The History of Silica Fume in Concrete- from Novelty to Key Ingredient in High Performance Concrete

Per Fidjestøl and Magne Dåstøl
Elkem Materials, Norway

Content

- Silica fume in concrete has a 60 year history,
- Development of the use in concrete has been a long story.
- A main hurdle were the needs for official recognition and acceptance of the technology - in the form of standards and related specifications.
- The talk give a brief summary of history, and of the standards development,
  - leading up to the present day when international standards are in place, new materials seek to emulate silica fume and existing structures testify to the benefits of silica fume in concrete.
- Also some projects are presented.

History

- Silica Fume, aka. Microsilica, condensed silica fume etc, was first mentioned in a US patent from 1944
- This patent mainly touched upon the use in mortar, and little is known of commercial use of the process.

Fiskaa Plant in Kristiansand, Norway ca. 1970

This is how silica fume is produced:

- Silica fume is an inherent co-product of silicon and ferrosilicon
- Silicon is not found in nature, and is normally produced from silica (SiO_2) and carbon (C)
- Ideally, the following reaction is intended

$$SiO_2 + 2C = Si + 2CO$$

where

- SiO_2 is normally quartz
- C is a mix of coal, coke and wood chips
- For ferrosilicon: an iron source is added, e.g iron oxide

- Production take place in large electric smelting furnaces at temperatures > 2000 ^{o}C

This is how silica fume is produced

- However, the chemistry is much more complex, and a number of side-reactions are involved
- Silicon carbide (SiC) and the (unstable) gas SiO are important intermediate products
- In practise, some of the SiO-gas escapes from the furnace and reacts with air

$$\boxed{SiO + \tfrac{1}{2}O_2 = SiO_2}$$

- This is silica fume. Of the quartz added to the furnace, some 10 - 25% ends up as silica fume

Production quantities of silica fume

- Quantities are significant, typical
  - 1000 kg Si -> 400 - 500 kgs silica fume
  - 1000 kg FeSi (75%) -> 200 - 250 kgs silica fume
- Globally, the production of silica fume is estimated at 1.5 mill tpy
  - Assuming all furnaces are running and all are filtered
  - A highly unlikely scenario, possibly 70-80% is available
- Important production countries are China (leading), Norway, South Africa, USA, Canada, Spain, Russia/CIS and France
- China is in the middle of a significant expansion in production capacity of Si and FeSi

Development of gas cleaning technology for silica fume – a challenge

- 1950: trials with blankets in test filter
- 1951: the first experiments with “The Fiskaa-stuff”
- 1953: Elkem gave up construction of large-scale filters
- 1965 - 1970: Some companies invest in electrostatic precipitators
  - Limited success, practically no longer in use
- 1970: First generation baghouse filters – also not successful
- 1974: Elkem succeeds with own filter design
  - Established business unit for sale of filters
- 1974: The authorities require cleaning of Norwegian smelting industry
- 1975 – 1980: The filtered silica fume creates a considerable disposal problem
  - Intense development work to develop use and applications
- 1980 - : commercial breakthrough for the use of silica fume in concrete
- 1984: introduction of membrane technology (PTFE) for filtration

New filter installations:

Spring 2001

Spring 2002

Xibei Ferroalloys, China

The first published works on silica fume in concrete

- James William Sharp (1944)
  - Patent on ”Silica modified cement”, assigned to Permanente Cement Company
  - Focussed on plastic cements, 3-5% silica fume
  - Noted that bleeding was substantially reduced
  - Also observed a 40% increase in 90-days strength for concrete
- Carl Johan Bernhardt (1952)
  - Worked with cement replacement – up to 30%
  - Reported a significant increase in compressive strength ”in reasonable mixes”
  - Documented improvements in sulphate- and freeze-thaw resistance in mixes with 10-15% cement replacement
  - First known published technical paper on silica fume-concrete (April 1952)

James William Sharp (1944) and C.J. Bernhard (1952) – pioneers for use of silica fume in concrete

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Patented Nov. 12, 1946 **2,410,954**

UNITED STATES PATENT OFFICE

2,410,954

SILICA MODIFIED CEMENT

James William Sharp, Los Altos, Calif., assignor to Permanente Cement Company, Oakland, Calif., a corporation of California

No Drawing. Application October 12, 1944, Serial No. 558,463

6 Claims. (Cl. 106—98)

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This invention relates to plastic cements having characteristics useful in mortar, stucco, and the like, and more particularly to Portland and other more or less similar hydraulic cements modified to increase their characteristics useful in plastic cements.

Hydraulic cements are ordinarily used by pouring the grout made therefrom, that is the mixtures of the cement fillers as desired, and water, into forms wherein the mixture is allowed to set. By the term "plastic" is meant that type of cement which forms grouts that can be applied with a trowel or plastered against or onto a backing, without the use of forms. Plastic or mortar cements have been made by intermixing various modifying agents with Portland cements which impart thereto increased adhesiveness, workability and plasticity by virtue of an effect resembling that of lubricant upon the solid particles of the grout. Without such a modifying agent, Portland cement mortars, stuccos, and the like are harsh, stiffen rapidly, and have a high degree of shrinkage and low elasticity.

Definite specifications for masonry mortars, have been laid down by the American Society for Testing Materials. These embrace only the items of compressive strength and flow characteristics of the mortar after suction, in specified apparatus by specified procedure. Plastic cements may have other uses than as mortar or stucco, however, for example for flooring, roofing and in lining irrigation ditches, and the like, without forms, by merely plastering rather than pouring the grout. It may also be desirable to use them by shaping the plastic grout in molds and allowing it to harden therein, due to the flow characteristics thereof which allow greater slump with less water, and their easier molding properties. Further, it may be desirable to use such cements in concrete such as mass concrete and in the construction of ships. Thus, in addition to meeting the specifications referred to above, it may become desirable for a general purpose plastic cement to have the proper degree of working properties, adhesiveness, fatness, plasticity, resistance to deterioration on drying, viscosity, rigidity, elasticity, capillarity, and lack of harshness, flaking tendency and bleeding, and the like.

A very useful plastic cement can be made by intermixing with conventional and special Portland (and other similar hydraulic) cements very reactive amorphous silica (SiO_2) in very minute particles, obtained by cooling vapors which form solid silica on cooling. Such silica appears to consist of smaller and more reactive particles

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the faster the cooling to the solid state, so that fast cooling is ordinarily preferred. It has previously been proposed to add crushed, ground, or powdered silica to Portland cement, but the particles thereof have different characteristics than those of the silica obtained by the quick cooling method described above.

Among other substance proposed for modifying Portland cement to improve the plastic qualities thereof are hydrated lime, calcium or aluminum stearate, paraffin oil with or without calcium chloride, limestone with or without colloidal clay, diatomaceous earth, blast furnace slag with or without hydrated lime, fly ash which is obtained by burning pulverized coal in suspension and contains about 43% silica as silicate, 25% alumina, 15% iron oxide, and some lime, magnesia, carbon, and other constituents. The silica which is formed as described above can be added to the cement either with or without any of the other modifying agents.

The silica useful in this invention can be produced by rapidly condensing solid silica from its vapor state whereby it is obtained in highly subdivided form and in the amorphous state. It may be obtained by subliming crystalline or coarse silica material under suitable temperature conditions or it may be obtained by the vapor phase oxidation of silicon or a lower oxide of silicon, and subsequent condensation of the silica to obtain the product in very small particle size. Preferably, the silica is rapidly condensed from the vapor phase to recover finely divided, amorphous silica.

One convenient method of obtaining the silica useful in this process is to recover that formed in the production of ferrosilicon the latter being a reducing agent which is employed, for example, in the recovery of magnesium metal from its oxygen compounds. The ferrosilicon is usually produced by reacting a siliceous material of coarse of crystalline nature, such as quartz, in an electric arc furnace with iron and a reducing agent such as carbon whereby the quartz is reduced by the carbon and the silicon produced enters into combination with the iron, forming the desired ferrosilicon. In order to obtain an alloy which contains a higher percentage of silicon, for example, 75% of silicon, an excess of quartz is reacted and there is recovered, from the gases passing out of the reaction zone, silica which is amorphous and which is also in a very finely divided state. The mechanism of the formation of this silica has not been fully determined but it may arise in one or more of several ways. The silica

BETONGEN IDAG

ORGAN FOR NORSK CEMENTFORENING

REDAKTØR: OVERING. S. W. STEPHENSEN

NR. 2 APRIL 1952 17. ÅRG

SiO_2-støv som cementtilsetning.

Innledning.

Det har lenge vært kjent at tilstrekkelig finkornet SiO_2 ved vanlig trykk og temperatur kan reagere med kalk og danne faste, cementliknende forbindelser som viser stor trykkstyrke. Dette forhold er utnyttet ved at f. eks. kiselgur og vulkansk aske (pussolan og trass) er blitt anvendt til støpearbeider i forbindelse med vanlig Portland cement. Enkelte industrielle avfallsprodukter som slagg og flyaske gir tilsvarende virkning.

I den senere tid har det vært gjort store framstøt spesielt i amerikansk forskning for å klarlegge fullt ut virkningen av disse stoffer (1). Ved A/S Fiskaa Verk, Kristiansand, fåes som biprodukt et stoff som kan betegnes som en flyaske. Kjemiske analyser viser et innhold av SiO_2 på 80—90 %. Av andre bestanddeler kan nevnes ca. 5 % Fe_2O_3 og ca. 7 % C. Det finnes ikke Ca og ikke S i stoffet. Stoffet er uhyre finkornet. Ved betraktning i mikroskop viser det seg at hovedmengden av stoffet består av kuleformede partikler av størrelsesorden 0,3 µ. Disse kuler klumper seg sammen i løse baller av størrelsesorden 10—12 µ. For å gi et inntrykk av størrelsesforholdet mellom SiO_2 støvet, cementpartiklene og de fineste partikler av vanlig støpesand er vist mikrofotos av de tre stoffer. Samtlige stoffer er siktet gjennom sikt med maskevidde 88 µ (4900 masker pr. cm²). Mikroskopets forstørrelse var 1000 x,

History

- Immediately before 1950, the first trial “production” underway in Norway, using very improvised techniques to collect the silica fume.
- Then investigations were initiated at the Norwegian Technical University in Trondheim and in the tunnels of the Oslo subway.
- The tests involved lab tests and marine field exposure in Trondheim and exposure in extremely aggressive environment in the subway tunnel dug through alun shale, adjacent to the Norwegian Parliament in Oslo.

Sulphate resistance – start of field test in Oslo, Norway 1952

- **Location: the tunnel "Blindtarmen" (the Appendix) – side tunnel in the Oslo subway system**
- **Acidic sulphate-containing ground water, known to be harsh to concrete**
  - **Due to alum shale – a sulphur-bearing rock common in the area**
- **A number of prisms 10*10*40 cm with different compositions, a.o.**
  - **OPC**
  - **OPC with 15% slag replacement**
  - **OPC with 15% silica fume replacement**
  - **SR cement**
- **Test went on for 30 years with inspection at regular intervals**
- **First thorough examination was after 12 years of exposure**
  - **Concrete specimens examined with standard methods vs sulphate attack**
  - **The report concluded: "Replacement of some of the Standard Portland Cement with the very fine grained silica dust showed to be very favourable, possibly due to its pozzolanic action"**
- **Results after 30 years exposure have not changed this conclusion**
  - **However, the reference-concrete specimens are gone long time ago**

The late 1960s: Renewed interest in silica fume-concrete

- **Although Prof. Bernhardts result were well known amongst concrete academics in Scandinavia, silica fume was not available in significant quantities, and little follow-up work was done in the next decade**
- **However, in the mid 1960-ies the first industrial filters were installed in Scandinavia and North America**
- **The increased availability of industrial quantities of silica fume initiated a new wawe of research of silica fume in concrete**
- **Prof. A. Markestad at the Norwegian Institute of Technology started a research programme, which included a number of student projects**
  - **Compared silica fume-concrete with OPC reference, several properties**
- **The results were published in a Nordic seminar in1968, where he concluded:**
  - **Well cured samples (14-28 days at 20 ^{o}C) exhibit ” partly remarkable improvements. This applies largely to all properties investigated such as bending – and compressive strength, permeability, water absorption, sulphate resistance and frost resistance”**

The 1970-ies: early commercial sales and increasing R&D

- The encouraging test results with silica fume in concrete resulted in Norway in a joint project between a cement producer and the ferroalloys industry
  - Purpose was to study if there was a basis for joint commercialization
  - However, a possible conflict area also became apparent
    - silica fume could be used for cement replacement in RMC
- Sales to the concrete industry started in Norway in the early 1970s
  - Main use was as cement replacement in concrete products (k = 3)
  - Existing standards limited use in structural concrete
- First known documented use in structural concrete was a silo roof slab cast in 1971 at the Fiskaa plant in an environment with corrosive gases
  - Half with OPC (320 kg/m^3), half with silica fume, 10% cement replacement
  - Evaluation after 7 years by the Norwegian Building Research Institute comparing the OPC-concrete with the silica fume-reference showed
    - 10-15 mm reduction in cover thickness
    - Double carbonation depth

International work 1970 - 1980

- Although much of the early (documented) development work was done in Norway, from the mid 1970-ies projects and R&D started in many countries
- *Sweden*:
  - Lars Johansson documented basic properties of silica fume-concrete (1975)
  - Gothenburg (1976 – 1978): two wharves were constructed with different concrete compositions, with and without silica fume
    - Exposed to chlorides
    - Follow-up report after 23 years exposure concludes with a ” dramatic effect of silica fume on the resistance to chloride penetration ” (Fidjestøl and Justnes, 2004)
- *Denmark*:
  - Hans Henrik Bache (Aalborg Portland) invented his DSP material
    - “Densified Systems containing homogeneously arrange, ultrafine Particles”
    - Utilizing particle packing concept with silica fume as the finestparticles
    - Demonstrated mortar strengthin the order of 250-300 MPa
  - Sellevold et al: comprehensive documentation of microstructure of silica fume-cement pastes

International work 1970 – 1980 (continued)

- ***Iceland*:**
  - **Severe ASR problems due to high-alkali cement combined with reactive aggregates**
  - **Comprehensive studies with different pozzolanas in the 1970-iess**
  - **Started using 5% silica fume in all cement from 1979**
    - **A follow-up study by Gudmundsson and Olafsson in 1999 concluded that ”After 20 years of service there are no signs of ASR in this concrete in Iceland”**
- ***USA* and *Canada*:**
  - **Both countries have significant ferroalloys industry, and developed filtration technology and installed filters in parallel with Scandinavia**
  - **Several universities and institutes studied silica fume in concrete in the late 1970-ies (e.g. Sherbrooke, Purdue, Berkeley)**
  - **Little published before 1980**

How the industry has developed
Metal production

- Silica fume results from the production of ferro-silicon and silicon
- >99% of the silica fume volume will not be produced unless the metal market is viable
- 70’s and early 80’s, metal production mainly in Norway, France, USA and Canada – with furnaces also in many other countries, South Africa, Russia etc.

International work 1970 – 1980 (continued)

- ***China***
  - **A quite large ferroalloys industry had been established**
    - **Most furnaces were small and not equipped with filters**
  - **In 1976, a semi-closed furnace with baghouse filter was installed in the Hunan province**
    - **It is not known if the silica fume from this furnace was used for concrete**
  - **Generally, it is first in the last decade that significant silica fume has been used in concete in China**
- ***Japan*:**
  - **Japan had a noticeable production of ferrosilicon and silicon in the period**
  - **Silica fume was filtered and offered commercially by companies such as JMC, Osaka Special Alloy, Toyo Denka and Yakushima Denko**
    - **The quantity was limited, probably < 20,000 tpy**
  - **Research on silica fume was going on**
  - **Shimazaki filed in 1971 a patent for a waterproofing of concrete based on fume from ferrosilicon production**
    - **An application still used in Japan today**

History -

- **Commercial use facilitated after the development of bag filter systems that allowed industrial scale collection and near 100% removal of particles from the furnace exhaust gases. This happened in the 70's and already around 1980 the Norwegian silica fume consumption was 50-60 000 tons.**
- **Global use increased, with focus on (Scandinavia), USA, Canada and France. Intense and widespread research was performed, by today there are several thousand of literature references.**

From 1980 and beyond

- **From 1980 and onewards there was virtually an exponential growth of research, published reports and papers related to silica fume in concrete**
  - **By 1985 we had registered about 500 reports and papers in our files**
  - **The number of publications is today probably approaching 10,000 Our library >5000, 3000 waiting**
- **Silica fume has come in common use in a majority of industrial countries and many developing countries**
  - **Silica fume has since long been an international tradeable product**
  - **It is estimated that over 10 million m^3 silica fume-containing concrete is cast every year**
- **Whereas the early years had a focus on silica fume as cement replacement, the overwhelming use today is to improve durability and strength**
- **Heavy investment in new ferroalloys capacity in China should warrant for a good supply situation in the coming years**
- **Solar quality silicon production can also have effect on supply**

History further

- Much of the technical knowledge of silica fume in concrete has been summarized in reports,
  - ACI and fib are key documents.
- The ACI report is fairly well updated and a new version was released in the summer of 2006.
- The fib-report is 20 years of age, and an update is in the works.
- Today, an estimate gives more than 15 million m^3/year silica fume concrete produced globally, and the accumulated volume must by now have exceeded 200 million or more m^3.

Metal production

- Currently metal production moving to China and other localities of inexpensive energy (and labor)
- Status metal industry:
  - Alloy consumption increasing
  - Shift in production locale
    - In particular for bulk ferro-silicon
  - Silicon alloys
    - Increasing amounts for specialist applications, Electronics, Chemistry and solar power

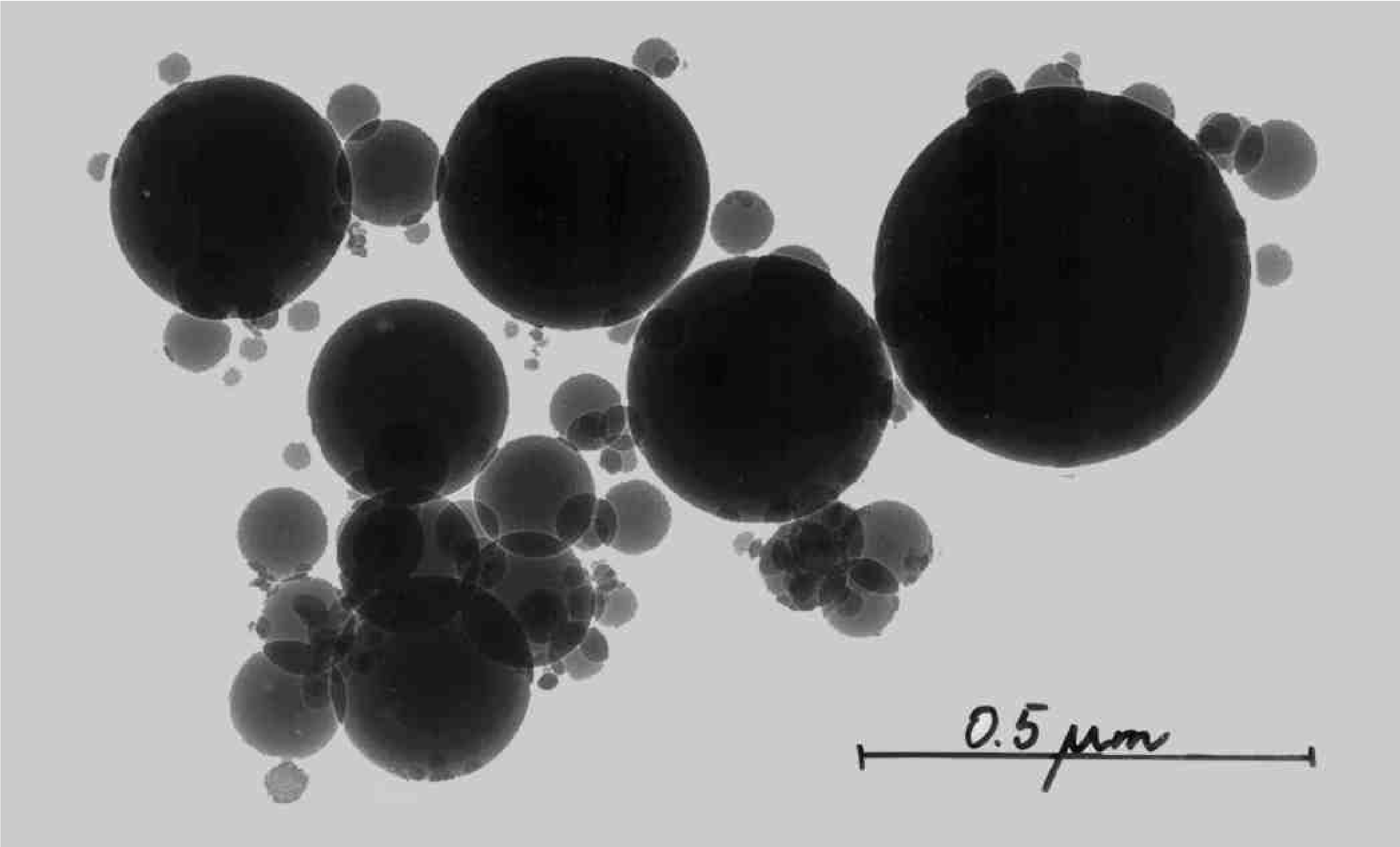
Important properties of silica fume

- **Particle size**
  - **25% of the particle volume less than 100 nm**
  - **50% of particle volume less than 150 nm**
  - **Specific surface (BET) typically 20 m^2/g (range 15-30)**

- **Spherical, solid particles**

- **Chemistry**
  - **> 85% SiO_2 – amorphous**
  - **Some aluminium oxide, iron oxide and alkalies**

Microsilica particles, TEM



Very light and difficult to handle

PSD – Silica Fume

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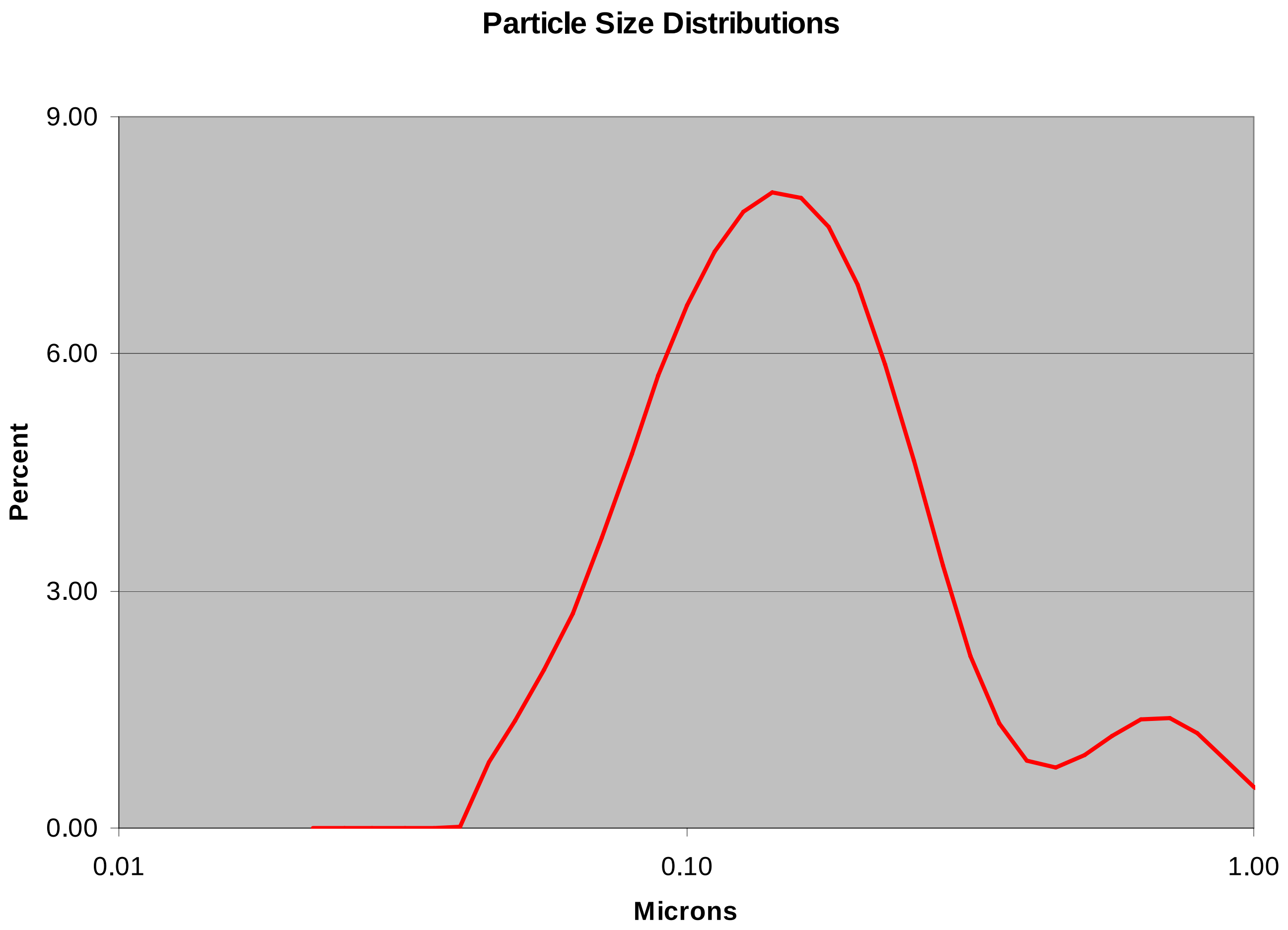

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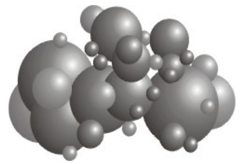

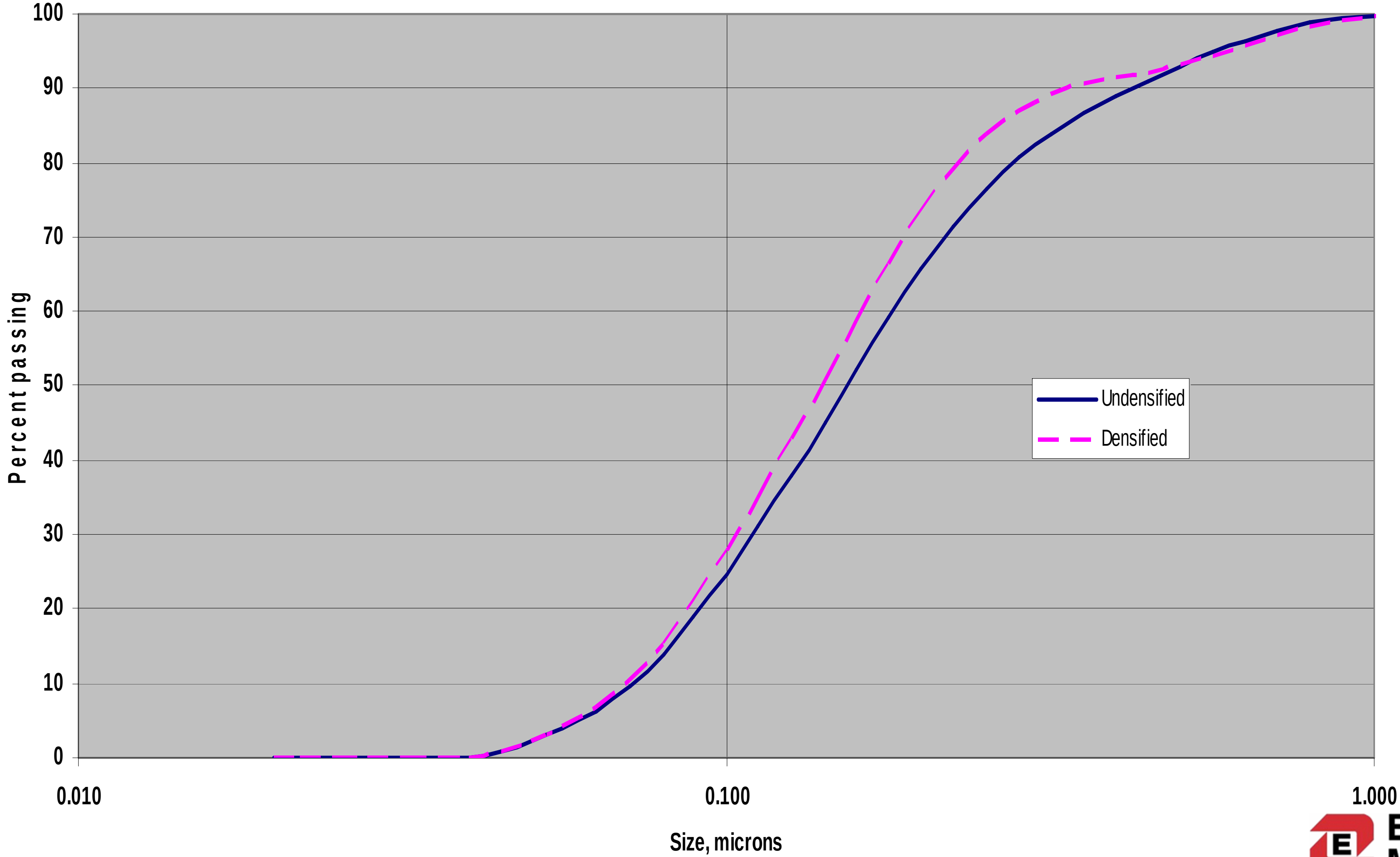

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Particle Size Distributions

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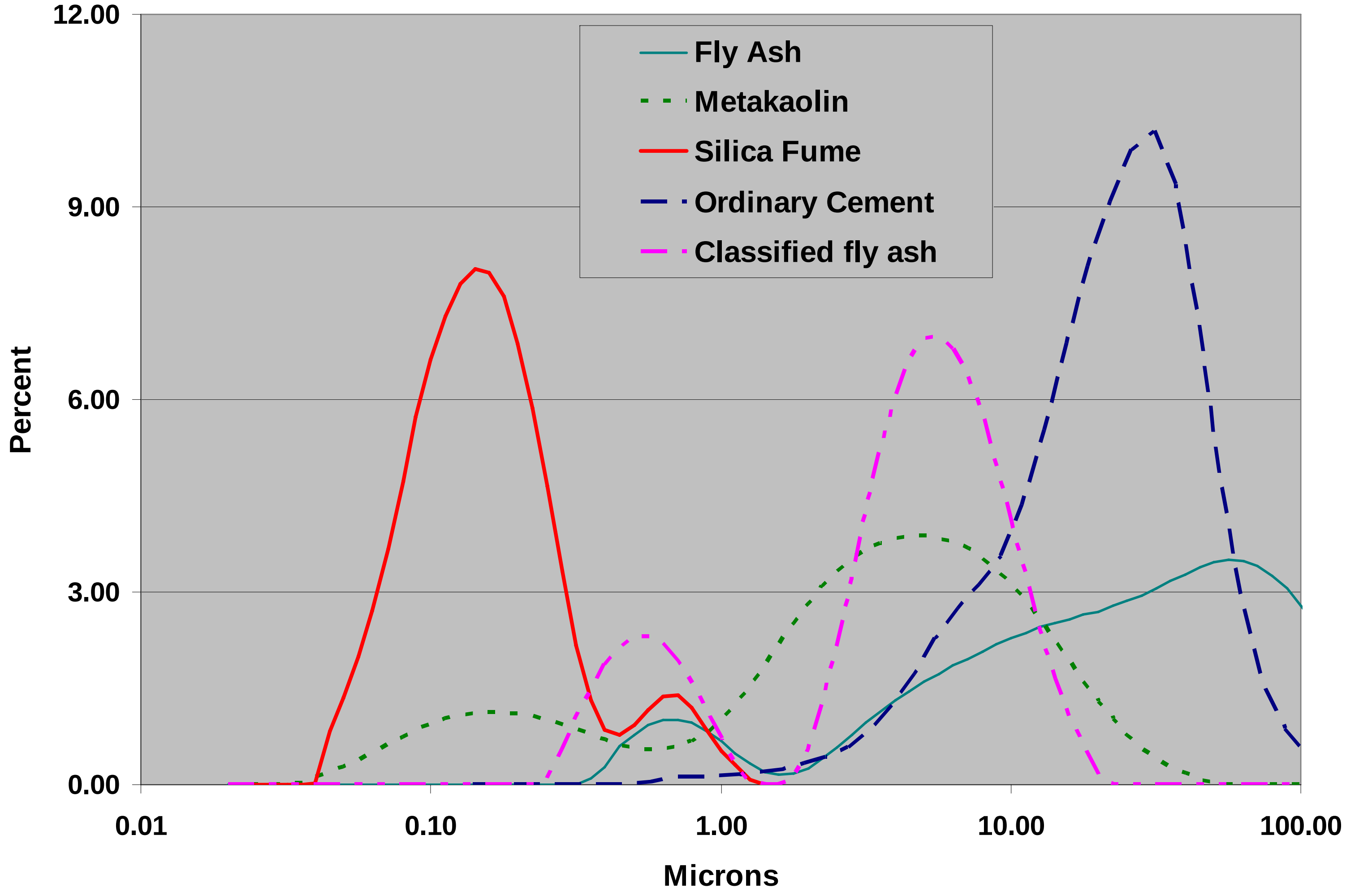

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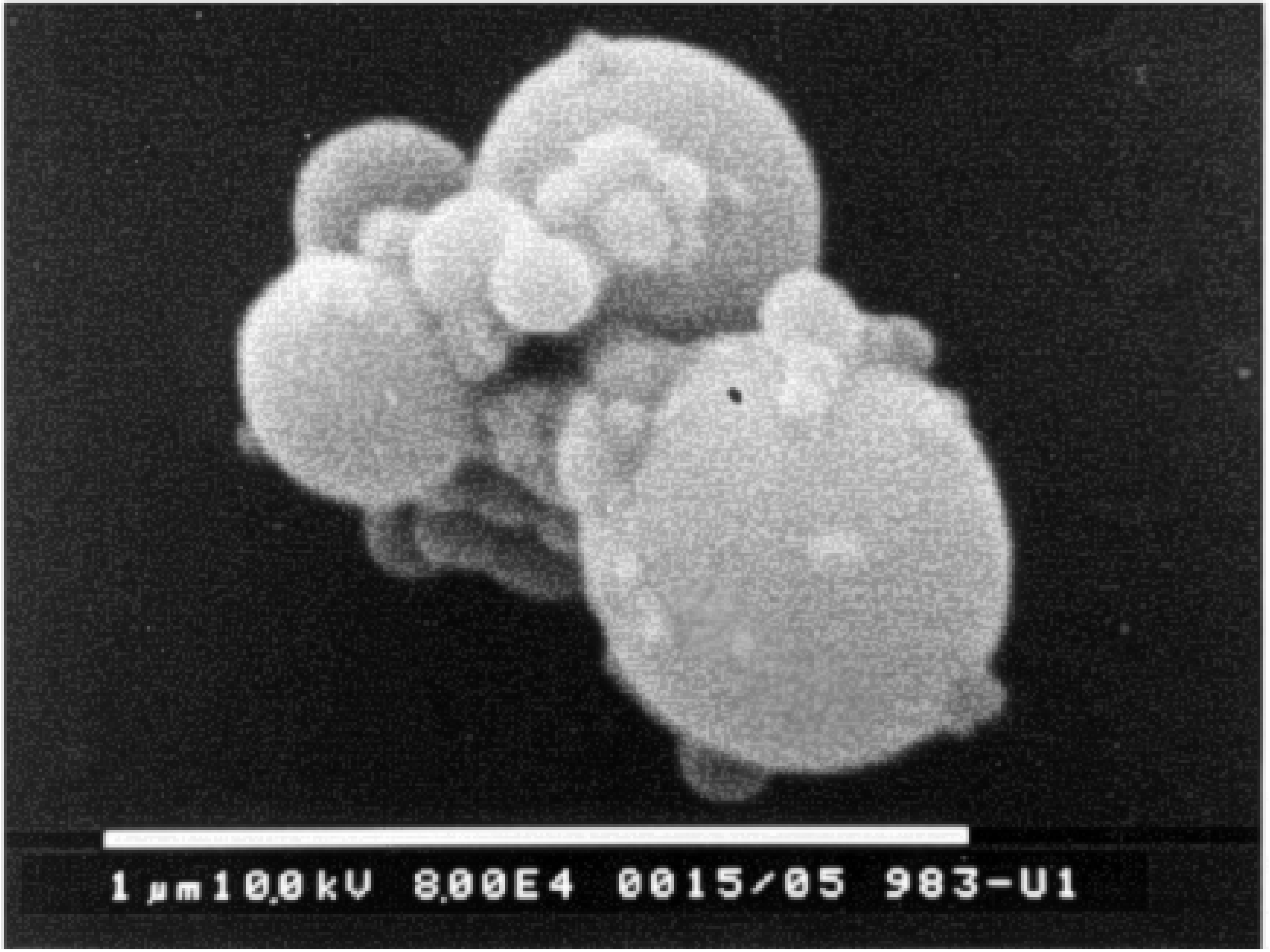
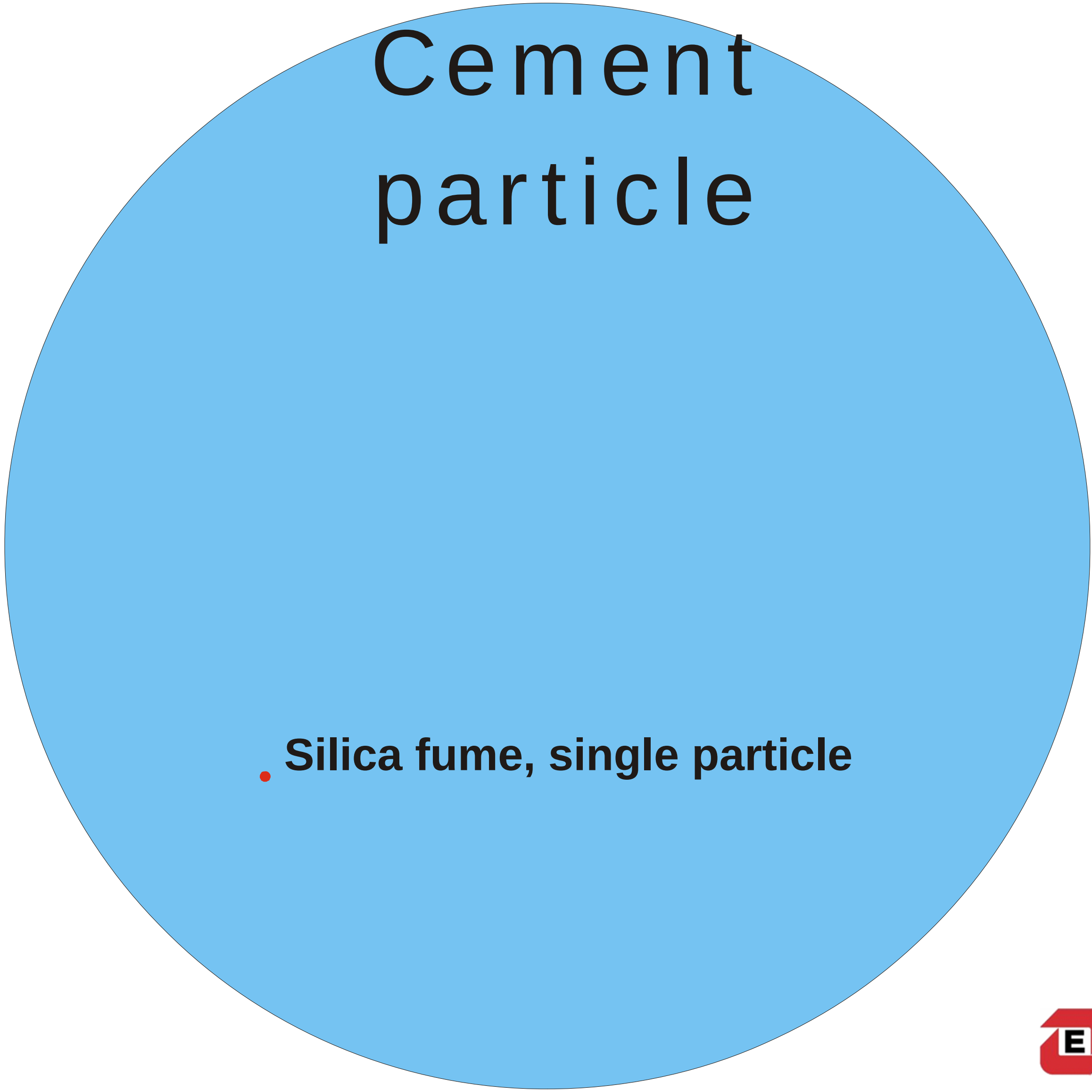
Microsilica particles, SEM



Actual size comparisons



Challenges of using silica fume

- **Dispersion**
  - **Slurry an advantage**
  - **Densified needs mixing energy**

- **Lack of bleedwater requires care with curing**
  - **Make curing part of bid**

- **The execution of the structure must be as good as the material**
  - **Quality systems and control**

What has been learnt (short version)

- A competent labor crew can place concrete with silica fume without real problems
- For high performance concrete, silica fume is a tool that can be applied for:
  - Shotcrete
  - Chloride resistance
  - Sulfate resistance
  - High strength
  - Abrasion resistoance
  - ASR
  - Heat of hydration
  - Underwater concrete
  - SCC
  - Pumping aid
  - Corrosion resistance
  - ……………………..

However:

- Silica fume required formal basis for the use.
- How has it been solved historically:
  - Project specifications
  - National standards
  - National guidelines
  - Guidelines from associations
  - Authority or regional specifications

Early years

- Norway allowed up to 8% (later 10) by weight of cement in structural concrete already from late 70's.
- In several countries the "typical" chemical composition of a "well-known" silica fume was used as material specification.
- Turnaround came with the introduction of the Canadian Standard in 1987.
  - This year also ACI published its first attempt at a report on silica fume,
- A number of countries including Japan, Australia, France, Brazil etc. have developed standards that a very important for the local use of silica fume

Canada deserves a special mention

- CANMET interest in supplementary cementing materials meant Canada pioneered the development of standards.
  - CAN/CSA A23.5-M86 Supplementary Cementitious Materials, was the first comprehensive national standard that also covered silica fume.
- The standard gives clear evidence of its parentage – the fly ash standard was inspiration to the structure and content of the silica fume standard.
  - This made the standard a mixed blessing, particularly to suppliers: On the one hand the standard opened for a broader use of silica fume – on the other hand a number of requirements present then, some of them still, are more suited to fly ash material than to silica fume.
- Being first, the Canadian standard gained popularity on a global scale, and several major projects in Asia used this standard, at least until ASTM or national standards were available.
  - The current revision of the requirements to silica fume is found in A3001-03 Cementitious Materials for Use in Concrete.
- Today, outside Canada, only Hong Kong is a regular user of CSA when specifying silica fume. There they will probably move to EN shortly

USA - ASTM

- ASTM – gives standards for materials in USA.
  - (Actually the official name is now ASTM International.)
- ASTM C1240 was published first in 1993.
- The ASTM standard has been revised almost annually, moving it more away from its fly ash heritage.
- An important change is the use of constant water/cementitious ratio for determination of pozzolanic activity index.
  - Several other national standards that have been modeled on ASTM still use a procedure where flow is adjusted by addition of water in stead of using a high range water reducer.

- Activity is ongoing to improve the reference method for SiO_2 content

Norway

- Standard Norge – the Norwegian body for standards -- called a committee to commence work a Norwegian Standard in 1989.
- The purpose was to have a National document to propose as the draft of a future European (CEN) standard.
- NS 3045 was published in 1992, and submitted to CEN (Comité Européen de Normalisation/European Committee for Standardization) for development into a European Standard.

Europe (CEN)

- Standards development for the European construction industry is governed by the Construction Products Directive (89/106/EEC) from the Commission.
  - In short, products used in structures shall be covered by a harmonized standard or by a European Technical approval.
- For silica fume, a Working Group (WG9) was established under the committee for Concrete and Related Products (TC 104), the group that is responsible for EN 206, “Concrete - Part 1: Specification performance, production and conformity”.
- For various reasons, not of technical nature, the development of the standard took a very long time, and EN 13263 “Silica Fume in Concrete” was only published in 2005.

Summary table (available on Internet)

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Mandatory chemical and physical requirements	American ASTM C1240 – 04	European EN 13263:2005	Canadian CAN/CSA A23.5 - 98	Japanese JIS A 6207 2000	Chinese GB/T18736 -2002	Brazilian NBR 13956:1997	Korean KS F 2567 2003	Vietnamese TCXDVN 311 - 2003	Indian IS 15388:2003
SiO_2 (%)	> 85,0	> 85	> 85	> 85	> 85	> 85	> 85	> 85	> 85,0
SO_3 (%)		< 2,0	< 1,0	< 3,0			< 3,0		
Cl (%)		< 0,3		< 0,1	< 0,2		< 0,3		
Free CaO (%)		< 1,0		< 1,0					
MgO (%)				< 5,0			< 5,0		
Free Si (%)		< 0,4							
Available alkalis (Na_2O equivalent, %)	Report					< 1,5			< 1,5
Moisture (%)	< 3,0			< 3,0	< 3,0	< 3,0		< 3,0	< 3,0
Loss on Ignition (%)	< 6,0	< 4,0	< 6,0	< 5,0	< 6,0	< 6,0	< 5,0	< 6,0	< 4,0
Specific surface (m^2/gram)	> 15	15 - 35		> 15	> 15		> 15		> 15
Bulk density, undensified	Report								
Pozzolanic Activity Index (%)	> 105 @ 7d, accel. curing	> 100 @ 28d, std curing		> 95 @ 7d > 105 @ 28d, std curing	> 85 @ 28d, std curing		> 95 @ 7d, accel. curing	> 85 @ 7d	> 85,0 @ 7d, 27 ^{0}C curing
Retained on 45 micron sieve (%)	< 10		< 10			< 10	< 5,0	< 10	< 10
Variation from average on 45 micron sieve (%-points)	< 5								< 5
Density (kg/m^3)	Report								
Autoclave expansion (%)			< 0,2						
Foaming			No foam						
Dry mass (%-points deviation from declared in slurry)		< 2					< 2		
Water requirement ratio (%)					< 125				

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Application standards

- **Example EN206**
  - **Allows the use of silica fume according to EN13263**
  - **Max amount of silica fume that can be included in calculation of w/cm and cement content is 11% of total cementitious.**
  - **Mostly an efficiency factor of 2 can be applied to silica fume (fly ash typically 0.4)**
    - **1 kg of silica fume can be set equal to 2 kg of cement**
    - **w/cm= c/(w+k*sf)**
    - **K=2 for silica fume**

Other important reference documents

- ACI Committee 234, provides guidance on the use of silica fume in concrete.
  - The committee report has recently been revised and is published as ACI 234R-06, Guide for the Use of Silica Fume in Concrete
- fib, federation internationale du beton,
  - in its previous incarnation as FIP, published a report called “Silica Fume in Concrete” in 1988.
  - This document is currently (2008) under revision in order to accommodate the huge volume of information generated since the original publication.
- SFA -- Silica Fume Association –
  - operates a web site (www.silicafume.org).
  - They have published a manual, “Silica Fume User’s Manual”, intended for the practitioner using silica fume.

How will the standards develop?

- CEN
- ASTM
- ISO?
- Others
  - Canada
  - Japan
  - China
  - Australia
  - Still others

- There is movement many places ~hopefully harmonization will result

Where do we, the producer, want to go

- **As simple a standard as possible**
- **No requirement tied to concrete performance**
  - **Sulfate, ASR, etc…….**
- **Remove metallic silicon requirement**
  - **This is not necessary. The one incident reported was in an extremely special application – and the silica fume was heavily contaminated**
- **Chlorides:**
  There should not be a requirement beyond reporting – it is the content of the concrete that isimportant
- **Pozzolanic activity index: Unfortunately needed by engineers**
- **Oversize: remove (procedure is a travesty)**
- **Better procedure for SiO_2-determination (XRF?)**

Some highlights of silica fume use

- **Prices:**
  - **Initial price meant cement replacement very cost effective**
  - **Today, mainly pay for performance**
- **Availability**
  - **Increasing total volume available**
  - **Demand increasing**
  - **Geographical shift in production**
  - **Logistics bottlenecks can give local scarcity**
  - **Quality issues on the increase**

  - **Metal production fickle – downturn in world economy can reduce production**

Example – changing world

- Norway 1980
  - Cement replacement
  - Low cost
  - 60 000 tons or more consumption
- Norway 2006
  - High performance concrete and mortar
  - High cost
  - Consumption 17 000 tons per annum
- From cement replacement to high grade addition

Volumes versus other SCM's

- Silica Fume theoretical 1.5 million tons, less than 1 million tons used, limited growth, maybe 2 Mtons theoretical in future
- Fly Ash availability > 700 million tons, increasing rapidly to?? (2000 million tons in 2020?)
- Other pozzolans:
  - Mainly manufactured materials – limited by capacity
- GGBS 200 million tons?
  - Limited increase – tied to steel production

- Cement >2200 million tons, growing at 7?% pa

Key factors

- **Sustainability**
- **CO_2**
- **National and international regulations**
- **Economic growth in China, India + SEA**

- Concrete is an essential part of industrial societies – the question is how?

Some examples

As time permits, some examples of where we are

Highrise

- 3 grades of strength
- Same formwork and layout throughout the structure
- Fasttrack construction
- Reduced column size

311 South Wacker Drive, Chicago

Petronas Towers, Kuala Lumpur

- Columns: Grade 80
- Beams: Grade 60
- Pumped 88 storeys high
- Triple blend: OPC/pfa/microsilica

Burj Dubai / Dubai Tower

- **350 000 m3 high strength concrete (80 and 60 MPa spec)**
- **Pumping all the way – single stage**
- **Ternary blends – PC/FA/SF**

Emirates Towers, Dubai

Hotel (309 metre) and office (355 metre) skyscrapers

• >80 MPa microsilica concrete

Large Infrastructure

Great Belt, Denmark

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The Øresund bridge

The Øresund Bridge - a high bridge and two approach bridges - total length 7845 m.

The high bridge has the longest cable-stayed main span in the world for both road and rail traffic.

Length of high bridge: 1092 m
Main span: 490 m
Passage height: 55 m
Height of pylons: 204 m

East approach bridge: 3739 m
West approach bridge: 3014 m

Tsing Ma bridge, Hong Kong

- Ternary blends
- 120 years
- >80 MPa

Tsing Ma bridge - built to last !

East Sea Bridge, Shanghai

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- Total length 32.5 km，
- including over-sea part,

harbor & bridge connection part and on-land part

East-Sea Bridge

Box girder precast yard

Cantilever bridge

East Sea bridge

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Nordhordland bridge, Norway

- LWC
- Floating pontoons
- LWC in bridge deck
- 1900 kg/m^3
- 60-70 MPa

Offshore – Troll platform

Troll platform

Troll A is 472 meter high and is the largest moveable structure ever built.

At tow-out it weighed 1,2 million MT. 245 000 m^3 concrete and 100 000 MT reinforcement steel (about 15 Eiffel-towers).

The structure operates in 303 meter water depth.

Offshore structures in the North Sea

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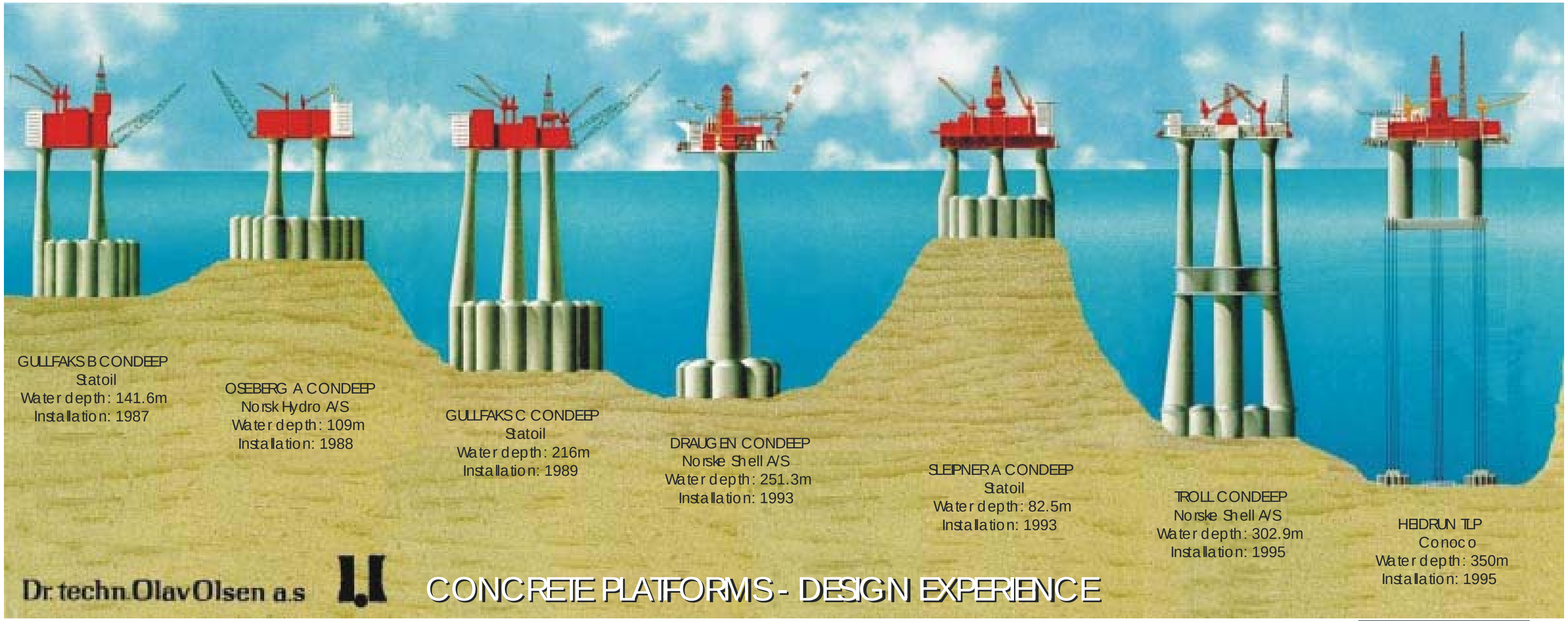

Silica fume used for pumpability and stability!!

Up to 14% reinforcement

Dams, Hydropower

Kinzua dam Stilling Basin, NY
Stilling basin repair
Still in good shape after 24 years

Alta Dam, North Norway
Reduced heat of hydration

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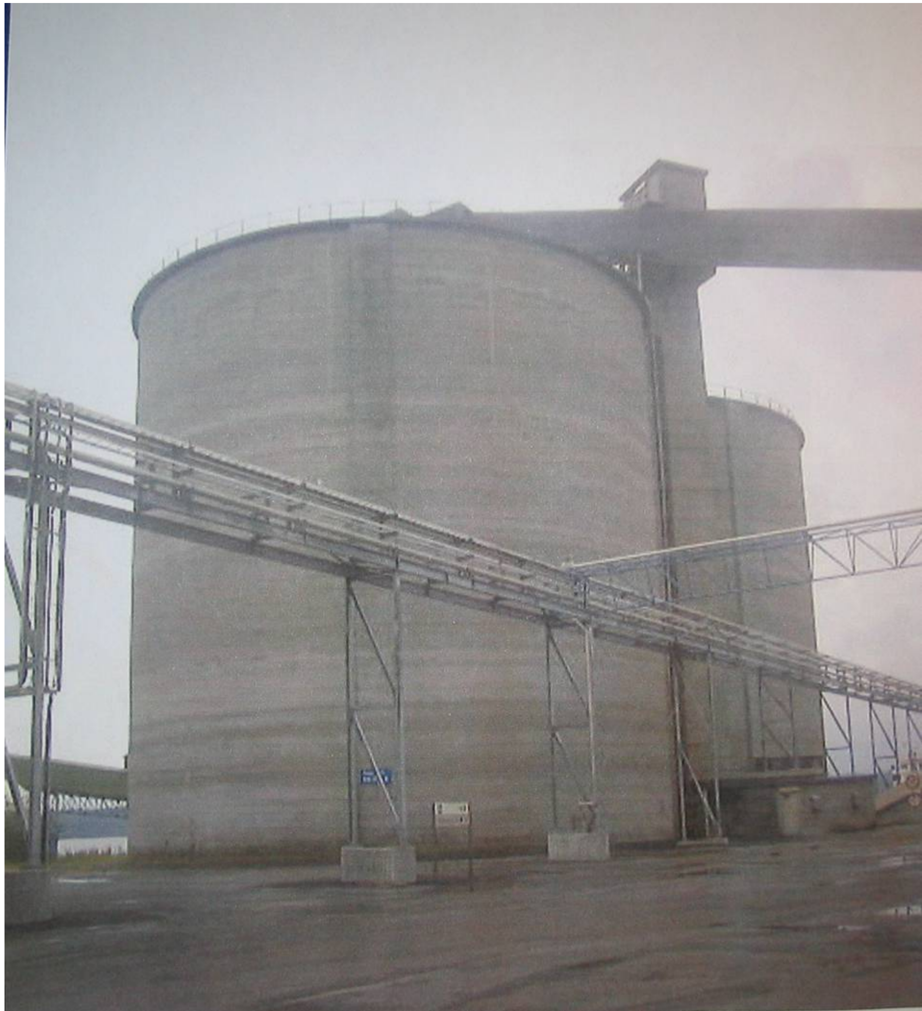
Storage silos, fertilizer
Hydro, Porsgrunn, Norway

- **Early 1970's application**
- **Calcium Nitrate**
- **Silica fume used in proprietary product**



Fiskebæk Bridge, Copenhagen

- Eksperiment with dividers
- Up to 50% silica fume bwo cement
- Excellent performance
- Condition reported

Bandra Worli, India

The Bandra Worli Sealink Project, currently under construction (to be finished in 2005), is a major precast, segmental concrete bridge traversing the Mahim Bay and Arabian Sea to connect the city and the western suburbs of Mumbai, India.

The bridge features a two-span 500 metre long cable-stayed bridge with approximately 3000 metres of approaches. The superstructure for the cable stayed span and approaches consists of twin precast segmental box sections supporting 4 lanes of traffic in each direction.

HPC volume: approx. 200 000 m^3

Stolma Bridge, Norway

World record span for free cantilever bridge, 301 m, when built
70 MPa LWAC (1940 kg/m^3) in main span

Scrapyard near London

- **Problem Conventional concrete**
  - **350 mm deck wore away after few months (300 mm/year)**
  - **then 1 month close-down for repairs**
- **Solution**
  - **High strength microsilica concrete**
  - **5-10-20 (?) times life time**

Scrap handling facilities

- By experience, a huge increase in lifetime of floors and decks exposed to abrasion:
  - Coal and other bulk-handling facilities
  - Scrap yards
  - Marshalling yards for heavy civilian and military equipment
  - Storage facilities
  - Warehouses

Now, microsilica concrete shows wear abt. 20 mm/yr,
i.e. lifetime of at least 10 years.

Nuclear plant Dome, Kaiga

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Dubai Airport

Microsilica concrete extensively used for durability reasons in sub-terrain concrete and in high-strength structural concrete elements in the extensions of the Dubai airport (2 million m^3)

Burj Al Arab Hotel, Dubai

World’s tallest (321 metre) and most luxurious hotel (7 stars)

- >80 MPa microsilica concrete (400 kg cement + 10% microsilica)
- Chloride permeability < 500 coloumbs

Use of silica fume, general

- Four main applications
  - Concrete
  - Refractory materials
  - Fiber cement (non-asbestos)
  - Oil well cementing

- Global volumes (guesstimate)
  - Concrete 500 000 tons
  - Refractory 100 000 tons
  - Fiber cement 100 000 tons
  - Oilwell <50 000 tons

About standards

- **Many of the structures shown were built before standards were available or without those currently in place**
- **All adhered to high (85%) SiO_2 and high specific surface (>15 m^2/g)**
- **Future challenges**
  - **Resist pressure to accept substandard material as silica fume**
  - **Develop guide on off-spec material and other pozzolans**

Closing words

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- The use of SCM's are increasingly relevant
  - High performance
  - High strength
  - Sustainability
- Standards should be developed with an eye to promoting their use where appropriate
- Application standards included in this concern
- Future includes
  - Fine natural pozzolans
  - Various clay minerals
  - Ash from biofuel processes
    - RRHA
    - Bagasse?
    - Other
  - "Waste" from other industrial processes
    - Ground glass
    - Mineral processing
    - Other ground slags

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On CO2

- Processing CO_2 must be accounted for
  - Calcination
  - Milling
  - Shipping/handling
- Total CO_2 of structure used must be focus
  - Construction often 10% of total
  - Balance against urgency of rapid reduction
  - Do not loose long term performance in search for early performance

It will be interesting

Thank you for your attention