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SILICA FUME IN CONCRETE
- AN OVERVIEW -

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Silica Fume has been used as one of the useful mineral admixtures for these 10 years in Japan. However, the physical and chemical properties of silica fume, especially in Japanese market, is still unclear. On this viewpoint, this paper deal with the characterization of silica fume as a construction material, the effect of silica fume on the properties of flesh and hardened concrete including concrete durability and applications of concrete containing silica fume. The author expects that this paper can provide some available information to engineers and researchers who are rested in silica fume.

Keywards: *silica fume, characterization, dispersion and agglomeration, fresh concrete, hardened concrete, durability of concrete, field application.*

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1. Foreword

Concrete structures have conventionally been considered highly economical, completely flexible in shape, and even maintenance-free. In recent years, however, various deteriorations have emerged in concrete structures, which are now requiring maintenance or even demolition and rebuilding before reaching their specified ages. This is the so-called "early deterioration" problem of concrete structures. Further, not only the structural role but also aesthetic appearances is now required of concrete structures.

With this as a background, the multiple roles of present-day high-performance concrete structures may be categorized as function, strength, and beauty. When expressed in terms of construction materials, this means that to enhance the performance of concrete is to impart greate, strength, durability, and fluidity of placement[1].

Such issues as materials selection, proportioning, mixing, placing, and curing become more important when the performance of the concrete needs to be enhanced. Imparting various capabilities to the concrete by suitably adding chemical and mineral admixtures may be a particularly important technology in this process. The mineral admixtures currently in use with concrete are typically fly ash, ground granulated blast furnace slag (BFS), and silica fume. These are all industrial by-products. The use of fly ash and BFS is already standard and commonly practiced, greatly contributing to environmental protection in terms of effective utilization of resources.

As for silica fume, standards have been established in major producing countries such as Norway and Canada on the basis of numerous studies, and many application examples have been reported. Appropriate standards are therefore urgently awaited in Japan.

This paper focuses on the silica fume available in Japan, and summarizes its physical and chemical properties, the properties of concrete containing silica fume, and examples of construction with such concrete based on recent studies. The aim is to serve as a reference for future study and standardization in Japan.

2. Production and form of silica fume

Silica fume is an industrial by-product collected in dust collectors during the refining of silicon alloys, such as silicon metals and ferrosilicon, which are used as deoxidizing or desulferizing agents at steel mills. It is a powder of ultrafine particles that undergo pozzolanic reaction, similarly to fly ash. Silica fume is referred to in this paper as consisting of "ultrafine particles" since particles less than 0.1 μm in diameter are referred to as ultrafine particles in the field of powder engineering. Silica fume is not supplied in large quantities nor at a low price, since the production of ferrosilicon or other such metals is a highly power-consuming process (see Table 1[2]). Silica fume is also referred to as "silica dust," "silica flour," or "amorphous silica," while "condensed silica fume (CSF)" appears to be the general term in other countries. A typical method of producing a silicon alloy, the main product of the process producing silica fume, is shown in Fig. 1[3]. Silica rock, coal, wood chips, and iron are charged into an arc furnace, where they are fused to refine the silicon alloy. During this process a large amount of SiO fume is generated. This is oxidized and collected in a filter, with the resulting filter cake being silica fume. The silica content in silicon alloys varies depending on the type of alloy and the types and proportions of raw materials. The resulting SiO_2 is reported to vary as given in Table 2[4]. Silica fume may therefore be expressed as Si-CSF (silica fume generated during the production of silicon metal) or FeSi-75-CSF (silica fume generated during the production of ferrosilicon with a silicon content of 75%).

Table 1 Annual Production and Utilization Rates of Siliceous By-products (Tons) (1988, Ref. 5)

	Fly ash x 10^6		Blast-furnance slag x 10^6		Condensed silica fume x 10^3	
Country	Production	Utilization	Production	Utilization	Production	Utilization
Australia	3.5	0.25	4.7	0.12	60	20
Canada	3.3	0.8	2.9	0.2	23	11
China	35	7.2	22	16	None	None
Denmark	1	0.45	None	None	None	None
France	5.1	1.5	10.4	1.9	60	None
Germany (Fed. Rep.)	2.6	2.0	15	2.8	25	None
India	19	0.5	7.8	2.8	None	None
Japan	3.7	0.5	24	8.2	25	None
Netherlands	0.5	0.3	1.1	1	None	None
Norway	None	None	0.1	None	140	40
South Africa	12.9	0.1	1.5	0.6	43	0
Sweden	0.1	0.02	0.1	0.03	10	1
United Kingdom	13.8	1.3	1.5	0.25	None	None
United States	47	5	13	1	100	2

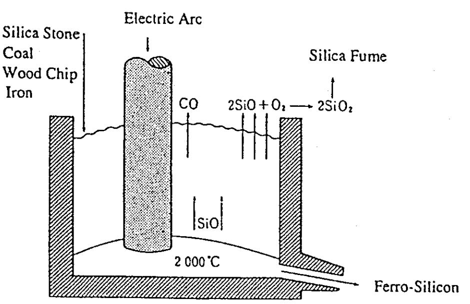


Fig. 1 Typical Production Process for Silica Fume

Table 2 SiO_2 Contnt of Silica Fume

Type of Ferro Silicon	SiO_2 Content of Silica Fume
Silicon Metal (98%)	93 ~ 98%
90% Ferro-Silicon	92 ~ 95%
75% Ferro-Silicon	84 ~ 88%
50% Ferro-Silicon	72 ~ 77%

The amount of silica fume produced is said to be 550 kg per ton of the main product in the case of silicon metal. However, the higher productivity of silicon alloys leads to a lower silica fume yield. The silica fume yield per ton may therefore diminish in the future. Due to the high power consumption of the arc fusion method, silica fume is mainly produced in Norway, the USA, and Canada, where hydroelectric power is available in large quantities at relatively low cost. China and Eastern European countries are potential producers: only requiring collecting devices to produce silica fume. In some parts of China, it is said that silica fume is already being collected and used on a commercial scale. The annual silica fume production worldwide estimated from silicon alloy production is around 1.6 million tons, indicating how rare a material it is compared with other by-product mineral admixtures.

Silica fume comes in three product forms: undensified (powder), densified (granular), and slurry. Some of them include products premixed with chemical admixtures. Granules are said to be produced by high-pressure treatment after being collected, but the know-how is concealed by manufacturers. Most silica fume types are undensified or densified in Japan. Table 3 gives the major proprietary silica fume brands in Japan.

Table 3 Types of Silica Fume in the Japanese Market

Type of Silica Fume	Company	Country	Main Product	Form
ELKEM Microsilica 971	Elkem Japan KK	Norway	Si-Met	Undensified
ELKEM Microsilica 940AGU	〃	〃	Fe-Si(75)	〃
ELKEM Microsilica 940AGU	〃	〃	Fe-Si(75)	Densified
ELKEM Mix Tite	〃	〃	Fe-Si(75)	〃
FESIL FeSi-Silica	Fesil International	〃	Fe-Si(75)	Undensified
FESIL FeSi-Silica	〃	〃	Fe-Si(75)	Densified
HOLLA METAL Silica	〃	〃	(*1)	〃
SCANCEN Micropoz	Anderson Technology	〃	Fe-Si(75)	Undensified
NORCEN Si-Met	〃	〃	Si-Met.	〃
EFACO Silica	Union Chemical	Egypt	Si-Met.	〃
JAPAN METALS & CHEMICALS (JML) CO., LTD.	〃	Japan	Fe-Si(75)	〃
TOYO DENKA KOGYO CO., LTD.	〃	〃	Fe-Si(75)	〃
YAHAGI IRON CO., LTD.	〃	〃	Fe-Si(75)	〃
SKW Fumed Silica	SKW East Asia	Canada	(*2)	〃

(*1) Si-Met. : Fe-Se = 35 : 65, (*2) Blend Ratio is Unknown

3. Historical background of application to concrete

Initially, silica fume was emitted into the air from flues, but was then required to be collected to protect the environment. Its use as a mineral admixture in concrete has been explored since the 1950s. Investigations began in Norway, one of the leading producers of the material, and other Scandinavian countries. The first application was a tunnel in Oslo in 1952, in which 15% of the unit cement content was replaced with silica fume[5]. In the early days of silica fume application, it was used simply to economize the cement mixture. However, the addition of such ultrafine powder to concrete increases the unit water content. Silica fume was therefore not considered to be a good material for concrete, and its applications were limited until the 1960s, when superplasticizers were developed. The use of silica fume in combination with superplasticizers was then proven to yield high strength and high durability concrete. A number of studies have been conducted since the 1970s in Western countries including Canada.

The first standards for quality and application were established in 1976 in Norway (NS-3050). The standards relating to silica fume in major countries are as given in Table 4.

Table 4 Specifications of Silica Fume in Main Countries

Country (or Author)	Canada	Norway NS3098	Denmark DS411	RILEM Mehta	Australia[*2] (proposed)	Deutsch DIN1045	USA ASTM Draft#13	Sweden PFS'85.2
Main Product (max %)	(Si≧75%)							
Chemical Composition								
So_3	1.0	-	4.0	-	-	2.0	-	4.0
L.O.I.	6.0	5.0	5.0	6	6.0	2.0	6.0	5.0
SiO_2	85	85	-	(yes)	85	-	85	-
Moisture	(3.0)	-	1.5	(yes)	-	-	3.0	-
MgO	-	-	5.0	-	-	-	-	5.0
$Na_2Oeq.$	-	-	1.5	-	-	-	1.5	-
Cl^-	-	-	0.1	-	-	0.1	-	0.2
Physical Properties								
Pozzolanic Activity Index	85[*1]	95	-	95	future	100[*3]	85[*5]	-
Length Change by Autoclave Curing	0.2	-	-	-	(yes)	(yes)	-	-
45μm Retained (Max)	10	-	40.0	-	10	1[*4]	10	-
Uniformity of Density (Max)	5	-	-	-	(yes)	-	5	-
Uniformity of 45 μm (Max)	X±5	-	-	-	-	-	5	-
Uniformity of AE Agent (Max)	(20)	-	-	-	-	-	20	-
Drying Shrinkage (Max)	(0.03)	-	-	-	-	-	0.1	-
Alkali-Aggregate Reactivity	(80)	-	-	-	-	-	80	-
Water Requirement	-	-	-	(yes)	-	-	-	-

*1 Replacement Ratio: 35%
*2 F.Papworth "Silica Fume Production and Its Action in concrete" Concrete for the Nineties-Laura, NSW Australia Sept. '90
*3 Replacement Ratio: 15%
*4 63 μm Retained
*5 Replacement Ratio: 10%

It was in the 1980s that silica fume attracted attention in Japan as a mineral admixture for concrete. At that time, the problem of early deterioration of concrete structures began to materialize, leading to increased demand for good-quality, high-durability concrete for constructing new buildings.

In line with this tendency, silica fume began to attract attention as an excellent mineral admixture with a remarkable effect of increasing concrete durability. However, there have been few examples of actual application in Japan, though a number of studies took up silica fume at least on a laboratory level. The reason for this is that it was an expensive material in Japan-- domestic production was mostly substituted by imported products year by year due to the high cost of electric power--and because no standards have been established regarding its quality as a mineral admixture for concrete.

With this as a background, the Japan Silica Fume Technology Associates (JSFTA) was established in 1989 on the notion that silica fume is essential for enhancing the performance of concrete. The establishment of standards regarding silica fume is under way, and is entrusted to the Japan Society of Civil Engineers (JSCE) and the Architectural Institute of Japan (AIJ) by the JSFTA.

4. Physical and chemical properties of silica fume and the current state of research

(1) Physical properties

a) Shape

Silica fume particles, cooled and solidified fused silica in the state of fume, are mostly spherical. The diameter of most particles is less than 1 μm in diameter and is approximately 0.1 μm on average. These particles are normally collected in an agglomerated state, and can be significantly agglomerated at the time of shipping even without condensation treatment. Since these agglomerates comprise mostly particles of several hundred microns, powder and granular products are almost undistinguishable to the naked eye. When observing the primary particles of silica fume through an electron microscope too, powder products cannot be distinguished from granular products, as there is no difference in the production methods up to the time of collection. Typical images of silica fume made by a scanning electron micrographs (SEM) are shown in Photo 1 and 2.

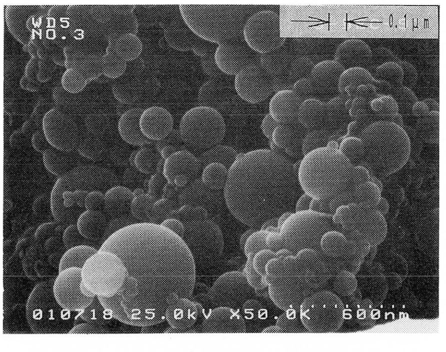


Photo 1 SEM Apparence of Undensified Silica Fume

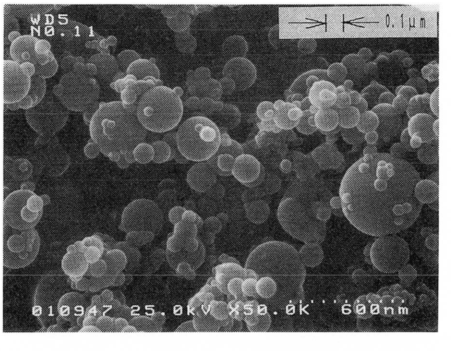


Photo 2 SEM Apparence of Densified Silica Fume

b) Specific gravity and unit weight

According to Aitcin et al[6], the specific gravity of silica fume is between 2.1 and 2.2. These values vary depending on the type of main product; the silicon content in the silicon alloy decreases, the specific gravity of the silica fume increases (Table 5[6]). The reason for this is that the content of SiO_2, the main component of silica fume, decreases, the proportions of K_2O, CaO, and other components increase, increasing the specific gravity.

Table 5 Specific Gravity of Silica Fume

Type of Ferro Silicon	Specific Gravity of Silica Fume
Silicon Metal (98%)	2.23
75% Ferro Silicon	2.21-2.23
50% Ferro Silicon	2.3
FeCrSi	2.42
CaSi	2.55
SiMn	3.13

The unit weight of silica fume depends on its form at the time of shipping. The unit weights of powder and granular silica fume are normally considered to be 80 to 430 kg/m^3 and 600 kg/m^3, respectively.

c) Fineness

Silica fume consists of very smooth, ultrafine and spherical particles with an average diameter as small as 0.1 μm. Its specific surface area is said to be approximately 20 m^2/g, which is 50 to 60 times that of ordinary portland cement. The fineness of silica fume particles may be visualized when it is compared with cigarette smoke, whose specific surface area is around 10 m^2/g.

(2) Chemical properties

a) Chemical composition

The chemical composition of silica fume is mostly SiO_2. It contains several other components, such as carbon, because the raw materials include coal and wood chips. This accounts for the light-gray color. Aitcin et al's diagram of tertiary systems of cementitious materials[6] shown in Fig. 2 reveals that silica fume has an extremely high SiO_2 content compared with other mineral admixtures for concrete.

Typical measurements of chemical components from proprietary silica fumes in Japan are given in Table 6. According to this table, the content of SiO_2, the main component, is considered to satisfy foreign standards for silica fume. However, as regards other components such as equivalent alkali content, not all types satisfy foreign standards[7]. Quality standards should, for this reason, be established promptly in Japan as well. Our research into the correlation between physical properties and chemical composition revealed the following four tendencies:

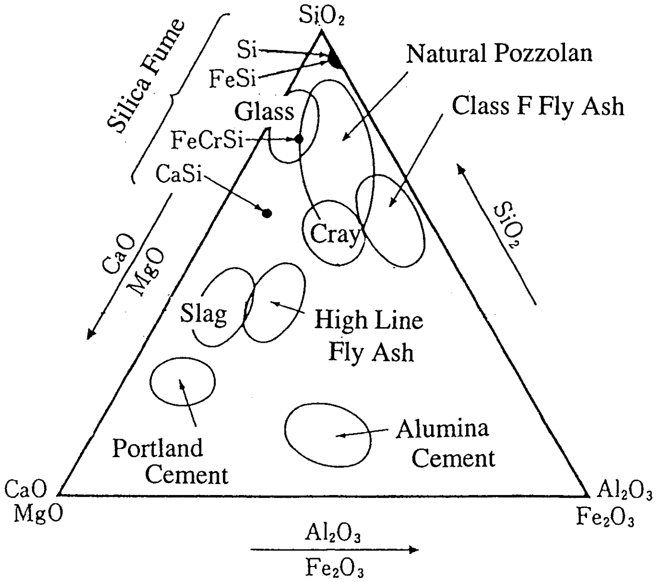


Fig. 2 Characterization of Cementitious Materials

Table 6 Typical Characteristics of Silica Fumes in Japan

Physical Properties			Chemical Composition %							
Specific Gravity (%)	Specific Surface Area	Moist. (%)	Ig.loss	Sio2	Fe2O3	CaO	MgO	SO3	C	Na2Oeq.
2.42	20.5(*)	0.63	1.38	97.5	0.06	0.19	0.29	0.15	0.78	0.53
2.56	19.55	1.25	2.36	93.6	0.36	0.23	0.85	0.26	1.47	1.49
2.50	17.55	1.29	1.98	93.3	1.21	0.16	0.49	0.31	1.00	1.37
2.46	17.73	1.14	2.24	92.7	0.26	0.21	0.71	0.39	1.27	2.04
2.31	20.92	0.23	2.76	90.7	0.75	0.26	1.71	0.53	2.06	2.36
2.29	19.28	0.26	2.62	90.8	0.60	0.23	1.87	0.38	1.63	2.40
2.49	21.77	0.96	1.60	92.7	1.31	0.69	1.55	0.35	0.80	0.86
2.43	17.21	1.02	2.42	90.0	1.37	0.47	1.91	0.41	1.31	2.06
2.40	18.05	0.66	1.96	96.0	0.07	0.22	0.28	0.31	1.58	1.07
2.42	17.85	1.12	2.28	92.1	1.17	0.37	1.60	0.35	1.19	1.48
2.69	17.74	1.03	1.34	91.8	3.13	0.21	0.38	0.78	0.60	1.35
2.66	15.95	1.76	2.26	85.8	1.03	0.61	1.97	0.52	1.58	4.02
2.49	17.64	0.75	2.84	93.6	0.26	0.28	0.29	0.29	3.56	0.67

(*)Unit: m^2/g

(1) Factors correlated with SiO_2: Na_2O, K_2O, and MgO
(2) Factors correlated with ignition loss: carbon
(3) Factors correlated with moisture: specific gravity
(4) Others: factors that do not belong to any factor groups or that are so marginal (less than 1.0%) that no cor-relation is noticeable

Figures 3, 4, and 5 show the relationships between SiO_2 content and equivalent alkali content, between ignition loss and carbon content, and between moisture content and specific gravity, respectively. It should be noted that these tendencies are also found in all silica fume measurements obtained in the past two years.

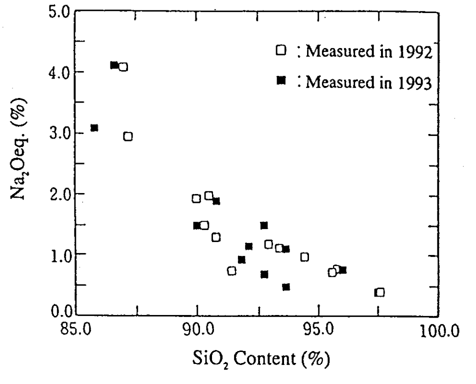


Fig. 3 Relation Between SiO_2 Content and Na_2O eq.

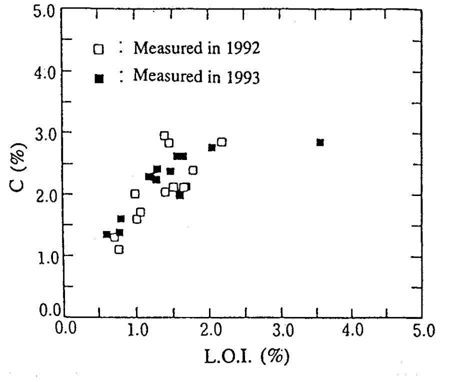


Fig. 4 Relation Between L.O.I. and C

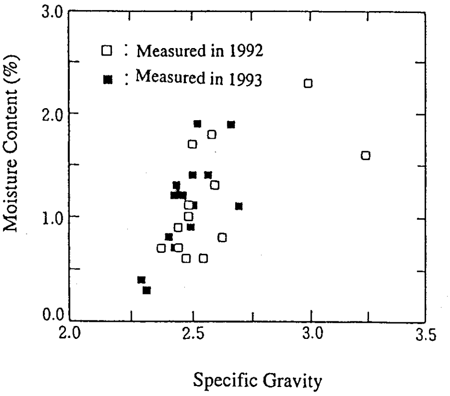


Fig. 5 Relation Between Moisture Content and Specific Gravity

b) Crystal structure

The state of crystallization of a substance is generally judged by means of X-ray diffraction[8].

Regular atomic arrangements of crystalline substances cause X-rays to diffract, producing peaks at certain diffraction angles. In the case of noncrystalline substances, irregular atomic arrangements scatter X-rays, resulting in smooth curves without peaks. Typical X-ray diffraction results are shown in Fig. 6. These results reveal that silica fume has a wide scatter near $2\theta = 22^\circ$ with no peaks that indicate crystallinity. Consequently, silica fume can be categorized as noncrystalline. Figure 6 also shows up a phenomenon referred to as "small angle scattering" (large scatter at small angles less than $2\theta = 10^\circ$). This phenomenon occurs when there is a nonuniform structure of 20 to 30° or more in the substance, independent of its atomic arrangement. This suggests microscopic nonuniformities in silica fume.

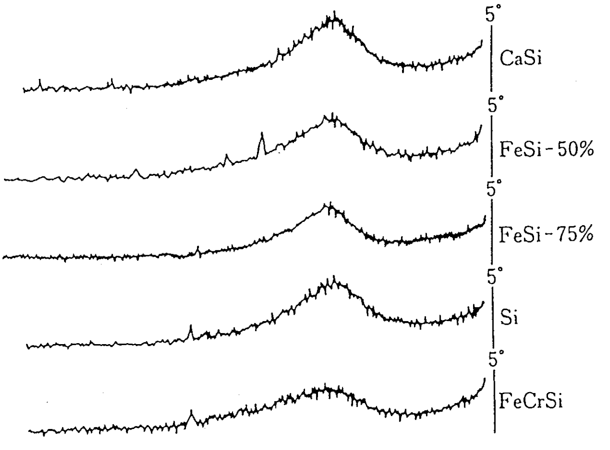


Fig. 6 Examples of Measurement Results for Silica Fumes by XRD

(3) Measurement technology for physical properties

a) Specific gravity

Over the past two years, the authors have measured proprietary silica fume brands in Japan using an autopicnometer. As a result, the range of specific gravity of silica fume in Japan was found to be from 2.3 to 3.0, and in one instance 3.24. This suggests that the specific gravity of silica fume in Japan tends to be slightly higher than that in Europe and America. A recent study [9] incidentally pointed out that specific gravity of silica fume can fluctuate depending on the method and conditions of measurement. Also, as stated above, the specific gravity of silica fume increases as components other than SiO_2 (K_2O or CaO) increase. None of the brands given in Table 6 contains an extraordinarily large amount of such impurities. Yet considering that silica fume is a highly reactive ultrafine powder and is highly sensitive to moisture, it is conceivable that certain changes due to moisture occur in the quality of silica fume on the Japanese market during transportation and storage, resulting in increased specific gravities. This phenomenon is peculiar to the Japanese market, and has not been reported in Europe and America. It is therefore necessary to consider the methods of transportation and storage in use, as well as Japan's characteristic meteorological conditions, when establishing methods of silica fume application.

b) Specific surface area and average particle size

Silica fume exists in an agglomerated state independent of the product form. It is therefore considered appropriate to apply the nitrogen adsorption method (BET method) to confirm the specific surface area[7]. It should be noted that the average particle size (specific surface area diameter) can be estimated using Eq. (1), assuming that the particles are spherical:

$$D = \frac{6}{\rho \cdot S} \qquad (1)$$

where D = diameter (μm)
ρ = specific gravity
S = specific surface area (m^2/g)

Silica fume particles can in practice be regarded as spherical. According to our measurements, the average particle size of silica fume confirmed by SEM observations agrees well with the diameter calcurated from specific surface area by Eq. (1).

Figure 7 shows typical gradings of silica fume products obtained in Japan as measured by a laser diffraction particle size analyzer. Typical silica fume gradings are shown in Fig. 8. These figures reveal that silica fume in its normal state without dispersion treatment is significantly agglomerated. Also, it has been shown that a dispersion process such as ultrasonic treatment alters the grading of silica fume significantly. In addition, when laser diffraction is applied, the initial forms (powder and granules) that are indistinct to the naked eye can be identified. This method is considered to be effective in judging the form of silica fume and confirming the degree of its dispersion.

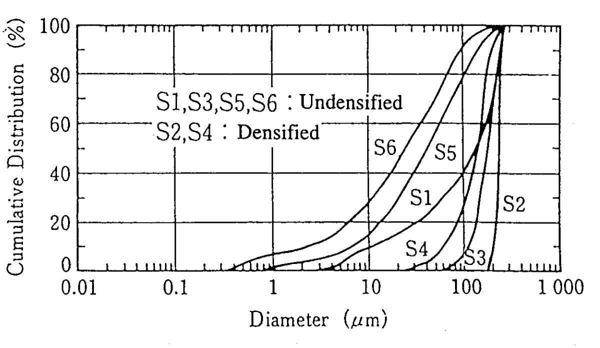


Fig. 7 Examples of Size Distribution Curves for Silica Fumes in Natural State

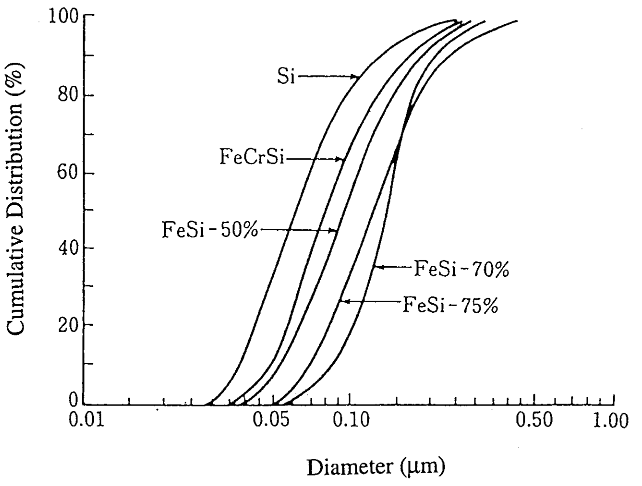


Fig.8 Size Distribution of Silica Fumes

5. State of research into concrete containing silica fume

(1) Studies on dispersibility

Fine powders in the order of microns are generally considered to agglomerate due to the following three forces[10]:

1) electrostatic force
2) van der Waals force
3) adsorptive force of moisture

The van der Waals force is generally around 10^2 to 10^3 times stronger than the electrostatic force, and adsorptive force of moisture is almost 50 times stronger than the van der Waals force, though this is dependent on whether the particles are in the gas phase or liquid phase. Given its particle size, silica fume is also considered to be governed by these forces, and can reasonably be expected to agglomerate significantly, independent of product form. It is therefore important to grasp the agglomeration/dispersion properties of silica fume in concrete when investigating the effects of silica fume on the properties of concrete.

In the case of materials such as fly ash and BFS, whose average particle size does not significantly differ from that of cement particles, dispersion properties in concrete have not been a serious problem to address. It is for this reason there have so far been few reports on the dispersion properties of silica fume in concrete. To mention a few of the past reports, Uomoto et al[11] pointed out that the effects of silica fume on the compressive strength and carbonation depth of mortar are enhanced by increasing the mortar mixing time. Also, the author has conducted compression tests on mortars containing 14 brands of silica fume[12]. As a result, the compressive strength of mortar was found to be higher with powder than with granular silica fume, and higher with slurry than with powder silica fume, if the mixing conditions are fixed, i.e., if the shear energy imparted to the materials is fixed. These studies suggest that the dispersion properties of silica fume in concrete and mortar can affect the compressive strength and other qualities of the hardened concrete and mortar.

In the field of powder engineering, there are two basic methods of dispersing fine particles: one is to physically impart energy from outside (ultrasonic wave method, ball mill method, etc.) and the other is to chemically add a suitable dispersing agent[13] Fig. 9 and 10 show the results of applying physical and chemical treatments to mixtures of silica fume and water and measuring their grading by a laser diffraction particle size analyzer. This reveals that the grading of silica fume in water is strongly affected by the physical dispersion treatment.

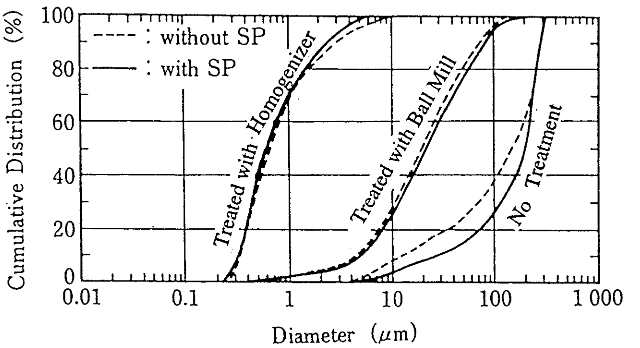


Fig.9 Cumulated Size Distribution Curves of Silica Fumes in Water Mixture with and without Physical / Chemical Treatment (S1)

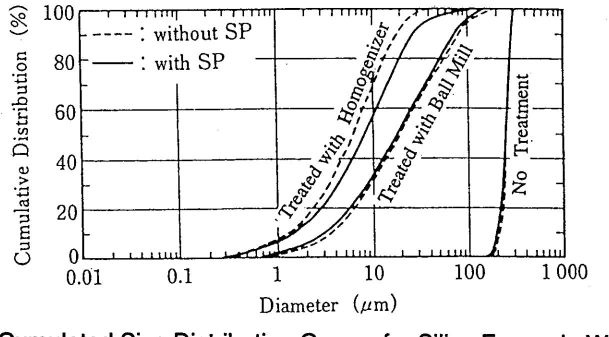


Fig. 10 Cumulated Size Distribution Curves for Silica Fumes in Water Mixture with and without Physical / Chemical Treatment (S2: Densified)

Fig.11 shows the relationship between exposure time to ultrasonic waves and the grading of the silica fume. As the exposure time increases, the grading shifts towards smaller particle sizes. The relationship between the fine particle content in mortar and the compressive strength is then shown in Fig. 12. This indicates that the addition of treated silica fume increases the fine particle content in mortar, and also increases compressive strength. However, this tendency has so far been reported mainly in mortar investigations. It has been pointed out that the same trends may not be observed in the case of concrete. In addition, the dispersion effect by the shear energy during mixing is reported to be affected by the concrete proportioning conditions, such as the water-binder ratio[14]. There is a lot of ambiguity particularly regarding this aspect. Recent studies include those in which the state of silica fume dispersion in freshly mixed concrete is evaluated by the power consumption of the concrete mixer[15] or by the mixing efficiency of mixers, utilizing the difference in silica fume dispersion in concretes with different mixing conditions[16]. Consequently, further investigation should be conducted regarding the dispersion properties of silica fume in concrete in consideration of such conditions as the proportioning, order of charging, mixing method, and initial form of silica fume.

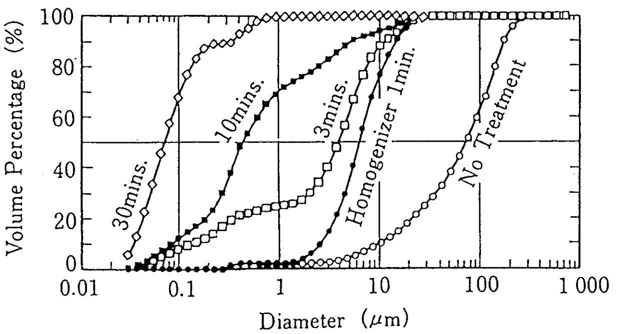


Fig. 11 Effect of Dispersion on Size Distribution of Silica Fumes

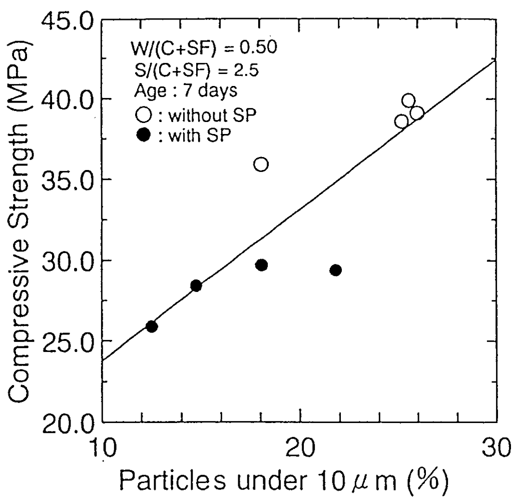


Fig. 12 Relation Between Ratio of Particles Under 10μm and Cpmpressive Strength of Hardened Mortar

(2) Studies on fresh concrete

Since silica fume consists of ultrafine particles, it increases the viscosity of concrete and reduces its slump[17]. As a result, the unit water content of concrete, needed to obtain the required slump significantly increases, and this has to be compensated by using a superplasticizer. In other words, the effective application of silica fume as a mineral admixture for concrete was only possible after the emergence of superplasticizers.

As for the air content of fresh concrete, silica fume hampers air entrainment due to the effects of carbon it contains and its ultrafineness. It is therefore necessary to increase the dosage of an air-entraining agent as the silica fume percentage increases (Fig. 13[18]).

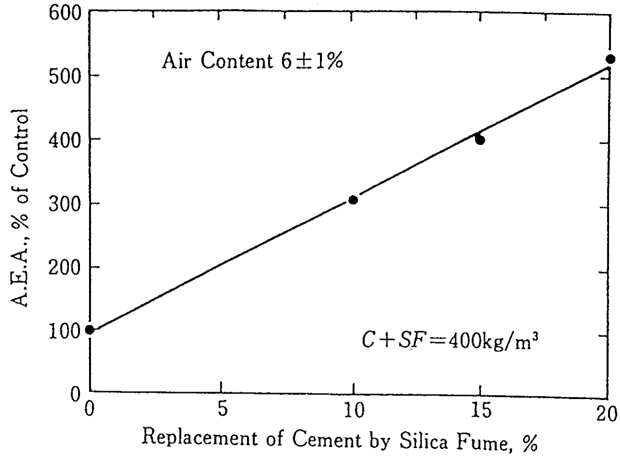


Fig. 13 Effect of Replacement of Cement by Silica Fume on the Dosage of Air-Entraining Agent

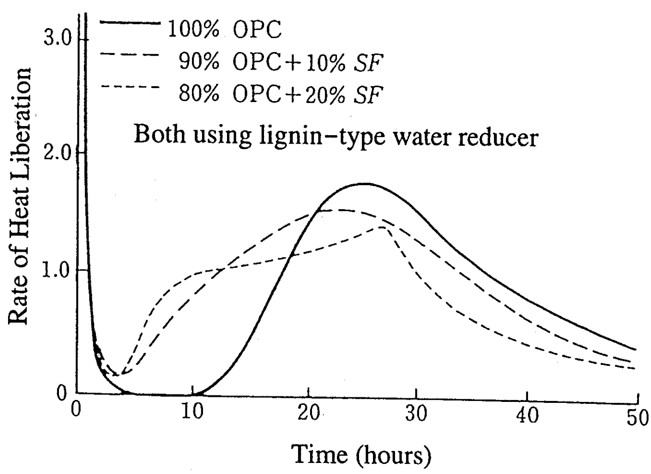


Fig. 14 Effect of Silica Fume on Change in Rate of Heat Evolution of C/(C+SF) Concrete with Time

Also, a high percentage of silica fume inhibits segregation; 15% or more of silica fume in place of cement leads to a almost no segregation or bleeding, even with a slump of 15 to 20 cm[19]. Heat generation at an early stage of hydration increases in concrete containing silica fume when compared with the case of no silica fume, as shown in Fig. 14[20]. It should be noted that this refers to the case of using a lignosulfonate admixture. It is also reported that when such an admixture is not used, the heat generation of concrete containing silica fume is smaller than without it for two days after mixing.

(3) Studies on hardened concrete

Mortar and concrete containing silica fume show particular characteristics in their strength development. Typical examples are shown in Fig. 15.

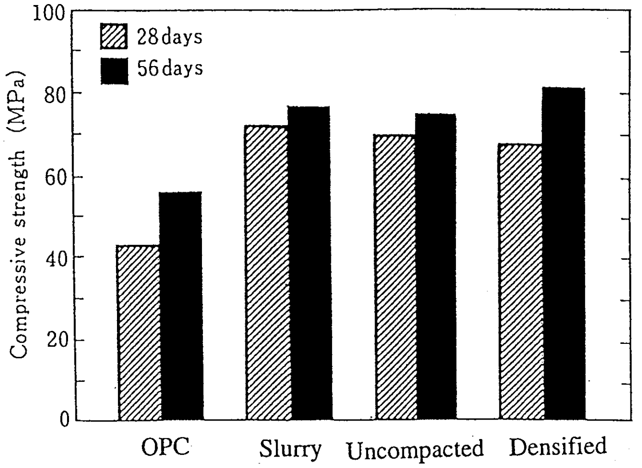


Fig. 15 Effect of the Type of Silica Fume on 28-and 56-Day Compressive Strength of Concrete

A compressive strength of approximately 80 to 100 MPa can be obtained relatively easily, though this is dependent on the type of silica fume, the type of cement, the silica fume percentage in place of cement, the curing method, and age[21]. The reason is that the addition of silica fume reduces the pore volume of concrete, producing dense concrete. Also, when curing is accelerated using steam or an autoclave, the pore diameter distribution and pore volume significantly differ from those of standard-cured concrete, indicating that the use of silica fume is effective for strength development at early ages[22]. It has been proven that a strength of 150 MPa can be obtained in such a case (Fig. 16). The static modulus of elasticity of concrete containing silica fume is lower than that of concrete without it, as shown in Fig. 17. This is because the addition of silica fume increases the cement paste content, which has a lower elastic modulus than aggregate. The unit creep of hardened concrete containing silica fume is larger than that of concrete of the same compressive strength containing no silica fume, if it is standard-cured and dried in air. If standard-cured and then water-cured, the unit creep of concretes with and without silica fume is nearly the same. In the case of autoclave curing, the unit creep is significantly lower than in the case of standard curing, and is higher with silica fume than without it, if followed by air curing. There is also a report which states that the microstructure of hardened cement containing silica fume becames more dense as hydration proceeds, and this inhibits the moisture supply from outside, thus drying the inside of the hardened mass. This generates internal stress, resulting in large shrinkage (autogenous shrinkage)[23]. Further detailed investigation of this aspect is required.

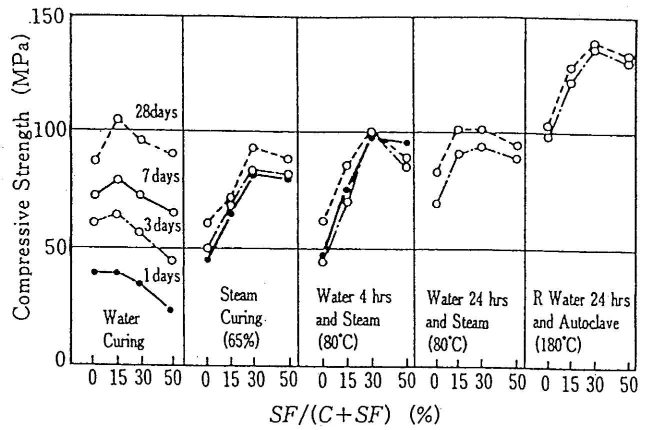


Fig. 16 Effect of Silica Fume Dosage on Compressive Strength of Mortar for Various Curing Conditions

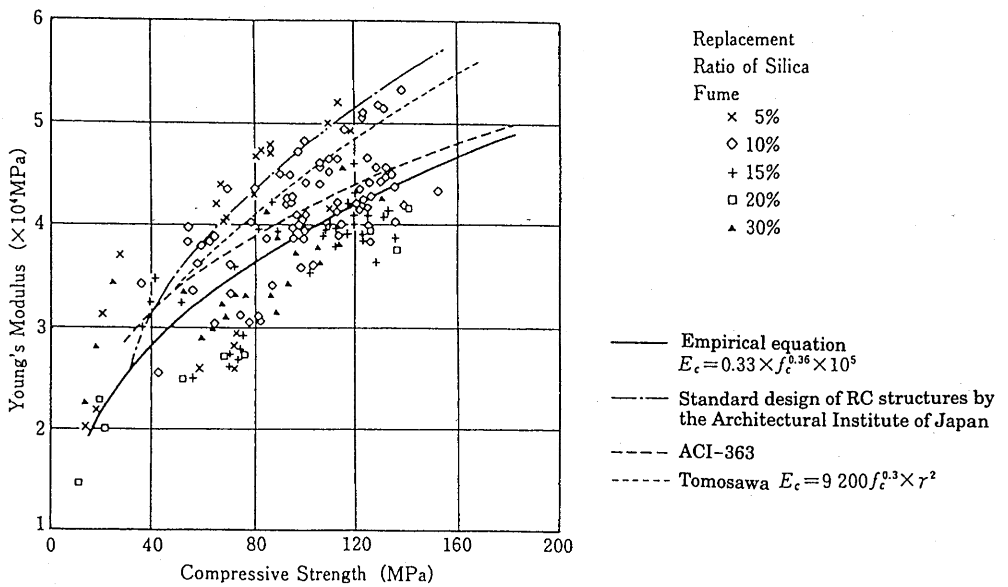
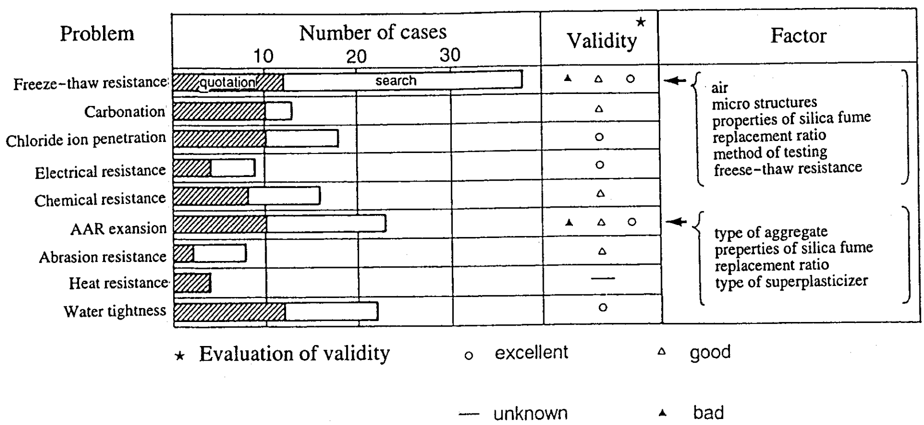


Fig. 17 Relationship Between Compressive Strength and Young's Modulus of Concrete

(4) Studies on concrete durability

A survey of past studies and reports related to the durability of concrete containing silica fume found the trends given in Table 7[24]. This table shows the number of technical papers (number of papers searched) published concerning the effects of silica fume in improving durability, such as freeze-thaw resistance and carbonation of concrete, as well as whether or not the papers judge that silica fume is effective. This reveals that silica fume is judged effective for such factors as resistance to chloride penetration, electrical resistance, and watertightness/airtightness. Interestingly, conflicting results are reported regarding freeze-thaw resistance and inhibition of the alkali-aggregate reaction.

Table 7 Comparison of References Studying the Validity of Silica Fume to Improve Durability of Concrete



Numerous studies have been conducted on the freeze-thaw resistance of concrete containing silica fume, yet the results are conflicting. Papers reporting that freeze-thaw resistance is "higher" with silica fume than without it account for 60% and those reporting "the same" or "lower" resistance account for 10-20% and 20-30%, respectively. By region, papers from Japan and the Scandinavian countries tend to report improvements in freeze-thaw resistance, while those from Canada tend to report the inferiority of silica fume concrete in freeze-thaw resistance. This may be because evaluations in terms of scaling due to surface deterioration, and in terms of surface and internal cracking due to internal deterioration led to different judgments. Also, differences in the type of silica fume, percentage of silica fume in place of cement, and proportioning, and the presence of an air-entraining agent may have led to different results. At present, it can be said that a suitable amount of air should be entrained independently of the mix proportion, as recommended by the ACI Committee Report[25] and the Canadian Standard[26].

There are also numerous papers on silica fume's effectiveness at inhibiting the alkali-aggregate reaction. Some report that silica fume is effective, some report that, though effective, it increases the expansion, and some report that the effects vary depending on the type of silica fume and type of reactive aggregate. Taking account of the high price of silica fume in Japan, it is considered more economical to use fly ash or BFS, which are proven to be effective in inhibiting the alkali-aggregate reaction.

6. Applications of concrete containing silica fume

Concrete containing silica fume is already in relatively frequent use in actual construction projects in other countries. The purpose of using such concrete is mostly to enhance strength and durability. On the other hand, few concrete structures have been made using concrete containing silica fume in Japan. This is partly due to Japan's special circumstances, in which silica fume has to be mostly imported, and is very expensive when compared with other mineral admixtures. In recent years, however, application examples have been reported, such as the case where a plant dedicated to silica fume concrete was completed for commercial application, and where silica fume concrete was used for shotcrete and precast concrete products. The state of commercial application of silica fume in Japan is summarized in this chapter, though it is somewhat out of the scope of this paper.

(1) Development of a plant for silica fume concrete and an application example

Concrete containing silica fume is considered awkward to supply an a continuous basis from conventional ready-mixed concrete plants, due to various problems concerning the storage, transportation, and dispensing of silica fume. A plant for ready-mixed concrete containing silica fume (hereafter referred to as an "SFC plant") was recently completed and started to supply concrete placing sites.

An outline of the SFC plant is shown in Fig. 18[27] Powdery brands are used, because they have (1) a higher dispersibility when mixed with concrete and (2) better effects, such as pozzolanic reactivity. The low bulk density of powder silica fume causes caking under compression, which in turn causes clogging during pneumatic conveyance. To avoid this problem, the SFC plant (1) adopted a horizontal silo to avoid gravitational discharge and (2) carries out quality control by measuring dispersibility, water absorption, and bulk density before and after pneumatic conveyance. According to Literature 25, no marked difference is observed between the basic properties of concrete containing silica fume before and after pneumatic conveyance.

Silica fume concrete produced at the SFC plant is recently reported to have been applied to a 39-story hotel of steel tube concrete construction[28] In this project, 10% of the cement was replaced with silica fume, with the water-binder ratio and unit binder content being 28% and 525 kg/m^3, respectively. This Satisfied the design strength of 600 kgf/cm^2. The compressive strength of control specimens is reported to have attained 900 kgf/cm^2 at 28 days. This project is also rated highly by various observers in that it realized an unprecedented pumping height of 61.9 m.

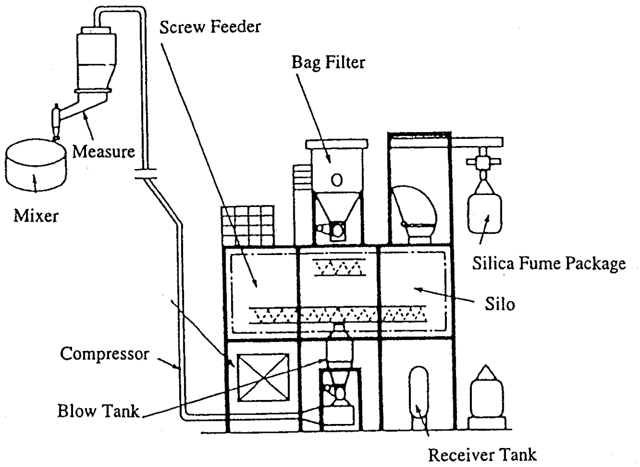


Fig. 18 SFC Plant

In addition, a post-tensioned precast concrete bridge (CNT Superbridge) was constructed using silica fume concrete produced at the SFC plant[29] The bridge, characterized by a very slender shape with a girder depth-span ratio of 1/40, was made of ultrahigh-strength concrete with a water-binder ratio of 20% and a compressive strength exceeding 1000 kgf/cm^2.

(2) Application to large-scale concrete structures

The first application of silica fume to a large-scale concrete structure with the aim of improving concrete properties was a mobile petroleum excavation platform for the North Sea, "Beaufort I", constructed in 1983. A sketch is shown in Fig. 19[30].

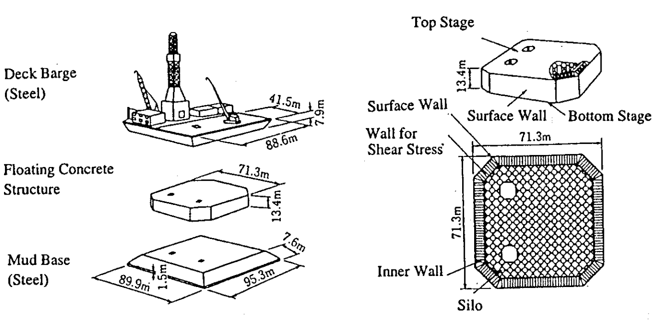


Fig. 19 Beaufort I

Concrete containing silica fume, 2330m^3 in total, was used for the exterior walls. The purpose of including silica fume was to improve the resistance to chloride penetration and abrasion, to control the heat generation from the massive concrete, and to improve the workability of the rich mixture. The use of artificial lightweight aggregate as the coarse aggregate to reduce the dead weight is reported to have led to a compressive strength of 634kgf/cm^2 at 56 days, comfortably exceeding the design strength.

(3) Application to shotcrete

It is pointed out that the addition of silica fume to shotcrete for tunnels increases the concrete adhesion, drastically reducing the rebound ratio. After hardening, as well, the compressive strength of the concrete is higher. As detailed in Literature 31, 32, and 33, application in shotcrete may be regarded as a representative usage of silica fume.

(4) Application to precast concrete products

Silica fume consists mostly of noncrystalline SiO2, and is said to have pozzolanic reactivity similar to that of fly ash. The effects of these characteristics on the compressive strength of concrete are particularly evident when the concrete is cured in an autoclave. For this reason, the use of silica fume has been increasing in such products as precast concrete piles and precast reinforced concrete rectangular beams[34].

7. Summary and subjects for the future

This paper is summarized below, and subjects for future work are mentioned as well.

(1) The physical and chemical properties of silica fume can be roughly classified into four groups. Also, being ultrafine particles of submicrons, silica fume is normally agglomerated whatever its physical form. It is therefore very difficult to measure its physical properties, such as specific gravity and grading. Such agglomeration of silica fume may be peculiar to Japan, where most silica fume is imported from distant countries.

(2) The properties of concrete containing silica fume are strongly affected by the dispersion of the silica fume in the concrete after mixing. In other words, various effects of silica fume may remain latent unless it is sufficiently mixed or certain measures are taken to disperse it. A more appropriate method of producing concrete containing silica fume should therefore be developed, using such admixtures as air-entraining and high-range water-reducing agents. The dispersion properties of silica fume in concrete should also be further investigated.

(3) Applications of concrete containing silica fume are increasing year by year in Japan, and the intended effects seem to be achieved. It should be noted, however, that different brands of silica fume have different qualities. These should be clarified, and domestic standards should be established, so as to elucidate the effects of silica fume when used with concrete in Japan.

8. Afterword

As described above, it is clear that there is demand for concrete with high strength, high durability, and high fluidity, though this depends on the usage and service conditions of the structure. To date, a striking number of studies have been conducted to enhance these capabilities. These have investigated the raw materials, structural design, construction, and all other areas of concrete engineering. However, it should be remembered that this demand for high performance from concrete did not suddenly emerge in recent years. In fact, it was nearly a century ago that valuable reports pointed out the importance of fine powder when proportioning concrete and that a theoretically optimum grading of all materials can exist for densifying the concrete structure. Now we have available numerous advantageous new materials and construction methods as compared with that time - a result of scientific development. Silica fume is one such highly effective material for the performance enhancement of concrete. It is therefore very important to aim for further improvements in concrete performance by using silica fume more appropriately, bearing these past achievements in mind.

The author sincerely hopes that this paper will assist future studies on silica fume, though it may not give full caverage of the field.

Acknowledgement

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