforcement), an increase in abrasion strength, a decrease in permeability, an increase in resistivity against corrosive chemicals, an increase in corrosion resistance of reinforced steel in concrete, and a decrease in expansion due to the ASR phenomenon [1–5]. Silica fume operates by means of three mechanisms: 1) pore-size reinforcement and matrix densification, 2) reaction with free lime (from the hydration of cement), and 3) interfacial refinement of cement-paste aggregates [1,6,7]. As-produced silica fume typically is purchased as bulk. Because silica fume has a high surface area (20,000 $m^2$/kg) and low bulk density (130–430 kg/$m^2$), this introduces challenges in loading, transportation, storage, and placement in the concrete mixer [8,9]; examples of practical challenges include raising and scattering of dust as well as high transportation and labor costs. These drawbacks have encouraged the use of new forms that do not suffer from these types of problems, such as condensed silica fume and slurry silica fume.

Condensed silica fume, with a bulk density 400–720 kg/$m^2$, is an accessible form of silica fume that can be transported conveniently. According to Committee 234 of the American Concrete Institute (ACI) [8], it is made by blowing compressed air from below and scattering fume particles in a silo, which leads to their agglomeration. The increase in popularity of using condensed silica fume is based on the assumption that agglomerates are weak, and would disintegrate easily and break during blend mixing with aggregates. However, according to ACI Committee 116R [10], subsequent studies showed that this seldom happens, and a

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considerable portion of the agglomerates do not disintegrate completely in hardened concrete. Studies have found that silica fume agglomerates sometimes are larger than cement particles in concrete, and this hinders the performance improvement expected from pore-size refinement and matrix densification. Microstructure studies have found that reduction in pozzolanic reactions and formation of calcium-silicate-hydrate (C-S-H) gel only occur in the surface layers of agglomerates, which hinders improvements in permeability, durability, and the mechanical properties of concrete [10–12].

Some initial findings by Hooton [13] have indicated a successful application of silica fume to control the alkali-silica reaction (ASR); this has led to an increase in silica fume usage for several applications. However, Juenger and Ostertag [11] as well as Maas et al. [12] showed that the agglomerates in condensed silica fume, which do not disintegrate nor uniformly scatter during the blend of concrete, could diminish the ASR-related improvements previously claimed. Moreover, these studies showed that this could intensify the undesirable ASR effects, similar to reactive aggregates, and have such consequences as increased expansion and cracking at the periphery of the agglomerates [11,12].

A method proposed for pulverizing silica fume agglomerates involves applying ultrasound waves to the particles or to the solution prior being used in cement blends. Ultrasound waves have been successfully used to pulverize and disperse silica fume agglomerates, which leads to more reactance and smaller particles sizes (i.e., below a micrometer) [14,15]. An alternative approach is to use a slurry silica fume, which leads to an increase in density, facilitates transportation, and resolves the agglomeration problem [1]. Its disadvantages are that, if stored, a water-based slurry silica fume can freeze at low temperatures; need special care during transportation, including such equipment as tanker trucks; and has the potential for precipitation after long periods of time.

Hypothetically, these issues may be addressed by the application of granulated silica fume in concrete. Granulation is a method of turning small particles into larger agglomerates with the same physical properties. The main goal of this process is to improve flow, transfer properties of the mixture, and prevent the separation of the constituents [16]. This method of granulation, very simply, induces the cohesion among small solid particles; it is achieved by means of the physical or chemical stimulation of the particles or by applying a binder material that covers the surface of the particles and adheres them together. In most cases, the products of this process contain a considerable amount of empty space between the particles [17].

A method for granulation proposed in the powder technology literature is wet granulation, which is used mainly in the powder-curing industry. This process involves the agglomeration of powder particles by means of a binder material, followed by drying, which typically is accomplished by using a high-shear mixer granulator. Dry granules might be sieved to obtain desired size distribution, and, in various contexts, might be final or intermediary products [16,18,19].

In this study, how properties of hardened concrete improve was assessed as well as how an application facilitates the process if the technique of wet granulation is used to increase the density of the silica fume that is mixed with solid super plasticizer. The use of silica fume as a partial replacement for cement would decrease the flowability of concrete mixtures [1,8]. If this reduction in flowability is compensated with an increase in water, then due to an increase in the water-to-binder ratio, no improvement will result from partially replacing cement with silica fume. Using water-reduction additives, such as plasticizers and super plasticizers, might enable improvements by using silica fume. The goal of this study was to produce an improved product by using certain combinations of super plasticizer (in solid form) and a silica fume during the granulation process; this would partially compensate the possible reduction in workability due to the addition of silica fume.

## 2. Methodology

First, the optimum ratios of solid super plasticizer were determined by measuring the workability of mortar samples during a flow table test [18].

In the next step, concrete mixtures were made, using two distinct water-to-cement ratios (0.35 and 0.45), two distinct cementitious material content (350 $kg/m^3$ and 400 $kg/m^3$), and two distinct modes of silica fume replacement (slurry and granule). The tests conducted were a compressive strength test, a bulk water absorption test, a water permeability test, a surface electrical resistivity test, a rapid chloride permeability test, and a rapid chloride migration test; these tests were conducted at different ages up to 90 days.

The optimum percentage replacement of cement with silica fume is 6%–12% [7,21–23]. Due to the previous research on similar sources of silica fume [24–26], in this study, 7.5% replacement of cement with silica fume was chosen as the optimum ratio. In order to make the mixtures comparable, the workability of the mixtures was refined by adding appropriate amounts of super plasticizer so that the slump index reductions were all in the interval of 70–100 mm.

## 3. Experimental program and materials

### 3.1. Materials

To prepare the mixtures, Type I cement was used, according to the ASTM C150 standard specification [27]. Additional chemical analyses and physical characteristics of the cement and used silica fume, presented in Table 1, were compared to ASTM C150. The sand used in the mortar was standard, with a fineness modulus of 2.67, a specific gravity of 2.62, and water absorption of 1%. Coarse aggregates had a maximum nominal size of 19 mm, with specific gravity and water absorption of 2.58 and 1.74, respectively. Sieved aggregates passed ASTM C33 criteria [28]. A super plasticizer of a solid based on naphthalene formaldeid sulphanate was used to make the slurry silica fume and the granules. Both for the slurry silica fume and granule silica fume, a liquid super plasticizer with the same base was used in addition to the solid super plasticizer in order to retain the workability of the mixtures in the interval of 70 and 100 mm.

### 3.2. Mixture proportion for mortar samples

To achieve the optimum amounts of solid super plasticizer, first, the effect of the additive on workability of mortar were compared

**Table 1**
Chemical and physical characteristics of ordinary Portland cement (OPC) and Silica Fume (SF).

| Chemical composition* (%) | OPC | SF |
|---|---|---|
| CaO | 65.3 | 1.27 |
| $SiO_2$ | 20.8 | 87.5 |
| $Al_2O_3$ | 4.3 | 0.5 |
| $Fe_2O_3$ | 2.2 | 1.53 |
| MgO | 2.17 | 1.01 |
| $K_2O$ | 0.63 | 1.14 |
| $Na_2O$ | 0.36 | 0.36 |
| Loss on ignition (%) | 0.91 | 5.92 |
| Specific gravity | 3.15 | 2.14 |
| Fineness** ($cm^2/g$) | 2800 | – |

* Chemical composition is specified according to ASTM C114.
** Fineness is determined by blaine apparatus based on ASTM C204.