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# Recovered Mineral Component, Silica Fume, in the U.S.

**Eckart R. Bühler**

*Manager of Engineering Services, Norchem, Inc. 13968 N. 151st Lane, Jupiter, FL 33478*
*<eckart@norchem.com>*

## ABSTRACT

The U.S. Environmental Protection Agency has designated silica fume, a very fine dust-like material generated during alloyed metal production, as a Recovered Mineral Component that functions as a concrete additive to increase strength and durability. Silica Fume incorporation into the concrete medium will reduce the burden of an otherwise designated waste material that would end up in landfills, substituting the amount of conventional cementitious materials to reduce the overall carbon footprint of concrete. Silica fume has been widely utilized in the U.S. for the past quarter century in the Ready-Mixed Concrete industry and is now universally known for its contributions to High Performance Concrete (HPC) and Low Permeability Concrete, offsetting the accelerating properties of Chloride-Induced Corrosion. Silica fume can also be beneficial in lesser known applications to provide Abrasion-, Impact- and Chemical- Resistance, low-heat generation, and as Viscosity Modifier in very high workability such as in Self-Consolidating Concrete (SCC).

## Recovered Mineral Components (RMC)

RMC is a definition utilized in Environmental Protection Agency (EPA) documents to "conduct a study to determine the extent to which current procurement requirements, when fully implemented… may realize energy savings and environmental benefits attainable with substitution of RMC in cement used in cement or concrete projects." Excerpts from the draft lists following RMC descriptions, uses and applications, as identified by Congress:

Coal combustion fly ash
A finely-divided mineral residue resulting from the combustion of ground or powdered coal in coal-fired power plants. Replacement for cement in concrete applications.

Ground granulated blast furnace slag (GGBFS)
A ferrous slag, produced during the production of iron, as a result of removing impurities from iron ore. Quick quenching (chilling) of molten slag yields glassy, granular product. If finely ground and mixed with free lime, GGBFS can be used as cement replacement, or, if less finely ground, as concrete aggregate.

Silica fume
A very fine, dust-like material generated during alloyed metal production. Concrete additive used to increase strength and durability.

Concrete applications incorporating above listed RMC are beneficial to the environment in taking industry by-products out of the national waste stream and substituting partially for high carbon footprint cement quantities. All replace cement, or reduce necessary cement content to achieve certain concrete characteristics. Silica Fume is often considered an additive or mineral admixture, because of dramatically improved changes in engineered concrete characteristics. Production/consumption varies by type of RMC:

| Recovered Mineral Components, identified by congress | Annual Quantity Produced, 2004 | Annual Quantity Beneficially Used, 2004 |
|---|---|---|
| | ( million metric tons ) | |
| Coal Combustion Fly Ash | 64.2 | 25.5 |
| Ground Granulated Blast Furnace Slag | 3.6 | 3.6 |
| Silica Fume | 0.1 - 0.2 | 0.08 |

Fig.1 Quantities of RMC produced versus quantity beneficially used in concrete

## Silica Fume

Silica fume has been routinely applied in the ready-mixed concrete industry for about a quarter century in the United States. Silica fume inclusion to the concrete design is primarily dictated by project performance specifications aiming to minimize corrosion concerns and maximizing concrete strength performance, but also abrasion-, impact- or chemical resistance. Some uses are non-project specific addressing improvement to other occasional challenges in concrete technology such as limiting aggressive alkali activity, reduction of heat of hydration generation, optimizing viscosity modifying properties and drying shrinkage potentials.

Typically, silica fume is utilized in concrete at an average addition quantity of 5-10% by the weight of total cementitious content, including cement replacement materials such as slag and fly ash. Silica Fume is largely incorporated into concrete mix designs for high strength and extended structure life-cycle performance, currently supplementing an estimated one million cubic yards of high performance concrete (HPC) in the United States annually. 5-10% addition rate of silica fume to the cementitious content, coupled with low and very low water-to-cementitious ratios, can routinely provide concrete with compressive strength in excess of 70 MPa (10000 psi) and/or provide very low chloride permeability of 1,000 coulombs or less (as per AASHTO T-277, Rapid Chloride Permeability evaluation). There are highly specialized applications that utilize much higher then the routine percentage additions of silica fume, ranging up to 30% addition rates. The Cement and Concrete Research Institute (CCRI) in Trondheim, Norway has conducted testing rendering 20% silica fume treated concrete at very low W/C ($\leq 0.30$), for all practical purposes, practically water impermeable. At these higher percentage addition rates silica fume can maximize the propagation period and the structural life cycle of concrete, protecting it from exposure of variety of deleterious, aggressive and abrasive elements that would ultimately lead to concrete deterioration and structure replacement.

## Rheology

The nature of silica fume as a mix ingredient in concrete being of relatively very fine particle size and high surface area acts as a stabilizing agent by reducing the mobility of water, an effect often visually witnessed as “little or no bleeding”. In addition, the “ball-bearing” effect of the relatively neutral silica fume particles between the larger cement and supplementary cementitious materials (SCM) particles can significantly reduce plastic viscosity. It has been stated that “silica fume is likely more important in high strength concrete due to its effect on fresh rather than hardened concrete.” The rheology of silica fume has played a significant role in providing self-consolidating concrete characteristics (SCC) in construction (Two Union Square, 1989 Seattle and Key Corp. Tower, 1991 Cleveland) of high strength columns where mechanical consolidation was not practical. At this time when terminology for SCC had not yet been coined, predating actual cast-in-place SCC field applications by approximately a decade.

## Case Histories

[ concrete mix designs & performance for projects listed in addendum ]

**Low heat of hydration.** At the construction of the canister storage building at the Hanford nuclear site in the State of Washington a variety of criteria made mix design selection unusual business. Requiring high compressive strength of 51.5 MPa (7500 psi) and limiting the maximum temperature in place to 38ºC (100ºF) to control thermal cracking are two contradicting characteristics when designing concrete. Limiting the concrete placing temperature to 21ºC (70ºF) through addition of ice and utilizing a low total cementitious content of 357 kg/m$^3$ (601 lb/yd$^3$) which included a 40% pozzolanic content, fly ash @ 28% replacement and silica fume @ 11% addition rates. Silica fume and fly ash do not generate heat immediately like Portland cement as soon as contact with water initiates the hydration process. Furthermore, silica fume can provide strength gain performance of up to a 4:1 ratio when compared pound-for-pound in cement substitution.

Fig.2-4 Low heat of hydration mass concrete for the Hanford Nuclear Site in waste deposit.

**Corrosion protection** of steel-reinforced concrete, in the U.S., is the single largest market for ready-mixed silica fume concrete. Silica fume provides for concrete permeability reductions to dramatically delay the onset of corrosion. Once corrosion in the embedded reinforcement steel is initiated, low electrical conductivity of silica fume concrete subdues the corrosion process. “Very low permeability” concrete performance criteria are often project-specified and evaluated as per the AASHTO T-277 Rapid Chloride Permeability with a limiting value of 1000 coulombs of charge passed at concrete age from 28 to 56 days, for compliance. One main area of corrosion concern exists in transportation structures where artificially deposited chlorides (de-icing salts used during the winter months) promote corrosion. Natural chloride attack in the vicinity of ocean water, spray or mist is specifically aggressive on nearby structures. 5 to 10% silica fume addition by the weight of total cementitious along with a W/C below 0.45 has become a standard formula to design concrete to protect steel reinforcement. Steel reinforcement is able to expand up to seven times its original volume when corroding, creating internal forces much stronger than the concrete itself, cracking and spalling it.

Fig.5-8 Texas navigational district utilizes corrosion-resistant silica fume concrete for new port. Location of oceanfront seaports are continually exposed to constant chloride ingress through salt water. In addition, abrasive forces from the ocean wake and potential impact scenarios from vessels and machinery can take an accelerated destructive toll on concrete life cycle. Recent report cards for infrastructure in water exposure rates such structures at a poor, below average performance. Structural life cycle today often incorporates a 50 to 100 year design life. Such criteria demand high performance concrete including silica fume to increase the impedance of concrete and minimize corrosion currents within the concrete medium once in service.

Fig.9-11 Mass concrete barged to location for a new US 1 bridge structure over an ocean inlet.

In the above shown project, the Roosevelt Bridge in southern Florida, a combination of fly ash and silica fume minimizes heat generation and also provides corrosion resistance. In this typically warm climate the corrosion process is often much accelerated, specifically in the "splash zone" where in addition to chloride-bearing water exposure, maximum amount of wet-dry cycles will be routinely encountered.

**High Strength & High Modulus of Elasticity** requirements have been steadily increasing over the past few decades, particularly employed for high-rise construction. Most versatile concrete mix designs are employed using a variety of modern concrete tools, such as very low water-to-total-cementitious ratios, polycarboxilate high range water reducing technology, incorporation of multiple RMC, high concrete workability and at times imported aggregate. Importing aggregate from far away can be a costly proposition and also an environmental burden, when considering large quantities of a major concrete ingredient which can constitute up to 50% of the concrete volume/weight, need to be shipped from afar relying on extra fuel consumption.

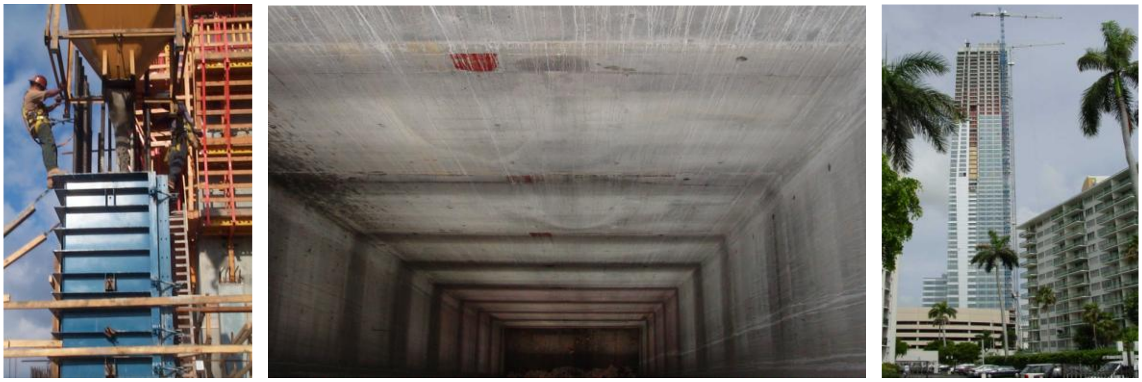

Fig.12-14 HPC column placement; internal view of elevator shaft and nearly finished structure.

For the Miami, Florida Four Seasons (Fig.12-17) hotel construction, approximately 15300 m$^3$ of HPC with a 35-42 GPa (5-6 x $10^6$ psi) modulus of elasticity requirement and a 55-69 MPa (8000-10000 psi) compressive strength specification, utilized imported granite from Nova Scotia, Canada. 11500 m$^3$ with the same compressive strength requirement, but a lower 28-35 GPa (4-5 x $10^6$ psi) modulus of elasticity requirement could forgo the imported granite aggregate through the use of silica fume in conjunction with local Florida limestone aggregate, at a combined savings for this concrete design of approximately $ 150.000,00. Historically Florida limestone aggregates' capacity to reach higher modulus of elasticity values diminishes at approximately 28 GPa (≈ 4 x $10^6$ psi), yet with incorporation of silica fume into this, one of the leanest volume high strength concrete mix designs in Florida's history, specified values were easily obtained.

Fig.15-17 Dense reinforcement necessitated self consolidating high performance concrete.

Without cooling mechanisms such as ice or liquid nitrogen, workability levels remained at constant SCC levels for up to two hours and plastic concrete temperatures were permitted up to 38ºC (100ºF). Silica fume, at a 5.6% substitution rate of total cementitious (or 11% addition rate to cement content only) balanced setting times for this 50% slag-cement mix design and beneficially modified the viscosity of SCC workability levels. At 230 meters (750 ft) height, the Four Seasons became the tallest concrete structure in Florida, specifically designed to withstand hurricane force winds, as can be expected in this geography. In the early 1990's Cleveland's tallest building to be, the Key Corp. Tower was designed with column concrete attaining compressive strength of 67.5 MPa (12000 psi) and minimum modulus of elasticity values of 47 GPa (6.8 x $10^6$ psi); the driving factor being seismic zone considerations. To achieve an optimized mix design with a reasonable amount of total cementitous quantity to limit shrinkage and creep potentials, an 8% silica fume addition played an integral part along with a 30% replacement value of slag cement, combined with a very low W/C of 0.24.

Fig.18-20 Full height single stage concrete pumping and filling columns from the bottom up.

A single stage pump delivered this HPC from the ground level to the floors above into column forms which were filled from the bottom up. Since there was no access to consolidate via mechanical vibration and vibrating forms were impractical, high concrete fluidity was required and specified as a minimum slump requirement of 250 mm (10 inches). Spread, or slump flow as coined a decade later with the advent of self-consolidating concrete (SCC), was measured and expected to exceed 500 mm (20 inches) to assure proper in-place consolidation. The average ultimate compressive strength achieved was in excess of 100 MPa (15000 psi), well above specified performance as a side effect to the more demanding performance of modulus of elasticity which with this HPC mix design attained an average of 48.3 GPa (7 x $10^6$ psi).

**Heavy Industrial Applications** of silica fume concrete can maximize the propagation period and structural life cycle of concrete before exposure of variety of deleterious, aggressive and abrasive elements will cause irreversible deterioration. Research and field performance have shown that high percentage (≥20%) silica fume concrete can be used to effectively mitigate chemical attack in a variety of exposure conditions (i.e. types of chemicals and concentration, pH levels, ambient conditions and number of wet/dry cycles). In the 1980's a variety of evaluations were conducted around the world testing loss of mass and decrease in modulus of elasticity of concrete exposed to magnesium-, calcium- and sodium chlorides, ammonium- and calcium nitrate, acetic-, formic-, nitric-, sulfuric-, lactic and hydrochloric acids and others. In general, and again depending much on specific exposure conditions, high percentage silica fume concrete can increase aggressive chemical resistance by a factor of 2 to 5 times that of ordinary Portland cement concrete, and can be used in place of other expensive protective systems such as epoxy coatings and acid brick. Waste transfer stations for example, experience very short life cycles of their transfer floors that are in operation around the clock. In addition to chemicals leaching from the waste, impact from dropping it and abrasion from heavy equipment moving it shortens the average specialty floor topping life to only two to three years. Downtime of any plant and the logistics of diverting constantly accumulating trash are a significant consideration during periodic floor replacement activities.

Fig.21-23 Waste transfer floor deterioration within 3 years of use are ready for replacement.

Average expense of Florida waste transfer station floor replacement in 1993 was approximately \$ 183/$m^2$ (\$ 17/$ft^2$) and shut a plant down for about 2 months during retrofit. A 20% silica fume HPC halved plant downtime to one month construction before reopening the facility. Construction cost approached \$ 97/$m^2$ (\$ 9/$ft^2$) for a topping twice as thick and twice the volume as compared to the conventional methods previously employed, but most importantly, high performance silica fume concrete then more than doubled the life of the waste transfer floor.

Fig.24-26 Full depth waste transfer floor replacement with 20% silica fume HPC doubled life.

A Nevada titanium production facility had similar experience with transfer floor performance as in the waste industry sector, where concrete is subject to chemical exposure, impact and abrasion wear. As freshly produced titanium exits the production facility in just post-melted status, the concrete floor could also be occasionally subjected to extreme heat. The constructability environment for HPC applied here would provide an additional challenge with the very high concrete temperatures that Nevada can expect, particularly during the summer months. Not only high ambient temperatures, but also very low humidity would be a liability to successful concrete production and execution, particularly with a high percentage silica fume HPC. The solution was provided by a hydration control admixture used at a low dosage of 65-260 ml/100kg (1-4 oz/cwt) of the total cementitious value. This dosage was varied according to weather of the day and reports back from the project during pours about workability consistency; it allowed for normal setting characteristics of the HPC while not sacrificing workability at any time.

Fig.27-28 Nevada titanium plant retrofit with ultra-durable, high silica fume percentage HPC.

**Life Cycle Optimization** is a most important consideration when designing concrete with sustainability in mind. The largest economical expense, the greatest use of natural resources and the highest carbon footprint would be for a concrete structure that would have to be re-build prematurely. The waste of a prematurely deteriorated structure, downtime and inconvenience to its users and the potential pollution and physical hazards during rebuilding can all be avoided. Fortunately we now see a strong trend, particularly in the publically funded construction sector, towards extended service life design. Incorporation of otherwise land-filled by-products into smart concrete design has proven to provide a significantly positive impact on long-term durability of concrete.

Fig.29-31 A 1000 year concrete design for the Great Stupa of Dharmakaya, Ft.Collins Colorado

## Conclusion:

The integration of RMC into the concrete of many projects has provided a safe track record and it has recycled material out of the national waste stream. The performance characteristics of RMC-optimized concrete can sufficiently improve concrete quality for the benefit of society obtaining longer lasting concrete structures.

| **RMC** | **Fly Ash** | **GGBFS** | **Silica Fume** |
|---|---:|---:|---:|
| | | | |
| Energy Savings (MJ) | 9,978 | 4,221 | 32,915 |
| Energy Savings (USD) | 274 | 116 | 905 |
| *Avoided CO2 Emissions (g)* | 1,490,419 | 668,889 | 699,876 |

Fig.32 Impacts per metric ton of RMC substituted for Portland cement, table excerpt.

The carbon footprint of silica fume is a mere fraction of that of Portland cement, yet silica fume yields approximately a 4 to 1 performance ratio in compressive strength when replacing Portland cement pound for pound. Silica Fume makes good “sustainability sense” for broader use in concrete, whether as a stand-alone addition to cement to increase overall concrete strength and durability, or as co-replacement in combination with another RMC such as fly ash or slag, to positively offset the effects on concrete properties that may have been altered beyond conventional construction methods’ comfort level, such as stiffening rates, setting times, early strength gain and more.

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## Addendum

**Ready-Mixed Concrete Design Proportioning & Performance of Projects Discussed.**

Canister Storage Facility, Hanford, WA -1998

| **Mix Design Materials :** | **lbs / yd$^3$** | **kg / m$^3$** |
|---|---|---|
| **Cement, Type I** | **391** | **232** |
| **Fly Ash, Class F ( 28% replacement )** | **150** | **89** |
| **Silica Fume ( 11% addition )** | **60** | **36** |
| **Aggregates** | **to yield;** | **non - air-entrained** |
| **Water / Cementitious Ratio** | **0.37** | **0.37** |
| **High Range Water Reducer** | **1.7 gal / yd$^3$** | **8.1 ltr / m$^3$** |
| **28 day compressive strength** | **6,300 psi** | **43 MPa** |
| **90 day “** | **7,500 psi** | **52 MPa** |
| **Max. Concrete Temp. delivered** | **70° F** | **21° C** |
| **Max. Concrete Temp. in place** | **100° F** | **38° C** |

Calhoun County Seaport, Point Comfort, TX -1990

| **Mix Design Materials :** | **lbs / yd$^3$** | **kg / m$^3$** |
|---|---|---|
| **Cement, Type I** | **611** | **363** |
| **Silica Fume ( 8% addition )** | **50** | **30** |
| **Aggregates** | **to yield;** | **4 % air-entrained** |
| **Water / Cementitious Ratio** | **0.40** | **0.40** |
| **High Range Water Reducer** | **0.8- 1.1 gal / yd$^3$** | **3 – 4 ltr / m$^3$** |
| **28 day compressive strength** | **8,600 psi** | **59 MPa** |

Roosevelt Bridge, Stuart, FL -1993

| **Mix Design Materials :** | **lbs / yd$^3$** | **kg / m$^3$** |
|---|---|---|
| **Cement, Type I** | **451** | **267** |
| **Fly Ash, Class F ( 36 % replacement )** | **257** | **152** |
| **Silica Fume ( 8 % addition )** | **57** | **34** |
| **# 67 Limestone** | **1778** | **1054** |
| **Natural Sand** | **966** | **573** |
| **Water / Cementitious Ratio** | **0.35** | **0.35** |
| **High Range Water Reducer** | **1 gal / yd$^3$** | **4.6 ltr / m$^3$** |
| **28 day compressive strength** | **8,300 psi** | **57 MPa** |
| **56 day compressive strength** | **9,100 psi** | **63 MPa** |
| **Specification Requirement:** | **very low permeability, i.e. < 1,000 coulombs** | |

Four Seasons, Miami, FL -2000

| Mix Design Materials : | lbs / $yd^3$ | kg / $m^3$ |
|---|---|---|
| Cement, Type I | 450 | 267 |
| Slag Cement (G.G.B.F.S. 50%) | 450 | 267 |
| Silica Fume ( 5.5 % addition ) | 50 | 30 |
| # 89 Limestone | 1652 | 980 |
| Natural Sand | 960 | 570 |
| Water / Cementitious Ratio | 0.29 | 0.29 |
| High Range Water Reducer | 1.1 gal / $yd^3$ | 5.5 ltr / $m^3$ |
| 28 day compressive strength | 11,700 psi | 81 MPa |
| 28 day modulus of elasticity | 5.5 x $10^6$ psi | 38 GPa |

Key Corp. Tower, Cleveland, OH -1992

| Mix Design Materials : | lbs / $yd^3$ | kg / $m^3$ |
|---|---|---|
| Cement, Type I | 685 | 406 |
| Slag Cement (G.G.B.F.S. 30%) | 285 | 169 |
| Silica Fume ( 8 % addition ) | 80 | 47 |
| Aggregates natural sand and traprock | to yield; | non - air-entrained |
| Water / Cementitious Ratio | 0.24 | 0.24 |
| High Range Water Reducer | 2.3-3.5 gal / $yd^3$ | 9 - 12 ltr / $m^3$ |
| 3 day compressive strength | 9,300 psi | 64 MPa |
| 7 day “ | 12,600 psi | 87 MPa |
| 28 day “ | 14,200 psi | 98 MPa |
| 56 day “ | 15,100 psi | 104 MPa |
| 56 day modulus of elasticity | 7.0 x $10^6$ psi | 48 GPa |

Solid Waste Authority, Delray Beach, FL -1993

| Mix Design Materials : | lbs / $yd^3$ | kg / $m^3$ |
|---|---|---|
| Cement, Type IP (incl.Class F fly ash) | 705 | 418 |
| Silica Fume ( 20 % addition ) | 141 | 84 |
| Aggregates | to yield; | non - air-entrained |
| Water / Cementitious Ratio | 0.34 | 0.34 |
| High Range Water Reducer | 2.25 gal / $yd^3$ | 11.2 ltr / $m^3$ |
| 1 day compressive strength | 4,500 psi | 31 MPa |
| 7 day compressive strength | 6,500 psi | 45 MPa |
| 28 day compressive strength | 10,000 psi | 69 MPa |
| Rapid Chloride Permeability | Aashto T-277 | 335 coulombs |
| NBS Abrasion Resistance | .356 mm @ ½ hr | .584 mm @ 1 hr |

Titanium Plant Retrofit, Las Vegas, NV -2006

| **Mix Design Materials :** | **lbs / $yd^3$** | **kg / $m^3$** |
|---|---|---|
| **Cement, Type V** | **700** | **415** |
| **Silica Fume ( 20 % addition )** | **140** | **83** |
| **# 67 Stone** | **1680** | **996** |
| **Manufactured sand** | **1120** | **665** |
| **High Range Water Reducer** | **1.5- 2.0 gal / $yd^3$** | **7.5 – 10 ltr / $m^3$** |
| **Hydration Control Admixture** | **5 - 40 ozs / $yd^3$** | **25 – 250 ml / $m^3$** |
| **Water / Cementitious Ratio** | **0.35** | **0.35** |
| **56 day compressive strength** | **≥ 10,000 psi** | **≥ 70 MPa** |

The Great Stupa of Dharmakaya, CO -1990 until 2005

| **Mix Design Materials :** | **lbs / $yd^3$** | **kg / $m^3$** |
|---|---|---|
| **Cement, Type I / II** | **730** | **433** |
| **Fly Ash, Class C ( 11 % replacement)** | **94** | **56** |
| **Silica Fume ( 9 % addition )** | **76** | **45** |
| **Aggregates** | **to yield;** | **5 % air-entrained** |
| **High Range Water Reducer** | **1.3 - 1.5 gal / $yd^3$** | **4 - 5 ltr / $m^3$** |
| **Water / Cementitious Ratio** | **0.35** | **0.35** |
| **7 day compressive strength** | **6,900 psi** | **48 MPa** |
| **28 day “** | **8,700 psi** | **60 MPa** |