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RECOMMENDATIONS FOR DESIGN AND CONSTRUCTION OF CONCRETE STRUCTURES USING SILICA FUME IN CONCRETE

- DRAFT -

(Translation from the CONCRETE LIBRARY No.80 published by JSCE, March 1995)

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SYNOPSIS: Recommendations for the Design and Constructions of Concrete Structures Using Silica Fume in Concrete which have been drafted for the first time in Japan, are presented. Silica fume consists of ultrafine particles obtained when collecting dust from the waste gas generated during the production of metallic silicon and ferrosilicon in an arc furnace. They are ultrafine spherical particles with a diameter of less than 1 μ m, average diameter of about 0.1μm, average specific surface area of about 20 m^2 /g by the BET method using nitrogen adsorption, and specific gravity of about 2.2. Silica fume is the mineral admixture in use with concrete in order to realize the high-performance concrete structures in the same sort as fly ash and ground granulated blast furnace slag (BFS). In this recommendations, the general requirements for design and construction when concrete containing silica fume is applied to general structures, marine structures, pavement, shotcrete, and precast concrete products are described. In addition to these recommendations, quality standards and new test method as for silica fume are reported.

KEYWORDS: concrete structures, silica fume, ultrafine spherical particles, high strength concrete, silica fume replacement ratio, $Si0_2$ content, activity index

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Preface

A variety of industrial by-products, such as fly ash and ground granulated blast furnace slag, are currently used in Japan as mineral admixtures for concrete. Among these materials, silica fume has not been discussed much in Japan due to the scarce domestic production. Nevertheless, it has already been applied to high strength concrete and high durability concrete, gradually calling for design and construction guidelines and quality standards.

Accordingly, the Committee on Concrete of JSCE organized the JSCE Research Subcommittee on Silica Fume in Concrete in 1992 entrusted by the Japan Silica Fume Technology Associates to formulate design and construction recommendations required when using this material for concrete and mortar. After extensively investigating the literature and conducting various experiments to collect necessary data, the Subcommittee compiled the *Draft Recommendations for Design and Construction of Concrete Structures Using Silica Fume in Concrete, Standard Specification for Silica Fume for Use in Concrete (Draft)* (JSCE-D 106-1995), and *Test Method for Specific Gravity of Silica Fume Using a Volumetric Flask (Draft)* (JSCE-D 502-1995). These were completed in March 1995, and submitted to the permanent committee of the Committee on Concrete, which deliberated this subject for 6 months and approved the publication of these recommendations and specifications.

The Subcommittee members hope that the opportunities of using silica fume for concrete will increase and that these recommendations will assist concrete engineers using this material.

March 31,1995

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CHAPTER 1 GENERAL

1.1 Scope

(1) This Recommendation (Draft) provides general requirements for the design and construction of concrete structures made using concrete containing silica fume. As to matters not specified herein, the JSCE Standard Specification for Design and Construction of Concrete Structures-1991 (hereafter referred to as the "Standard Specification") shall apply.

(2) Silica fume covered by this Recommendation (Draft) shall normally conform to JSCE Standard Silica Fume for Use in Concrete (Draft)."

(3) The replacement ratio of silica fume covered by this Recommendation (Draft) shall normally be in the range of 5 to 15%.

[Commentary]

Silica fume consists of ultrafine particles obtained when collecting dust from the waste gas generated during the production of metallic silicon and ferrosilicon in an arc furnace. They are ultrafine spherical particles with a diameter of less than 1 µm, average diameter of about 0.1 µ m, average specific surface area of about 20 m^2 /g by the BET method using nitrogen adsorption, and specific gravity of about 2.2. The main component is amorphous silicon dioxide (SiO_2), which is soluble in an alkali solution. Its content in silica fume varies depending on the type and production method of metallic silicon and ferrosilicon, normally ranging from 70 to 98%. Those with a higher SiO_2 content are generally said to be more reactive. Due to the enormous power consumption from the production of metallic silicon and ferrosilicon, silica fume is mostly produced in countries where the supply of electric power is abundant and inexpensive. The largest producers include Northern European countries, Canada, and USA, where electrical furnaces must be furnished with dust collectors for environmental protection. In these countries, silica fume has long been used as an admixture for concrete and a substitute for cement. Due to the high cost of electric power, silica fume was produced in small amounts in Japan, and scarcely used as an admixture for concrete. In recent years, however, silica fume has gradually found applications, as the material has been proven to have remarkable effects of improving strength, durability, and placeability of concrete, and as import/distribution channels have become established. On the other hand, silica fume may not lead to desired effects, unless used with sufficient understanding of its properties. Also, being mostly imported, silica fume is an expensive material when compared with fly ash and ground granulated blast-furnace slag, and the long transportation could alter its qualities. This Recommendation (Draft) has been established to address these concerns and encourage the effective use of silica fume.

Regarding (1) above

This Recommendation (Draft) contains general requirements for design and construction when concrete containing silica fume is applied to general structures, marine structures, pavement, shotcrete, and precast concrete products. When applying such concrete to special structures other than these, sufficient preliminary research should be made with reference to this Recommendation (Draft), to ensure the placeability and design safety.

Matters not covered by this Recommendation (Draft) should be in accordance with the Standard Specification.
It should be noted that Chapter 4 (Mix Proportions) puts stress on the proportioning to maximize the effects of using silica fume in place of cement, and that Chapter 9 (General Design Requirements) incorporates the concept of high strength concrete to address strengthening, the most demanded quality of silica fume, so as to encourage the use of silica fume in a more effective way.

An appropriate amount of good quality silica fume contained in concrete brings such effects as (1) improvement in strength, (2) improvement in durability, (3) improvement in placeability, and (4) other effects, which are sensitive to the quality and replacement ratio of silica fume. Accordingly, the quality and replacement ratio should be carefully selected according to the purposes. It should also be burn in mind that the qualities of the resulting concrete are strongly affected by the product form of silica fume and the method and period of curing.

Regarding (2) above

It has been pointed out that the quality of silica fume varies depending on the type and manufacturing method of metallic silicon and ferrosilicon and that its quality may be altered by the long time from shipping to use. For this reason, silica fume with confirmed quality should be used as an admixture for concrete. JSCE Standard "Silica Fume for'Use in Concrete (Draft)" specifies the required activity index and chemical components on the premise that silica fume in place of part of cement increases the strength and durability of the concrete. When using silica fume, this Recommendation requires that its qualities meet the requirements of JSCE Standard "Silica Fume for Use in Concrete (Draft)", as standard practice.

Regarding (3) above

The replacement ratio required to attain the desired effects varies with the purpose of use, but experiences have concentrated around 10%. This Recommendation (Draft) therefore adopted a range of 5 to 15% as the range to be covered. The replacement ratio referred to in this Recommendation (Draft) is the ratio of silica fume mass to the total mass of binders, which consist only of cement and silica fume. The replacement ratio is set at 5 to 15% as the standard, in consideration of the fact that a ratio below this range will not evidently bring the desired effects, that a ratio above this range will require special care for mixing, curing, etc., and that only limited literature and application examples are available for ratios outside this range. Past applications tended to adopt lower ratios when the major concern is the improvement of placeability, and higher ratios, when the strength improvement was intended. Where a ratio outside the range of 5 to 15% is to be adopted, sufficient preliminary research should be carried out with reference to this Recommendation (Draft).

1.2 Definition of terms

The definitions of certain terms used in this Recommendation (Draft) are as follows:

Silica fume - Spherical ultrafine particles comprising amorphous SiO_2 generated during the production of metallic silicon and ferrosilicon.

Binder - A generic term for cement and silica fume that bind aggregate particles in concrete.

Silica fume replacement ratio - The ratio of the mass of silica fume to the total mass of the binders. This is generally expressed as a percentage.

Water-binder ratio - The ratio of the mass of water to the total mass of the binders. This is generally expressed as a percentage.

Silicon dioxide (SiO_2) content - The content of SiO_2 as a chemical component in silica fume. This is generally expressed as a percentage.

Activity index - The ratio of the compressive strength of mortar containing silica fume to the compressive strength of mortar made using the reference cement as tested in accordance with JSCE Standard "Silica Fume for Use in Concrete (Draft)." This is expressed as a percentage.

Powder silica fume - Silica fume as collected from waste gas during the production of metallic silicon and ferrosilicon and not yet subjected to treatment to increase the unit weight or slurrying treatment.

Granular silica fume - Silica fume with an apparent particle size increased by special treatment to increase the unit weight to facilitate transportation and handling.

Slurry silica fume - Silica fume slurried by being dispersed in water by using dispersing and stabilizing agents.

[Commentary]

Regarding Silica Fume above

Silica fume collected at dust collectors is made into different product forms depending on whether or not it is subsequently treated, and its unit weight may vary due to agglomeration during storage and transportation. It is therefore important to confirm the reference values provided by the manufacturers when accepting silica fume or when designing equipment for silica fume. When such reference values are not available, the unit weight can be confirmed by measuring the loose apparent density using the static method of JIS K 5101 (Method of Test for Pigments), JIS Z 2504 (Method for Determination of Apparent Density of Metal Powders), or a powder tester.

Silica fume comes in three product forms, i.e., powder, granules, and slurry. Powder silica fume is an as-collected form at dust collectors, and is referred to as "as-produced silica fume" or "undensified silica fume" in Western countries. This type is highly dispersible, but its unit weight as low as 100 to 300 kg/m^3 causes difficulty in handling and low transportation efficiency. Deaerated products are also available to cope with this problem and facilitate its transportation. This is also included in powder silica fume.

Granular silica fume is powder silica fume specially treated to increase the unit weight so as to facilitate handling and improve transportation efficiency. This type is referred to as "densified silica fume" or "pelletized silica fume" in Western countries. Its unit weight is 500 to 800 kg/m^3 The method of increasing the unit weight of powder silica fume comprises stirring in air or with water to promote agglomeration. This type tends to be less dispersible in concrete than the powder type. The type with a unit weight of as large as 600 to 800 kg/m^3 is used in Western countries for producing silica fume cement by grinding together with cement, and is not suitable as an admixture for concrete.

Slurry silica fume is as dispersible as the powder type, while its transportation efficiency is improved. However, the slurry type is outside the scope of this Recommendation (Draft), as the quality of silica fume as such is difficult to identify. This does not limit the use of slurry silica fume made, e.g., on site from powder silica fume with a confirmed quality.

Regarding Binders above

Cement and silica fume are generically referred to as binders in this Recommendation (Draft). Ground granulated blast-furnace slag and fly ash, the normally used mineral admixtures, are excluded from the definition of the binders of this Recommendation (Draft), as the data for their use in combination with silica fume is limited and not yet systematized. When using these materials, their properties must be confirmed in advance by testing.

Regarding SiO_2h content above

The chemical composition of silica fume is mostly SiO_2, which is mostly amorphous SiO_2 that is soluble in alkali solution. Generally, the higher the content of this amorphous SiO_2, the higher the reactivity. The SiO_2 content is measured by the method specified in JIS M 8852 (Method for Chemical Analysis of Silicastone). In this case, crystalline a-quartz included in the raw material is also counted with amorphous SiO_2. Nevertheless, SiO_2 content measured by the method of JIS M 8852 is an important index to the quality of silica fume, as the a -quartz in silica fume is not more than 3% when measured by the powder X-ray diffraction method.

Regarding Activity Index above

The activity index evaluates the strength-developing properties of silica fume by strength testing on mortar, and is also an important index to the quality of silica fume.

CHAPTER 2 QUALITY OF CONCRETE CONTAINING SILICA FUME

2.1 General

Concrete containing silica fume shall, in combination with a high-range water-reducing agent (HWRA) or air-entraining and high-range water-reducing agent (AEHWRA), develop the required performance, and possess qualities with minimum variabilities.

[Commentary]

The purposes of using silica fume for concrete are to increase strength and improve durability and placeability. Uniform dispersion of ultrafine particles of silica fume in concrete is a prerequisite for developing these properties of silica fume. To this end, the use of a HWRA or AEHWRA is required as standard practice. When applied to real structures, the qualities of silica fume to be used, effects of the HWRA or AEHWRA, and mix proportions must be thoroughly examined to minimize quality variabilities, so as to obtain the required material properties. It should be noted that the total chloride ion content in concrete must not be more than 0.3 kg/m^3 also in the case of concrete containing silica fume.

The following are the properties of concrete containing silica fume and matters to be attended to, to assure the required performance.

(1) Properties of fresh concrete

When silica fume is used in combination with a HWRA or AEHWRA, workable concrete can be produced even with a significantly reduced unit water content. Also, when producing high strength concrete with a low water-cement ratio, high fluidity can be attained by replacing part of the cement with silica fume. Whereas silica fume tends to reduce the fluidity of concrete with a high water-binder ratio (about 40% or higher), it increases the fluidity of concrete with a low water- binder ratio (about 35% or lower) containing a HWRA or AEHWRA.

Silica fume is also effective in preventing segregation of high fluidity concrete. Silica fume in pumped concrete may increase the pumping load, but reduces clogging by the reduced water segregation under pressure. In the case of high strength concrete, the pumping load as such is reduced. The viscosity-increasing effect of silica fume improves the applicability of shotcrete to, e.g., tunnels and excavated shaft walls by reducing the rebound and increasing the layer thickness.

Being ultrafine, silica fume particles have large surface areas to adsorb moisture, and therefore have a high moisture-retaining capability. This reduces bleeding and improves the segregation resistance of concrete. The HWRA demand or AEHWRA demand to obtain a specified slump of concrete containing silica fume increases as the silica fume replacement ratio increases. The properties of fresh concrete are reported to depend on other factors as well, such as the type and product form of silica fume, type of the HWRA or AEHWRA, binder content, water-binder ratio, sand-aggregate ratio, and mixing method. It is therefore important to confirm each of the required properties in advance when using silica fume for concrete.

The amount of bleeding water on concrete generally decreases as the unit cement content increases or as the unit water content decreases. When cement is partially replaced with silica fume, it significantly decreases, e.g., down to less than 1/3 at a silica fume replacement ratio of 10%. One report states that bleeding was scarcely observed when the water-binder ratio and unit water content were 40% and 162 kg/m^3, respectively, with the replacement ratio at 10% of Ordinary Portland Cement.

The air content of concrete containing silica fume tends to be lower than that of ordinary concrete without silica fume. This may be attributed to the adsorption of the air-entraining agent by silica fume and unburnt carbon included in it. The air content is also affected by the workability, viscosity, and the product form of silica fume. However, it is possible to assure the specified air content by adjusting the dosage of the air-entraining agent.

The setting time of concrete containing silica fume is generally extended, due to the increased dosage of a HWRA or AEHWRA.

(2) Consolidation and curing

Concrete containing silica fume, while fresh, assumes properties different from those of concrete without silica fume. These include small bleeding water amount, high segregation resistance of aggregate, and long setting time. It is therefore important to examine the methods of conveying, placing, consolidating, and curing, so that the required performance can be obtained.

For ordinary concrete, plastic shrinkage cracking can be prevented by protecting the concrete from drying beginning immediately after placing. In the case of high strength concrete, however, the significant autogenous shrinkage at an early age may cause plastic shrinkage cracking, even if the concrete is properly protected from drying. High strength concrete containing silica fume should therefore be wet-cured beginning immediately after placing by, e.g., spraying water on the concrete surfaces.

(3) Strength properties

Though slightly dependent on operators, silica fume's effect of increasing compressive strength of standard-cured concrete falls in the range of 10 to 30% with a replacement ratio of around 10%. This may be because the air voids in hardened concrete are reduced by the pozzolanic reaction and microfiller effect (a physical effect to increase the packing) of silica fume.

It has been proven that the compressive strength of concrete containing silica fume has a linear relationship with the binder-water ratio up to a water-binder ratio of about 25%, and increases with the decrease of the water-cement ratio, provided that properly selected materials are thoroughly mixed. Concrete containing silica fume shows large strength gains at relatively early ages from 3 to 28 days, but the effect diminishes at later ages from 3 to 5 years. The flexural strength and tensile strength of concrete containing silica fume increase along with the increase in the compressive strength. However, the ratios of the flexural and tensile strengths to the compressive strength generally decrease as the silica fume replacement ratio increases. The moduli of elasticity with a replacement ratio of 5 to 15% are 25 to 35 ×,10^3 N/mm^2- and 30 to 45 × $l0^3$ N/mm^2 when the compressive strengths are 40 N/mm^2 and 80 N/mm^2 , respectively. The gain in the elastic modulus appears to be smaller than the strength gain.

(4) Shrinkage and creep

Shrinkage of concrete includes autogenous shrinkage due to hydration of cement and drying shrinkage due to escape of moisture. The shrinkage of concrete varies with the differences in the pore structure in paste due to the differences in the unit cement content and water-cement ratio. In addition, the shrinkage of concrete containing silica fume is also affected by the silica fume replacement ratio. Concrete containing silica fume generally undergoes substantial autogenous shrinkage, and this tendency is particularly significant with high strength concrete. In extreme cases, most of the shrinkage could be derived from autogenous shrinkage and the effects of drying could be insignificant. This requires attention.

The creep of concrete containing silica fume, similarly to shrinkage, reportedly shows different tendencies depending on conditions.

(5) Durability and physical and chemical properties

The microfiller effect and pozzolanic reaction by the use of silica fume shift the pores to small sizes, reducing the pore volume. With the silica fume replacement ratio in the range of 5 to 15%, an increase in the replacement ratio reportedly decreases 50 nm and larger pores, and this effectively improves the durability.

Regarding the resistance of concrete containing silica fume to frost damage, both positive and negative effects are conceived. The positive effect is that silica fume densities the microstructure of hardened concrete and shifts pores towards small sizes, and this reduces the amount of frozen water, lowering the freezing temperature.

The negative effect is that the dense microstructure conversely tends to increase the pressure of freezing expansion. It is therefore difficult to tell which of the concretes with and without silica fume is superior in resisting frost damage. At any rate, it is important to assure a sufficient air content using an air-entraining agent so that the boil distance factor is 200 µ m at a maximum.

Whereas the microstructure of hardened concrete is densified by the use of silica fume, the $Ca(OH)_2$ content in hardened cement is reduced. Carbonation resistance of concrete containing silica fume is therefore nearly the same as that of concrete without silica fume. Carbonation will be no concern for both concrete with and without silica fume, if their water-binder ratios are not more than 30% and if sufficient curing is carried out after hardening.

In the process of hydration of Portland Cement after contact with water, K^+, Na^+, and OH^- ions in the pore solution increase with time. When silica fume is contained in the concrete, silica fume adsorbs or reacts with alkalis, causing reductions in the ion concentrations. This tendency is recognized with a silica fume replacement ratio of as low as 5%. This suggests that silica fume is effective in inhibiting the alkali-aggregate reaction (AAR), particularly the alkali-silica reaction. However, silica fume is not reported to have been used for this purpose in Japan. According to reports, whereas the AAR-inhibiting effects of silica fume are recognized with a replacement ratio of 10 to 15% in concrete containing deleterious aggregates in general, a replacement ratio of as high as 20% is required when opal aggregates are contained in the concrete. However, the AAR- inhibiting effects of silica fume also depend on the properties of aggregate (e.g., reactivity, composition, and porosity), type of silica fume (e.g., alkali content), and type of HWRA or AEHWRA. It is also reported that a small replacement ratio of silica fume could lead to an increase in the expansion. It is therefore essential to examine thoroughly the effects of silica fume before use.

Many reports suggest that chloride ion penetration is significantly inhibited in concrete containing silica fume when compared with concrete without silica fume. This is attributed to the densified microstructure of hardened concrete, and a silica fume replacement ratio of 10% is assumed to be optimum. It has been pointed out that the passivating film in concrete containing silica fume is more vulnerable to damage by the same content of chloride ions than that of concrete without silica fume. This is because silica fume increases the $Ca(OH)_2$ consumption with the progress of the pozzolanic reaction, lowering the pH values in the pore solution, and this limits the amount of chlorides confined in the hydration products. However, this poses a problem only when the chloride ion content in concrete is high and near the limit chloride content, and probably not in Japan where the chloride ion content at the time of mixing is strictly controlled (0.30 kg/m^3).

The resistance of concrete containing silica fume to sulfates is mostly reported to be higher than that of concrete without silica fume, and equivalent to or higher than that of concrete made using sulfate-resisting cement. This is attributed to the densified microstructure of hardened concrete or the reduced $Ca(OH)_2$ content in hardened cement.

Silica fume significantly reduces the air and water permeability of concrete by densifying the microstructure of hardened concrete and improving the interface properties between the paste and aggregate. Silica fume in place of cement is reported to reduce the pores with a diameter of the order of 10 to 100 nm, while increasing those with a diameter of the order of 1 to 10 nm. It should be noted that the air and water permeability decreases as the silica fume replacement ratio increases but that the permeability-reducing effects cannot be expected to increase in proportion to silica fume when the silica fume replacement ratio exceeds 10%.

2.2 Selection of quality and replacement ratio of silica fume

The quality and replacement ratio of silica fume shall be appropriately selected according to the purpose of use so that the required qualities of concrete can be attained.

[Commentary]

The purposes of using silica fume for concrete are generally (1) to increase the strength, (2) improve the durability, and (3) improve the placeability, etc. of concrete, with emphasis on increasing the strength. When using silica fume, there are suitable ranges of silica fume quality and replacement ratio for each purpose of use. However, such ranges may not at present be set as binding standards for all cases. The quality of silica fume for the above-mentioned purposes is therefore specified in JSCE Standard "Silica Fume for Use in Concrete (Draft)" as follows: The SiO_2 content shall be not less than 85%; the specific surface area shall be not less than 10 m^2 /g; and the activity index shall be not less than 95 and 105 at 7 days and 28 days, respectively. Silica fume is mostly used at a replacement ratio ranging from 5 to 15%. This is because a ratio higher than this tends to lead to plastic shrinkage cracking and low resistance to frost damage, and does not lead to improvements in concrete properties in proportion to the increase.

Accordingly, when selecting the quality and replacement ratio of the silica fume to be used, it is important to confirm its effects by making a thorough examination in consideration of its compatibility with the cement and HWRA or AEHWRA and with reference to this Recommendation (Draft). **Commentary Table 2.1** summarizes the past domestic and overseas survey results on the types of structures and purposes of using silica fume. This table may be referred to when selecting the silica fume replacement ratios for respective purposes.

Commentary Table 2.1 Typical silica fume replacement ratios and intended effects for various types of structures

Type of structures		Silica Fume Replacement Ratio(%)	Intended Effects							
			Strength	Durability				Placeability		
			S1	D1	D2	D3	D4	P1	P2	P3
Domestic	Tunnels (Shotcrete)	5-9	○				○	○		○
	Marine Structures	9	○		○	○				○
	Brigdes	8-15	○							○
	Buildings	10	○							○
Overseas	Tunnels (Shotcrete)	5-10	○					○	○	○
	Marine Structures	8-10	○			○				○
	Pavements (Incl. Repair)	5-15	○	○	○	○	○			
	Brigdes	4-9	○	○	○		○			○
	Parking Facilities	8-10	○	○		○				
	Buildings	7-8	○							○
	Concrete Products	4-8	○	○						

Note S1: Increase Strength
D1: Reduce Water Permeability
D2: Improve Abrasion Resistance
D3: Prevent Salt Damage
D4: Improve Durability
P1: Reduce Rebound
P2: Improve Adhesion of Short Fibers
P3: Improve Pumpability
○ denotes intended effect

2.3 Strength

(1) Generally, the strength of concrete containing silica fume shall be based on 28-day compressive strength.

(2) In the case of pavement concrete, the strength shall generally be based on 28-day flexural strength.

[Commentary]

Regarding (1) above

The 28-day compressive strength may be used as the strength of concrete containing silica fume, similarly to concrete without silica fume, provided the concrete is properly cured. Where high-temperature curing is applied, the strength development should be confirmed in advance by testing, as long-time strength gains are not as large as early gains.

Regarding (2) above

This requirement is included because pavement concrete slabs are subjected to bending by traffic loads, and design requirements of pavements are based on their flexural strength. However, compressive strength converted from flexural strength may be used as the design basis, if a relational equation between compressive and flexural strengths has been obtained from tests on the materials to be employed for the actual construction.

CHAPTER 3 MATERIALS

3.1 General

Materials to be used shall be of confirmed quality.

[Commentary]

When using silica fume in place of part of cement, the materials should not only be of confirmed quality as such, but also, preferably be confirmed to produce concrete of desired qualities in the presence of silica fume, so as to fully develop the intended effects. Particularly when silica fume is used with the aim of increasing the strength of concrete, attention should be paid to aggregates and other admixtures as well as the quality of silica fume. Also, since the qualities of concrete containing silica fume vary depending on the silica fume replacement ratio and curing temperature, etc., its properties should be confirmed by trial mixing using the materials, mix proportions, and mixing conditions to be employed in the actual construction.

3.2 Silica fume

Silica fume to be used shall normally conform to JSCE Standard "Silica Fume for Use in Concrete (Draft)."

[Commentary]

The diameter of primary particles of silica fume is not more than 1 μ m and is around 0.1 μ m on average. These primary particles exist in the form of agglomerated secondary particles.

Silica fume comes in three product forms: powder, granular, and slurry. Powder silica fume is highly dispersible, but low in unit weight, bulky, lightweight, and therefore easily puffed away and unwieldy. On the other hand, granular silica fume allows reductions in transportation cost, as it is not puffed away and is easy to Handle, with its bulk density larger than that of powder silica fume. However, its dispersibility is lower than that of powder silica fume. Slurry silica fume, i.e., silica fume dispersed in water, is highly dispersible in concrete, but requires the extra step of slurryig before mixing with concrete. Cost of bulk transportation of slurried silica fume is also high. Another problem is the difficulty in specifying the quality of silica fume in the slurry.

The requirements of chemical components and activity index of JSCE Standard "Silica Fume for Use in Concrete (Draft)" are established on the premise that an addition of silica fume increases the strength and durability of concrete. The content of $SiCO_2$, the main component of silica fume, is an important quality requirement for considering the pozzolanic activity. In this Standard "Silica Fume for Use in Concrete (Draft)," the lower limit of SiO_2 content is set at 85% taking account of the situation and strength-increasing effects of SiO_2. Upper limits are set for SO_3 and MgO contents, as their excessively high contents may cause such adverse effects as strength loss and abnormal expansion. A standard value is set for ignition loss as well, with the aim of controlling the contents of unburnt carbon and impurities.

To measure the specific gravity of silica fume, which is generally about 2.2, for designing mix proportions, this Standard "Silica Fume for Use in Concrete (Draft)" specifies a "Test Method for Specific Gravity of Silica Fume Using Measuring Flasks (Draft)."

Silica fume's AAR-inhibiting effects can largely be counted on, but unclearness remains in the relationship between alkali content of silica fume and the amount of alkali consumed for AAR; there are reports indicating that the AAR-inhibiting effects may not be produced with a replacement ratio of 5% on concrete with a high unit cement content and a low water-binder ratio, and that silica fume with a relatively high alkali content may aggravate the expansion due to AAR. For this reason, this Standard Silica Fume for Use in Concrete (Draft)" does not specify the requirement for alkali content in silica fume. It is therefore advisable, when using silica fume, to confirm in advance the expansibility of the concrete to be used by a method in accordance with JIS A 5308, Appendix 8 (Method of Test for Alkali-silica Reaction of Aggregate - Mortar Bar Method), e.g., the concrete bar method by the Japan Concrete Institute, in consideration of the actual concrete proportions.

Chloride content in silica fume is generally considered to be marginal, judging from the raw materials and manufacturing processes. However, certain types of silica fume could have high chloride ion content (0.1% or more) due to the location of plants, e.g., coastal areas, and effects of sea transportation. It is therefore advisable, when using silica fume, to measure the chloride content in silica fume in accordance with JIS R 5202 (Method for Chemical Analysis of Portland Cement), and confirm in advance that the total chloride content of the actual mix proportions of the materials to be employed is not more than 0.3 kg/m^3 by such methods as JCI-SC6(Test Method for Chloride Ion Content in Fresh Concrete by Chloride Ion-selective Electrode Method).

The benefits of silica fume, such as its void-filling property and high reactivity, derive from its consisting mostly of ultrafine particles of less than 1 μ m in diameter. Accordingly, JSCE Standard "Silica Fume for Use in Concrete (Draft)" requires the specific surface area to be not less than 10 m^2 /g by the BET method, to distinguish silica fume from other mineral admixtures.

The activity index is one of the indices to the strength-developing properties of pozzolanic materials. The activity index of silica fume is generally higher than that of ground granulated blast-furnace slag. JSCE Standard "Silica Fume for Use in Concrete (Draft)" requires the activity index to be not less than 95 and 105 at 7 and 28 days, respectively.

3.3 Cement

(1) Cements shall conform to JIS R 5210, and Ordinary Portland Cement shall normally be used. When using High-early-strength Portland Cement or Moderate-heat Portland Cement, the strength-developing properties and exothermic properties of concretes made using such cements shall be confirmed.

(2) When using Portland Blast-Furnace Slag Cement, Portland Pozzolan Cement, and Portland Fly Ash Cement conforming to JIS R 5211, JISR 5212, and JIS R 5213, respectively, the methods of use shall be thoroughly examined.

[Commentary]

Regarding (1) above

The cement to be used with silica fume is required, as standard practice, to be Ordinary Portland Cement. This is because the properties of concrete made using Ordinary Portland Cement partially replaced with silica fume can be predicted from past study results and construction records. However, silica fume's physical and chemical properties vary, and such properties as strength development and fluidity depend on the brand of cement to be used. It is therefore recommended to confirm in advance the properties of concrete by trial mixing using the silica fume and cement to be employed in actual construction when the properties of concrete cannot be predicted from existing data.

An increase in the silica fume replacement ratio in concrete may not lead to a noticeable reduction in temperature rise due to heat of hydration. It is therefore necessary, when using High-early- strength Portland Cement or Moderate-heat Portland Cement, to confirm by testing in advance that the purpose of using these cements is fulfilled.

Regarding (2) above

In composite cements, such as Portland Blast-furnace Slag Cement, Portland Pozzolan Cement, and Portland Fly Ash Cement, the content of the added component varies by type and brand. Accordingly, when using silica fume, adequate ratios of silica fume in place of such cements to obtain the required concrete performance cannot be established unless the content of the added component is determined. It is therefore necessary to confirm in advance the contents of blast- furnace slag, fly ash, etc., in the cement to be used. In the case where the content of such added components cannot be confirmed, the silica fume replacement ratio should be established by assuming that the added component equals the maximum and minimum JIS values for considering the strength and heat generation requirements, respectively, taking account of the intended use and safety.

3.4 Aggregate

Aggregates shall be clean, hard, and durable with proper grading, and shall not contain a deleterious amount of organic impurities, chlorides, and so on.

[Commentary]

When silica fume is used with the aim of increasing the strength, durability, etc. of concrete, special attention should be paid to the aggregates to be used as materials for concrete.

Chlorides contained in aggregate cause corrosion of reinforcing steel in reinforced concrete. Aggregate must be used with its chloride content reduced to a value lower than the permissible limits specified in the Standard Specification [Construction] by washing, etc., particularly when using sea sand.

There are reports indicating that the alkali-aggregate reaction can be inhibited by a silica fume replacement ratio of 15 to 20%. However, only aggregates proven to be harmless should be used as a rule, since silica fume's AAR-inhibiting effects vary depending on the type of aggregate, type of cement, and type of silica fume to be used (particularly alkali content), as well as the type and dosage of chemical admixtures.

With certain aggregates, a silica fume replacement in high strength concrete may not lead to the intended effects of strength improvement. This is attributed to the fact that the strength of the aggregate approaches that of the cement matrix, and therefore the effects of the aggregate strength on the compressive strength of concrete become evident. For this reason, aggregate used for high strength concrete should be of a quality confirmed in advance. It is generally desirable to use such hard aggregates as crushed hard sandstone or crushed limestone for high strength concrete containing silica fume.

3.5 Mineral admixtures

(1) Fly ash to be used as a mineral admixture shall conform to JIS A 6201 (Fly Ash).

(2) Ground granulated blast-furnace slag to be used as a mineral admixture shall conform to JIS A 6206 (Ground Granulated Blast-furnace Slag for Use in Concrete).

(3) For mineral admixtures other than (1) and (2), their quality shall be confirmed and the method of use shall be thoroughly examined.

[Commentary]

Regarding (1) and (2) above

Quality fly ash has such effects as improving the workability, reducing the hydration heat generation, and increasing the long-term strength of concrete. Ground granulated blast-furnace slag also has durability-increasing effects, AAR-inhibiting effects, etc. However, when using these mineral admixtures in combination with silica fume, their effects may vary depending on the type and content of silica fume and these mineral admixtures, water-binder ratio, etc. It is therefore necessary to confirm their properties in advance by testing.

Regarding (3) above

Mineral admixtures other than (1) and (2) include expansive admixtures (JIS A 6202), natural pozzolan, siliceous fine powder, and mineral admixtures for high strength. Adequately used expansive admixtures reduce cracking due to drying shrinkage, etc., of concrete. However, when using mineral admixtures for which no quality standard is available in combination with silica fume, their quality should be confirmed, and the method of use and the resulting concrete properties should be thoroughly examined by testing.

3.6 Chemical admixtures

(1) A high-range water-reducing agent (HWRA) or air-entraining and high-range water-reducing agent (AEHWRA) shall be used for concrete containing silica fume, as standard practice. The HWRA to be used as a chemical admixture shall be confirmed by testing that it produces concrete of the required

quality. Also, the AEHWRA to be used as a chemical admixture shall conform to JIS A 6204 (Chemical Admixtures for Concrete).

(2) When using an air-entraining agent, water-reducing agent, or air-entraining and water-reducing agent as a chemical admixture, they shall conform to JIS A 6204 (Chemical Admixtures for Concrete). Superplasticizers shall conform to JSCE Standard "Superplasticizers for Concrete".

(3) As for chemical admixtures other than the above, their quality shall be confirmed, and the method of use shall be thoroughly examined.

[Commentary]

Regarding (1) above

Being ultrafine particles, silica fume may not be sufficiently dispersed in concrete by normal mixing. Also, concrete containing silica fume with a high water-binder ratio tends to require an increased unit water content to obtain the same slump, due to the reduced fluidity. For this reason, this Recommendation (Draft) requires the use of a HWRA or AEHWRA as standard practice, to disperse silica fume sufficiently .in concrete and obtain the required consistency of concrete without increasing the unit water content. It should be noted that, without a HWRA or AEHWRA, the mere production of plastic concrete is impracticable in the case of high strength concrete.

As performance tests for AEHWRAs, JIS A 6204 (Chemical Admixtures for Concrete) is available. While JIS A 6204 covers a design strength of not more than 40 N/mm^2 , certain types of AEHWRA have a significantly increased water-reducing capability intended for a much higher strength range, and therefore may not conform to JIS A 6204. The performance of such admixtures is required to be confirmed before use by reliable records or testing.

When using a HWRA or AEHWRA, it is also advisable to select the type and dosage after confirming their compatibility with silica fume by testing, as their increased dosage could cause significant delays in setting and hardening.

Regarding (2) and (3) above

In the case of concrete containing silica fume, an air entraining agent, water-reducing agent, air-entraining and water-reducing agent, superplasticizer, and other admixtures may be used similarly to the case of ordinary concrete. Admixtures conforming to the quality standards by JIS or JSCE, where applicable, should be used. The performance of those for which no such standard is available should be confirmed by reliable records or testing.

Among admixtures generally accepted as having high performance, there are certain types which have not yet been proven to develop their full performance in combination with a high replacement ratio of silica fume. For instance, the air-entraining agent dosage for obtaining the required air content tends to increase with the increase in the specific surface area, carbon content, or replacement ratio of silica fume. It is therefore necessary to confirm not only the quality of the admixture, but also the method of use and properties of the resulting concrete in advance by testing.

CHAPTER 4 MIX PROPORTIONS

4.1 General

(1) Mix proportions of concrete containing silica fume shall be established so as to minimize the unit water content in the range of providing the required strength, durability, watertightness, steel-protective capability, as well as adequate workability.

(2) For concrete containing silica fume, a high-range water-reducing agent (HWRA) or air- entraining and high-range water-reducing agent (AEHWRA) shall be used as standard practice.

[Commentary]

Regarding (1) above

Mix proportions of concrete containing silica fume are basically the same as those of ordinary concrete, and should, as a rule, be established so as to minimize the unit water content. In addition, it is important to select the mix proportions so that the purpose of using silica fume can be sufficiently fulfilled.

Regarding (2) above

Since the use of silica fume generally tends to reduce the slump, a HWRA or AEHWRA is required to be used for concrete containing silica fume, as standard practice.

Without these agents, the unit water content has to be increased, causing various problems, such as increased thermal stress due to increased unit binder content, increased drying shrinkage and creep, and reduced strength. It is therefore necessary to use a HWRA or AEHWRA to reduce the unit water content.

4.2 Replacement ratio

The silica fume replacement ratio shall be appropriately established within a range of 5 to 15% according to the intended use. However, a replacement ratio out of this range may be used, if the performance has been confirmed in regard to the purpose of using silica fume.

[Commentary]

Silica fume brings such benefits as a higher strength, improved durability, and improved placeability of concrete. Effects of incorporating silica fume vary by the purpose of using silica fume and method of producing concrete. This Recommendation (Draft) specifies the silica fume replacement ratio for general purposes at 5 to 15% as the standard. Here the replacement ratio refers to the ratio of the mass of silica fume to the total mass of binders, which consist only of Portland Cement and silica fume.
The silica fume replacement ratios recommended for the purposes of increasing strength, improving durability, and improving placeability are given in **Commentary Table 4.1**.

To increase the strength of concrete, a replacement ratio of around 10% is mostly used domestically and overseas. Replacement ratios of 20 to 30% have also been adopted for autoclave-cured precast concrete products, to obtain a very high strength.

Commentary Table 4.1 Recommended silica fume replacement ratios

Silica Fume Replacement Ratio(%)	Purpose of Use						
	Strength	Durability				Placeability	
	S1	D1	D2	D3	D4	P1	P2
-5						△	△
5-10	○		○	△	○	○	○
10-15	○	△	○	△	○	△	△
15-	△	○			△		

Note S1: Increase Strength
Dl: Inhibit AAR
D2: Inhibit Chloride Resistance
D3: Improve Chemical Resistance
D4: Improve Abrasion Resistance
P1: Reduce Rebound
P2: Improve Pumpability
○ and △ denote "good" and "Fair", respectively.

As for durability improvement, each purpose has a different optimum replacement ratio. Whereas silica fume generally has AAR-inhibiting effects, it is also reported that a small addition of silica fume to a concrete containing an aggregate with a high alkali-aggregate reactivity can accelerate the alkali-silica reaction. There are also reports overseas that silica fume is used at a replacement ratio of about 5% as a solution to the case of using low-strength aggregate. Accordingly, it is advisable to establish the replacement ratio after confirming the expansibility of concrete in accordance with such methods as the concrete bar method discussed in Section 3.2.

Due to its dense hardened microstructure, concrete containing silica fume has a higher chemical resistance and watertightness than concrete without silica fume having the same water-binder ratio. It also significantly inhibits the penetration of substances involved in the corrosion of reinforcing steel, such as chloride ions, moisture, and oxygen. The increased electric resistance also restricts corrosive currents. However, a high silica fume content could weaken the freeze-thaw resistance, as the internal water pressure in the densified microstructure of concrete increases during freezing, or could aggravate chloride-induced corrosion of reinforcing steel, as the pozzolanic reaction lowers the pH values. The establishment of the replacement ratio therefore requires sufficient consideration.

To assure the resistance to freezing and thawing, it is preferable that the silica fume replacement ratio be not more than 15%.

There are examples in which a silica fume replacement ratio of 5% or less was applied to improve the pumpability or reduce the amount of bleeding water.

4.3 Water-binder ratio

4.3.1 General

The water-binder ratio of concrete containing silica fume shall be established suitably in consideration of the purpose of its use.

[Commentary]

As silica fume is expensive when compared with other mineral admixtures, its use should increase the added value of concrete. When increases in the strength and durability are intended, it is desirable that the water-binder ratio of concrete be not more than 50%. However, when a durability improvement is confirmed in concrete containing silica fume, the water-binder ratio may be established in accordance with the requirements of the Standard Specification [Construction] for ordinary concrete without silica fume. For the purpose of improving placeability, such as to improve the pumpability or to apply it to shotcrete, the water-binder ratio may also be established in accordance with the requirements for ordinary concrete without silica fume, when the performance is confirmed.

Where the purpose of use of the concrete requires resistance to frost damage and chemical action, the water-binder ratio may be established in accordance with Section 4.3 of the Standard Specification [Construction]. Also, where watertightness is required, the water-binder ratio may be established in accordance with Section 19.2 of the same.

4.3.2 Water-binder ratio based on compressive strength

(1) When establishing the water-binder ratio of concrete containing silica fume based on compressive strength, the relationship between compressive strength and the water-binder ratio shall, as a rule, be determined by testing. The standard test age shall be 28 days.

(2) The water-binder ratio, W/(C+SF), to be used for proportioning shall be the inverse number of the binder-water ratio corresponding to the proportioning strength, fcr, on the relationship line between the binder-water ratio, (C+SF)/W, and the compressive strength, fc at the specified age. This proportioning strength shall be obtained by multiplying the design strength, fck, by an appropriate factor. This factor shall be so established that the probability of strength test values falling below the design strength does not exceed 5%, according to the variation coefficient of compressive strength of concrete expected at each construction site.

[Commentary]

Regarding (1) above

Similarly to the case of ordinary concrete without silica fume, the compressive strength of concrete containing silica fume has a linear relationship with the binder-water ratio. Accordingly, the water-binder ratio of concrete containing silica fume is required, as a rule, to be established also by determining the relationship between the compressive strength and the binder-water ratio by testing. The determination of the relationship between the water-binder ratio and the compressive strength should be in accordance with the Standard Specification [Construction].

However, for concrete containing silica fume having a water-binder ratio of less than 25%, the compressive strength is not necessarily related linearly to the binder-water ratio. In such a case, the relationship between the compressive strength and the water-binder ratio should be carefully determined by testing.

Though the compressive strength of concrete containing silica fume increases beyond 28 days, 28days is specified as the standard age for compression tests, similarly to the case of ordinary concrete without silica fume. However, the establishment of the water-binder ratio may be based on a different age, if a different age is specified for the design strength or if the concrete is required to be proportioned early and the relationship between the 28-day strength and the strength at the specified age is clear.

Regarding (2) above
The variation coefficient of the compressive strength of concrete containing silica fume may be regarded to be nearly the same as that of ordinary concrete without silica fume.

4.4 Unit water content

Unit water content shall be established by testing so as to be at a minimum while the required qualities and adequate workability are obtained.

[Commentary]

The unit water content of concrete containing silica fume required for obtaining the specified slump depends on the quality, product form and replacement ratio of silica fume, maximum size of coarse aggregate, grading and shape of aggregate, sand-aggregate ratio, type of HWRA or AEHWRA, air content, and water-binder ratio, etc. The unit water content is therefore required to be established by testing on materials to be employed.

The slump of concrete containing silica fume generally decreases as the silica fume replacement ratio increases. For this reason, a suitable dosage of a HWRA or AEHWRA should be used as standard practice.

Without such agents, the unit water content increases, causing various problems, such as increased heat of hydration due to increased unit binder content, increased drying shrinkage and creep, and reduced strength. The unit water content should therefore be minimized as the water-binder ratio decreases. Though the unit water content depends on the HWRA or AEHWRA, air-entraining agent, and aggregate to be used, as well as sand-aggregate ratio, the upper limits of the unit water content are given in **Commentary Table 4.2.**

Commentary Table 4.2 Upper limits of unit water content of concrete

Maximum Aggregate Size (mm)	Untied Water content (kg/m3)
20-30	175
40	185

As a trend of the latest concrete technology, attempts are being made to improve the workability of concrete significantly by combining various mineral admixtures, a HWRA or AEHWRA, and a viscosity-increasing agent, and such concretes are beginning to be applied to real construction. It is important that the unit water content of such concretes should also not exceed the upper limit given in **Commentary Table 4.2.**

Also, the fluidity of concrete with a water-binder ratio of less than 35% tends to be improved when silica fume is incorporated. For such concrete as well, the establishment of the unit water content, type and dosage of the HWRA or AEHWRA, and sand-aggregate ratio should be carefully examined by testing.

4.5 Unit binder content

Unit binder content shall be established from the unit water content, water-binder ratio, and silica fume replacement ratio.

[Commentary]

The unit binder content should be established from the unit water content and the water-binder ratio established so as to obtain a concrete having the required strength, durability, watertightness, etc. The unit silica fume content can be determined from the unit binder content and silica fume replacement ratio.

The unit binder content of high strength concrete significantly increases with a reduction in the water-binder ratio. Accordingly, high strength concrete and mass concrete tend to be vulnerable to cracking due to hydration heat. This effect should be carefully taken into account when establishing the unit binder content.

4.6 Slump

The slump of concrete shall be minimized within the range suitable for transportation, placement, and consolidation, and shall be, as a rule, not more than 18 cm.

[Commentary]

Similarly to ordinary concrete without silica fume, the slump of concrete containing silica fume should, as a rule, also be minimized within the range suitable for work. However, a HWRA or AEHWRA is required to be used for concrete containing silica fume as standard practice, and in such a case, the concrete can be regarded as equivalent to superplasticized concrete. In consideration of this and the fact that concrete containing silica fume has high segregation resistance and scarce bleeding, the upper limit of the slump is specified to be 18 cm, similarly to superplasticized concrete.

When silica fume and a HWRA or AEHWRA are used in combination, a concrete can be easily made to have a slump of more than 18 cm, and this scarcely impairs the qualities of concrete. However, this Recommendation (Draft) specifies the slump to be not more than 18 cm as a rule, in consideration of the fact that there have been few applications of concrete containing silica fume with a slump of over 18 cm. When using such concrete with a slump of 18 cm or more, it should be proven to produce no deleterious effects, such as segregation, on the qualities of concrete by testing.

4.7 Sand-aggregate ratio

The sand-aggregate ratio shall be established by testing so that the unit water content is minimized while adequate workability is obtained.

[Commentary]

Silica fume generally tends to reduce the fluidity of concrete with a high water-binder ratio. It is therefore advisable that the sand-aggregate ratio be reduced from the value for ordinary concrete without silica fume, corresponding to the silica fume replacement ratio.

For instance, the sand-aggregate ratio can be reduced by 0.5 to 2 percentage points at a silica fume replacement ratio of 5 to 15%.

4.8 Air content of air-entrained concrete

(1) The air content of air-entrained concrete containing silica fume shall normally be 4 to 7% of concrete volume.

(2) Tests for determining the air content of air-entrained concrete shall be conducted in accordance with JIS A 1116, JIS A 1118, or JIS A 1128.

[Commentary]

Regarding (1) above

Concrete containing silica fume is also required, as a rule, to be air-entrained concrete, if it is subjected to severe weathering. Similarly to ordinary air-entrained concrete, the adequate air content should normally be 4 to 7% of the concrete volume. When the silica fume replacement ratio exceeds 15%, the freeze-thaw resistance is weakened in spite of entrained air. It is therefore undesirable to incorporate an excessively high replacement ratio of silica fume where concrete is subjected to severe weathering.

As the silica fume replacement ratio increases, entraining of air becomes more difficult. Also, a high percentage of entrained air hampers the benefits brought by silica fume, resulting in strength losses and wider quality variabilities. For this reason, the air content should be minimized within the range of obtaining resistance to freezing and thawing, when using air-entrained concrete where the weathering is moderate.

4.9 Unit content of admixtures

(1) The unit content of a HWRA, AEHWRA, air-entraining agent, and air-entraining and water-reducing agent shall be established by testing so as to obtain adequate workability and the required air content.

(2) The unit content of admixtures other than those mentioned in (1) above shall be established on the basis of test results and field experience so as to obtain the required effects.

[Commentary]

Regarding (1) above

The water-reducing ratio of a HWRA or AEHWRA varies depending on their main component and dosage. HWRAs and AEHWRAs may or may not be compatible with silica fume and/or cement, and therefore certain combinations of them can strongly affect the workability and strength properties, depending on the water-binder ratio. The carbon content in silica fume affects the air- entraining properties. Also, setting of concrete containing silica fume with a low water-binder ratio generally tends to be delayed. For this reason, the unit content of chemical admixtures, e.g., HWRAs and AEHWRAs, is required to be established by testing.

4.10 Form for expressing mix proportions

(1) Mix proportions of concrete shall be generally indicated in the form shown in **Table 4.1.**

Table 4.1 Form for expressing mix proportions

Max Size of Coarse Aggregate (mm)	Slump (cm)	Air Content (%)	Water Binder Ratio $\frac{W}{C+SF}$ (%)	Silica Fume Replacement Ratio $\frac{SF}{C+SF}$ (%)	s/a (%)	Unit Content (kg/m^3)					
						Water	Binder		Fine Aggregate	Coarse Aggregate G	Chemical Admixture
						W	Cement C	Silica Fume SF	S	mm -	

(2) In the specified mixes, fine aggregate is defined as entirely passing a 5 mm sieve, and coarse aggregate, entirely retained on a 5 mm sieve. Both aggregates shall be expressed in terms of their respective saturated surface-dry conditions.

(3) When converting the specified mix proportions into field mix proportions, the following shall be taken into account: the state of moisture absorption of aggregates, percentage of fine aggregate retained on a 5 mm sieve, percentage of coarse aggregate passing a 5 mm sieve, and the quantity of water used to dilute chemical admixtures.

[Commentary]

Regarding (1) above

Table 4.1 is specified on the basis of the Standard Specification [Construction], so as to clarify the replacement ratio and unit content of silica fume. The slump and air content of concrete containing silica fume must be controlled to fall in the specified ranges, similarly to the case of ordinary concrete without silica fume.

CHAPTER 5 PRODUCTION AND PLACING OF CONCRETE

5.1 General

(1) When producing concrete using silica fume, silica fume of the specified quality shall be accurately measured and thoroughly mixed to yield a uniform concrete.

(2) Adequate plans shall be formulated prior to producing, transporting, and placing concrete

containing silica fume.

[Commentary]

Regarding (1) above

When producing concrete using silica fume, it is necessary to recognize fully that silica fume forms a part of the binders and that silica fume as such has a high reactivity compared with other mineral admixtures, e.g., ground granulated blast-furnace slag and fly ash, and therefore has strong effects on the qualities of concrete.

Silica fume consists of agglomerates of ultrafine particles 0.1 μ m in average diameter, which are far finer than cement particles. In addition, silica fume in place of part of cement tends to reduce the fluidity of concrete, if the water-binder ratio is high. Silica fume is therefore hard to disperse in concrete. To obtain the full effects of incorporating silica fume, it is necessary to use silica fume of the specified quality, measure it accurately, and mix it thoroughly using an efficient mixer so as to disperse it uniformly in concrete.

Regarding (2) above

Being ultrafine particles, certain product types of silica fume may require special equipment with special operation. Also, concrete containing silica fume tends to have a reduced fluidity and increased segregation resistance, if its water-binder ratio is high. Accordingly, the production, transportation and placing plans should be formulated in consideration of silica fume's speciality as a material as well as the changes in the properties of concrete due to its reduced fluidity.

Since the use of a high-range water-reducing agent (HWRA) or air-entraining and high-range water-reducing agent (AEHWRA) is required for concrete containing silica fume as standard practice, the properties of concrete containing a HWRA or AEHWRA should also be considered. The slump of such a concrete can drastically change over time depending on the temperature conditions and transportation time. The transportation and placing plans should take this into account as well.

5.2 Transportation and storage of silica fume

(1) Suitable methods of transportation and storage shall be selected for silica fume according to the characteristics of each product form.

(2) Silica fume shall be transported and stored so as to prevent alteration of the quality and inclusion of foreign substances.

[Commentary]

Regarding (1) above

Silica fume is classified into powder, granules, and slurry by its product form. Since each product form requires different handling, care should be exercised according to each product form when using silica fume.

Due to its dustiness, powder silica fume tends to cause clogging in tanks and pipes, obstructing its conveyance. Special attention should therefore be paid to the equipment for acceptance/storage and conveyance to batchers. The use of powder silica fume in bulk is impracticable unless special equipment is available.

Granular silica fume is an improvement of powder silica fume to facilitate its handling. It is not dusty and easy to convey. In addition to the handling by bags, it can be transported in bulk by cement tankers, trucks, and railroads. Also, granules can be stored in ordinary cement silos, and are therefore suitable for concrete production at ordinary ready-mixed concrete plants.

There have been application examples of slurry silica fume in Japan, in which silica fume was slurried immediately before producing concrete with the aim of mixing it uniformly into concrete. When slurrying, its concentration should be carefully established, as it is directly related to the mixing water content and dosage of the HWRA or AEHWRA.

Regarding (2) above

Most of silica fume consumed in Japan is imported. It takes a long time to transport silica fume from its origin, e.g., Norway and Canada, and it may be stored for a certain period at port and warehouses. The routes of inland transportation may also be complicated. Accordingly, care should be exercised in the handling of silica fume during transportation and storage, as inadequate handling could cause inclusion of foreign substances and alteration of its qualities, such as an increased moisture content and caking due to moisture absorption.

Basically, dedicated equipment is desirable for the storage of silica fume. Where silica fume has to be stored in silos for cement or fly ash, it must be confirmed before charging silica fume that the previously stored materials are clearly removed, and the silos are thoroughly cleaned. As the apparent specific gravity of silica fume is smaller than cement, attention should be paid to its storage capacity.

The SiO^2 content of silica fume fluctuates depending on the types of metallic silicon and ferrosilicon, and the qualities of silica fume also fluctuate from one lot to another. It is therefore necessary to store silica fume of different lots separately, similarly to the above-mentioned separation from cement and fly ash, unless the qualities are proven to be the same by the manufacturer's test records or acceptance inspection.

When storing bagged silica fume, direct contact with the floor and walls should be avoided, similarly to the case of cement, to protect it from the effects of ground moisture and condensation on the walls during storage.

Slurried silica fume should be stored with special care. It should of course be stored in a dedicated tank that allows regular recirculation and agitation, and should be stabilized in an acid state by being acidified with dilute sulfuric acid to prevent gelling expansion.

5.3 Batching of silica fume

(1) The batching equipment for silica fume shall, as a rule, be dedicated to this purpose, and it shall be capable of weighing the quantity within the specified allowances for batching errors.

(2) Silica fume shall be weighed for each batch of concrete.

(3) Batching errors for powder and granular silica fume and silica fume slurried on site shall not be greater than 2% and 1% per batch, respectively.

[Commentary]

Regarding (1) above

Accurate batching is one of the key points to producing concrete containing silica fume. Silica fume forms a part of the binders and is a material by which the qualities of concrete are sensitively affected. An excessive batching error could cause not only failure to obtain the required qualities of concrete, but also failure to achieve the functions of the entire concrete structure required by the design. Accordingly, dedicated batching equipment is required to be used, as a rule. Where it is inevitable to use batching equipment for cement, its measuring accuracy must be carefully examined, to confirm that it is capable of judging the batching errors of silica fume. AHWRA or AEHWRA is required to be used as standard practice for producing concrete containing silica fume. Such admixtures may be batched using dispensing systems for such ordinary admixtures as water- reducing agents and air-entraining agents.

Regarding (2) above

Silica fume must be measured for each batch, similarly to other materials for concrete.

Powder and granular silica fume must be measured by weight.

When cumulatively batching powder or granular silica fume with cement, it is necessary to batch silica fume first, and then add cement to make cumulative batching. In such a case, the batching system must be capable of weighing each batch with an error of not more than 2% of silica fume for a batch.

Silica fume may be measured, according to the intended properties of concrete, by a method other than by weight in the following cases, but only after careful confirmation of the measuring accuracy by testing: when using silica fume slurried on site, etc., when using a special measuring system, such as a continuous dispenser for shotcrete, or when using bagged silica fume for a small-scale application.

Regarding (3) above

Minimizing batching errors is crucial for assuring the required qualities of concrete, because silica fume forms a part of binders, and the qualities of concrete are particularly sensitive to silica fume, while the replacement ratio of silica fume is relatively small at 5 to 15%.

When batching powder or granular silica fume, the batching system must be capable of weighing silica fume alone with a batching error of not more than 2%, and in addition, capable of weighing silica fume and cement with a cumulative batching error of not more than 1%.

When batching silica fume slurried on site, etc., mixing water is included in the measurement. For this reason, the allowance for the batching error is required to be 1%, according to the allowance for the batching error for mixing water. Silica fume slurried on site, etc., which is premixed with a HWRA or AEHWRA, requires further special consideration for batching accuracy.

5.4 Mixing

(1) The type of mixer and the order of charging materials into the mixer shall be appropriately established in advance.

(2) The mixing time shall, as a rule, be established by testing.

[Commentary]

Regarding (1) above

To obtain concrete with the required qualities using silica fume, it is essential to disperse silica fume uniformly in concrete. When the replacement ratio is high, a forced mixing type batch mixer must be used to ensure sufficient dispersion. Forced mixing type batch mixers include the pan type, uniaxial type, and biaxial type. These mixers may also have a variable rotation speed function or inverter function.

The fluidity of concrete containing silica fume generally tends to decrease when the water-binder ratio is high. It is therefore important to examine in advance the order of charging materials according to the characteristics of the mixer, so that concrete with the specified qualities can be efficiently mixed without overloading the mixer.

It is generally considered advisable to charge silica fume simultaneously with cement or immediately following cement. A HWRA or AEHWRA is required to be used for concrete containing silica fume. The timing of their addition should also be examined in full consideration of the required properties of concrete and production equipment.

When using silica fume slurried on site, etc., part of the mixing water is simultaneously added with silica fume. This requires attention, as the optimum mixing method for this case differs from those employed for powder and granular silica fume.

When a special mixer, such as a continuous mixer, is used, e.g. for shotcrete, it is advisable to select suitable equipment and production methods by which adequate mixing can be performed on the premise that silica fume is used.

Regarding (2) above

To assure the required qualities of concrete containing silica fume, the batch should be mixed for a sufficient period of time until silica fume and cement disperse uniformly in concrete. The time required for sufficient mixing in a batch mixer depends on the type and capacity of the mixer, batch size against the capacity, mix proportions of concrete, types of admixtures, order of charging materials, and concrete temperature. It is therefore advisable to establish the mixing time based on tests for the variability of unit weights of mortar and coarse aggregate as well as variability of slump, air content, and strength, using actual materials, production conditions, and temperature conditions to be employed.

5.5 Transportation and placing

(1) Concrete shall be quickly transported and immediately placed.

(2) The construction plan shall be formulated in consideration of the fluidity losses of concrete.

(3) After placing, concrete shall be consolidated quickly so that it is thoroughly worked around the steel reinforcement and into all comers of formwork.

(4) The surfaces of the placed concrete shall be finished by a method that takes account of the fluidity losses of concrete.

(5) Concrete shall be placed according to an appropriate construction plan to prevent cold joints.

[Commentary]

Regarding (1) above

Transportation and placing of concrete containing silica fume can be carried out similarly to ordinary concrete without silica fume. However, concrete containing silica fume tends to contain a high dosage of a HWRA or AEHWRA when compared with ordinary concrete, and the unit binder content also tends to be high in high strength concrete. This may lead to variations in the slump retention and setting time, depending on the brand and dosage of such admixtures. It is necessary to formulate transportation and placing plans in consideration of this and according to the construction conditions, so that the concrete properties necessary for placing are ensured.

Regarding (2) above

When the water-binder ratio is high, the fluidity of concrete containing silica fume tends to be lower than that of ordinary concrete without silica fume. When placing concrete, this fluidity loss must be taken into account in the plan.

The matters to be considered, e.g., for transportation are as follows: it takes longer to discharge concrete from an agitator truck; a considerable amount of mortar remains adhering to the interior of the drum of an agitator truck after the discharge; when pumping concrete, the suction efficiency of the concrete pump is lowered; and pressure losses in the piping are larger than with ordinary concrete.

Regarding (3) above

Concrete containing silica fume also requires thorough consolidation using a vibrator so that concrete is worked around the steel reinforcement, around embedded items, and into all comers of formwork to produce dense concrete. However, due to the lowered fluidity, the vibration propagation from the vibrator tends to be hampered in concrete containing silica fume with a high water-binder ratio. Consolidation of such concrete should therefore be carried out more carefully than for ordinary concrete without silica fume.

Concrete in which silica fume is incorporated with the aim of increasing the strength has a low water-binder ratio and high unit binder content, and therefore consolidation becomes even more difficult. The vibration scarcely propagates, with the radius of action being limited to 30 to 45 cm in some cases. The use of, e.g., vibrators with a large diameter and large amplitude should be considered in such a case. When placing such concrete, the construction plan should take account of this increased viscosity.

Regarding (4) and (5) above

Due to the low fluidity and scarce bleeding of concrete containing silica fume with a high water-binder ratio, finishing work tends to be more difficult than on ordinary concrete. Accordingly, it is necessary to prepare the work force, equipment, and curing materials required for the placing, consolidation, and finishing, so as to avoid the effects of high temperature, strong winds, low humidity, and direct sunlight as much as possible. There are also examples in which leveling work is carried out after spraying the finishing surfaces with a mist of water.

When fresh concrete is left as placed, a thin film tends to form on the surface, which would result in a cold joint if retained when the subsequent layer is placed. The time and method of jointing should therefore be examined as well when formulating a construction plan.

CHAPTER 6 CURING

6.1 General

(1) Beginning immediately after placement, concrete containing silica fume shall be cured by being maintained under the temperature and humidity conditions required for hardening and protected from the effects of deleterious environmental conditions.

(2) At early ages, concrete shall be cured so as to prevent plastic shrinkage cracking.

[Commentary]

Regarding (1) above

The qualities of concrete containing silica fume are strongly affected by the quality of moist curing, particularly at early ages, when compared with ordinary concrete without silica fume. Sufficient care should therefore be exercised for curing.

Since the long-term strength tends to become lower as the initial curing temperature rises, care should be taken to avoid excessively high temperatures for initial curing as well as placing, when silica fume is used for the purpose of strength enhancement. On the other hand, excessively low initial curing temperatures can adversely affect the development of long-term strength, as well as initial strength. This also requires attention. It is advisable that the maximum and minimum initial curing temperatures be around 35? and 10? , respectively.

Regarding (2) above

Concrete containing silica fume is vulnerable to plastic shrinkage cracking, since it undergoes large autogenous shrinkage at early ages and is easily exposed to drying due to scarce bleeding. This requires attention, as it tends to lead to low strength gains and significant durability losses. This tendency is more evident in mixes with lower water-binder ratios.

6.2 Moist curing

When curing concrete, moisture loss due to exposure to direct sunlight and wind shall be prevented. Exposed surfaces of concrete shall also be maintained wet throughout the curing period.

[Commentary]

Due to its large autogenous shrinkage at early ages, concrete containing silica fume is vulnerable to plastic shrinkage cracking. The influence of autogenous shrinkage on the early shrinkage is particularly strong in the case of high strength concrete. On the other hand, autogenous shrinkage and drying after the disappearing of bleeding water can cause plastic shrinkage cracking in the case of concrete with relatively low strength. Accordingly, it is advisable that curing of concrete containing silica fume include not only preventing of moisture loss but also wetting of the concrete surfaces.

Immediately after finishing, concrete should be moist-cured by coating with curing mats, etc., by a membrane-forming curing compound, or by ponding, to maintain the exposed concrete surfaces in a moist condition. To produce a watertight membrane using a membrane-forming curing compound, the following procedure is adopted: Level the concrete using wood floats or trowels and spray a sufficient amount of water. Sprinkle a membrane-forming curing compound evenly and then cover the surfaces with plastic sheeting. When using a membrane-forming curing compound, the coverage of the compound and time and method of application must be thoroughly examined by testing in advance.

To minimize the moisture loss, surfaces in contact with forms should also be covered with plastic sheeting, etc., to serve as shade and windbreak during the curing period. If the forms are thin or likely to become dry because of high temperature, they must be sprayed with water to keep the concrete wet. Where the forms of walls, beams, and columns have been partially removed, the exposed concrete surfaces must be maintained wet.

6.3 Period of moist curing

The curing period of concrete containing silica fume shall, as a rule, be established by testing.

[Commentary]

To increase the strength of concrete, the wet condition should generally be maintained as long as possible. Since silica fume is mostly incorporated with the aim of producing a high-strength concrete, initial curing is important from the standpoint of strength development as well. Accordingly, it is desirable to maintain the wet condition as long as possible, but it may be difficult for most ordinary structures. In accordance with the requirements for Ordinary Portland Cement, the curing period required for concrete containing silica fume is considered to be about 5 days at the shortest.

However, the required curing period may depend on the type of silica fume, type of cement, type and location of the structure, weather conditions the structure is to be exposed to, construction period, and construction method. Accordingly, the curing period is required to be established, as a rule, by thorough examination of the construction conditions and testing in advance.

It is advisable that the judgment of the time of form removal be made on the basis of the compressive strength of concrete specimens cured under the same conditions as the concrete in the structure.

6.4 Temperature-controlled curing

(1) Where necessary, concrete shall be cured with its temperature controlled, so as to maintain the concrete at temperature conditions required for hardening and protect it from deleterious effects of excessively low and high temperatures and sharp temperature changes for the period required for hardening.

(2) When curing concrete at controlled temperatures, the method of temperature control and period of curing shall be appropriately established in consideration of the type of concrete, shape and size of the structure, construction method, and environmental conditions.

[Commentary]

Regarding (1) and (2) above

An excessively low atmospheric temperature can hamper hydration of cement, leading to delayed strength development and initial frost damage. In such a case, temperature-controlled curing should be employed for a certain period by heating or heat insulation. When the daily mean temperature is 4C or lower, the curing method must be selected in accordance with Chapter 16 (Cold Weather Concreting) of the Standard Specifications [Construction]. On the other hand, an excessively high atmospheric temperature can lead to insufficient long-term strength gains and insufficient durability and watertightness, though it contributes to rapid strength development at early ages. Also, the concrete surfaces tend to be dry. When the daily mean temperature is 25°or higher, the curing method must be selected according to Chapter 17 (Hot Weather Concreting) of the Standard Specification [Construction].

Where an excessive temperature difference is expected or where the large size of a member suggests an excessive temperature rise, thermal cracks may occur due to thermal stress, similarly to the case of ordinary concrete without silica fume. Such a temperature or temperature gap should be controlled by embedded pipe cooling and/or surface insulation.

When temperature-controlled curing is to be employed, the method and duration of temperature control must be appropriately established in consideration of the type of concrete and the shape and size of the structure, so as to avoid deleterious effects of sharp temperature changes.

6.5 Accelerated curing

For accelerated curing, such as steam curing, the time to start curing, heating rate, cooling rate, curing temperature, and curing period shall be established, so as to avoid adverse effects on the concrete.

[Commentary]

When steam curing and other accelerated curing procedures are to be employed to accelerate hardening of concrete, the time to start curing, heating rate, cooling rate, curing temperature, and curing period should be established, with a thorough examination of past records, to avoid adverse effects on concrete.

CHAPTER 7 READY-MIXED CONCRETE

7.1 General

When silica fume is used for a ready-mixed concrete, the concrete shall, as a rule, conform to JIS A 5308.

[Commentary]

Ready-mixed concrete containing silica fume is also required, as a rule, to conform to JIS A 5308 (Ready-mixed Concrete). In addition to the provisions of JIS A 5308, this chapter provides matters specially required when producing concrete using silica fume at ready-mixed concrete plants.

7.2 Selection of concrete plants

(1) The supplier's plant of ready-mixed concrete shall, as a rule, be selected from among JIS-accredited plants operated or controlled by personnel who are authorized by JCI as Chief Concrete Engineer or Concrete Engineer.

(2) When selecting a plant, the following matters shall be taken into account: transportation time to the site, unloading time, concrete production capacity, number of transportation vehicles, and manufacturing equipment of the plant. Also, attention shall be paid to the storage equipment, batching equipment, and batching recorders for silica fume, as well as the state of controlling such equipment.

[Commentary]

Regarding (1) above

The use of silica fume for ready-mixed concrete has not been widely practiced yet, and the industry has only limited experience. Accordingly, when selecting a ready-mixed concrete plant, the selection is required, as a rule, to be made from among JIS-accredited plants that satisfy the requirements of Chapter 5 (Production and placing of concrete) and also are controlled or operated by a Chief Concrete Engineer or Concrete Engineer, to assure as high reliability as possible.

Regarding (2) above

As the fluidity properties of concrete containing silica fume are strongly affected by temperature, they can be significantly altered if the transportation and unloading take a long time. The plant should therefore be selected in consideration of the time during which the required fluidity properties can be retained. Silica fume should be handled as a high quality binder in the same way as cement. The plant to be selected should therefore be furnished with equipment to store silica fume under the same conditions as those for cement and equipment to batch it with the specified accuracy as stated in the Commentary of Section 5.3. The plant should also be such that the storage and batching are strictly controlled. It is desirable from the standpoint of mutual trust between the plant and the purchaser to select a plant equipped with a batching recorder that prints out the amount and replacement ratio in each batch so that the quantity of silica fume used can be confirmed.

7.3 Specification of qualities

When ordering a ready-mixed concrete containing silica fume, the nominal strength, slump, and air content shall be specified by establishing the qualities required at the point of unloading.

The purchaser shall further specify the following items, where required, by consulting with the manufacturer:

(a) Quality of silica fume
(b) Replacement ratio of silica fume
(c) Type of high-range water-reducing agent (HWRA) or air-entraining and high-range water-reducing agent (AEHWRA)
(d) Type of cement
(e) Type of aggregate
(f) Maximum size of coarse aggregate
(g) Class of aggregate by alkali reactivity (if Class B, method of inhibiting alkali-aggregate reaction)
(h) Type of admixture
(i) Upper limit of chloride content, if different from JIS A 5308
(j) Age of concrete to assure the nominal strength
(k) Maximum or minimum temperature of concrete
(l) Upper limit of water-binder ratio
(m) Upper limit of unit water content
(n) Lower or upper limit of unit cement content
(o) Slump gain of superplasticized concrete from ready-mixed concrete, if applicable
(p) Other necessary items

[Commentary]

When specifying the quality of silica fume, the properties of silica fume should be fully grasped in advance by testing for its quality.

The strength development properties, workability, and durability of concrete are affected by the replacement ratio of silica fume, type of HWRA or AEHWRA, type of cement, type of admixtures, and temperature. An order must therefore be placed after confirming by trial mixing that the order will lead to a concrete that satisfies these requirements.

Since silica fume and cement may or may not be compatible with certain types of HWRAs or AEHWRAs, their compatibility must particularly be confirmed in advance without fail.

7.4 Acceptance of supplied concrete

(1) Acceptance of supplied ready-mixed concrete shall be in accordance with the Standard Specification [Construction], Section 6.4 (Acceptance of Supplied Concrete), Subsections (1) through (4).

(2) The acceptance inspection of strength, slump, and air content shall be in accordance with JIS A 5308. The manufacturer shall make available, on demand by the purchaser, the quantity or replacement ratio of silica fume in each batch by means of printed records, etc.

[Commentary]

Regarding (1) above

The preparation for acceptance of concrete, communication with the manufacturer, point of unloading ready-mixed concrete, and other matters to be noted are required to be in accordance with the Standard Specification [Construction].

Regarding (2) above

Where the replacement ratio of silica fume is to be inspected, the inspection is required to be made by confirming the quantity or replacement ratio of silica fume in each batch on special printouts from a batching recorder.

CHAPTER8 QUALITY CONTROL AND INSPECTION

8.1 General

Concrete materials, machinery, equipment, and concreting operation shall be controlled in order to economically produce concrete and construct concrete structures with the required qualities using silica fume.

[Commentary]

The quality control and inspection of concrete containing silica fume may be carried out similarly to ordinary concrete without silica fume.

However, it should be noted that the qualities of concrete containing silica fume are strongly affected by environmental conditions, e.g., temperature, as well as the type and mixing efficiency of the mixer. Accordingly, when silica fume is incorporated, quality control and inspection of machinery, equipment, and concreting operation are particularly important as well as the concrete materials including silica fume.

Matters not specified in Chapter 8 should be in accordance with the Standard Specification [Construction].

8.2 Test methods

Test methods shall, as a rule, conform to the methods specified in JIS.

[Commentary]

It is important to conduct tests by common test methods for the quality control of concrete, regardless of using silica fume or not. Tests methods should conform to JIS, as a rule, but JSCE and ASTM standards may be used as required.

8.3 Tests on concrete materials

(1) Necessary tests on the materials shall be conducted to confirm their qualities prior to commencing construction.

(2) Tests on materials shall be conducted as required during construction to confirm their qualities and fluctuation of the qualities.

(3) Test methods specified in JSCE Standard "Silica Fume for Use in Concrete (Draft)" and JSCE Standard "Test Method for Specific Gravity of Silica Fume Using Measuring Flasks (Draft)" shall be normally employed for testing silica fume.

[Commentary]

Regarding (1) and (2) above

Regardless of using silica fume or not, it is important, from the standpoint of economically producing concrete with the required qualities, to conduct tests on materials to be used, including silica fume, cement, water, fine aggregate, coarse aggregate, and admixtures to judge their adequacy before starting construction. For concrete containing silica fume, tests should be conducted carefully particularly for the quality of silica fume, to establish the type and product form of silica fume.

Regarding (3) above

JSCE Standard "Silica Fume for Use in Concrete (Draft)" specifies the quality requirements, and JSCE Standard "Test Method for Specific Gravity of Silica Fume Using Measuring Flasks (Draft)" specifies the method of determining the specific gravity of silica fume necessary for mix design. However, these Standards (Draft) may not be sufficient for grasping the quality fluctuation of silica fume used for certain purposes. It is therefore necessary to control the quality of silica fume also referring to the results of quality tests on concrete.

8.4 Tests on concrete

(1) Preliminary tests for establishing mix proportions shall be conducted prior to construction. There shall also be inspections on the performance of machinery and equipment.

(2) Tests for the following shall be conducted as required during construction:

(a) Slump
(b) Air content
(c) Unit weight of concrete
(d) Chloride content of fresh concrete
(e) Compressive strength of concrete
(f) Temperature of concrete

(3) The concrete specimens cured under conditions as close to the field conditions as possible, shall be tested for strength to estimate the time for form removal and prestress application, as well as to ensure safety in case loading is applied to the structure at an early age.

(4) If necessary, non-destructive tests and tests on cores taken from the structure shall be conducted upon the job completion.

[Commentary]

Regarding (1) above

The slump-retaining capability and changes in air content over time of concrete containing silica fume depend on the type and brand of the high-range water-reducing agent (HWRA) or air- entraining and high-range water-reducing agent (AEHWRA), product form and replacement ratio of silica fume, water-binder ratio, sand-aggregate ratio, mixing method, etc. For this reason, in addition to the description in the Standard Specification [Construction], Section 13.2.3, Commentary (1), mix proportions of concrete must be established by testing, so as to obtain the specified slump and air content at the time of placing, in thorough consideration of the air temperature, transportation time, and construction conditions.

Regarding (2) above

The purposes of using silica fume for concrete are mostly to enhance the qualities, e.g. the strength, durability, and placeability, of concrete. Tests on concrete must therefore be conducted during construction to confirm that the structure is being constructed to possess the required qualities uniformly. It must be confirmed in advance that particularly the slump, air content, and compressive strength fall within the prescribed ranges.

Regarding (e) Compression test on concrete above

Conventional tests may be conducted for normal strength concrete containing silica fume. In the case of high strength concrete, however, the resulting compressive strength varies depending on the top surface finish, of concrete specimens. It is therefore desirable that the top surfaces of specimens be ground with greatest care using a good grinder to a plane perpendicular to the axis of each specimen. When capping the top surfaces, a high strength material matching the concrete strength should be used, and the caps should be as thin as practicable.

Regarding (3) above

Generally, it is necessary to estimate the strength of concrete in the structure, in order to determine the time of form removal and time of prestress application, or to ensure safety for applying loading. For this purpose, strength tests must be conducted using specimens cured under the same conditions as the concrete in the structure. When the strength test results fail to meet the requirements, the curing procedure must be reexamined. Where necessary, modification should be made to the curing procedure and/or materials and mix proportions.

Due to the relatively high dosage of a HWRA or AEHWRA, the strength development properties of concrete containing silica fume tend to be strongly affected by the adequacy of the initial curing procedure. Tests on specimens cured under conditions simulating the concrete in the structure are important for judging the adequacy of the curing method, particularly for concreting in cold weather.

8.5 Quality control of concrete

Quality control of concrete containing silica fume shall be exercised in accordance with the Standard Specification-1991 [Construction], Sections 13.3.1 and 13.3.2.

[Commentary]

Quality control of concrete containing silica fume may be exercised similarly to ordinary concrete without silica fume. However, when silica fume is incorporated in high strength concrete, the time and frequency of sampling should be established in consideration of the scarcity of service records compared with the case of normal strength concrete. It may be effective to establish a high testing frequency in the beginning of the construction and modify it after grasping the tendency of quality fluctuation.

8.6 Quality inspection of concrete

Quality inspection of concrete containing silica fume shall be exercised in accordance with the Standard Specification-1991 [Construction], Section 13.4.

[Commentary]

The quality inspection of concrete containing silica fume may be exercised similarly to ordinary concrete without silica fume. When failure to attain the required qualities is suspected or evident from the inspection results, a reassessment must be made on the quality of the materials, mix proportions, and equipment and procedures for batching, mixing, transporting, and placing. When the causes of the nonconformity are identified, adequate remedial measures must be taken.

CHAPTER 9 GENERAL CONSIDERATIONS FOR STRUCTURAL DESIGN

9.1 General

(1) For the design of a concrete structure or its members incorporating silica fume, design values suitable for the required concrete strength shall be employed.

(2) This chapter provides general considerations specially required for the design of structures using concretes with a design strength of more than 60 N/mm^2 and not more than 100 N/mm^2. Matters not contained in this chapter shall be in accordance with the Standard Specification-1991 [Design].

(3) Design of concrete with a design strength of 60 N/mm^2 or less shall be in accordance with the Standard Specification-1991 [Design]. For concrete with a design strength of more than 100 N/mm^2, the required safety shall be confirmed as a rule by appropriate testing.

[Commentary]

Regarding (1) above

One of the purposes of using silica fume for concrete is to increase its strength. It is known that mechanical properties of concrete vary depending on its strength. In particular, the fracture of high strength concrete is known to tend to become brittle. This is indicated by stress-strain curves of high strength concrete under uniaxial compression; the ascending portion and post-peak descending portion of such curves become steeper than those of normal strength concrete. For this reason, when designing a structure or its members using concrete with a high strength, its safety must be ensured by employing design values relevant to the strength. Also, the qualities of high strength concrete are expected to be strongly affected by the quality of silica fume, quality of aggregate, mix proportions of concrete, and construction conditions. Accordingly, care should be exercised for these items, and where any of these items causes a significant design concern, appropriate design values must be established by sufficient testing for the item in question.

Regarding (2) and (3) above

Mechanical properties of concrete gradually change, starting from a strength of over 40 N/mm^2, and the properties of high strength concrete become evident from over 60 N/mm^2. This Recommendation (Draft) sets a boundary at 60 N/mm^2, where the properties of concrete begin to change, and applies the concept of high strength to concretes with a strength exceeding that.

There are many reference materials for concrete with a strength of up to 100 N/mm^2, since a lot of experimental data from all aspects have been accumulated in recent years, and standards are being devised overseas.

This chapter provides general considerations related to the design values and design concept for concrete with a strength of more than 60 N/mm^2 and not more than 100 N/mm^2, using such data and reference materials. Matters not contained here and considerations for strengths of 60 N/mm^2 or lower should be in accordance with the Standard Specifications [Design]. As for concrete with a strength of over 100 N/mm^2, only limited experimental data under limited conditions is available. This Recommendation (Draft) requires that safety of such concrete should be confirmed, as a rule, by appropriate testing.

The presence of silica fume is considered to scarcely affect the mechanical properties of concrete, e.g., strength properties and deformation properties, provided the strength is the same. Accordingly, the requirements of this chapter are also applicable to high strength concrete without silica fume. However, high strength concretes incorporating synthetic resins, such as polymer concrete, are not covered by this chapter, as their mechanical properties widely differ from cementitious concretes.

9.2 Design values of materials

9.2.1 Strength of concrete

(1) The characteristic values of concrete strengths shall be established, as a rule, on the basis of the strengths tested at 28 days. However, test strengths at an appropriate age other than this may be employed depending on the purpose of the structure, construction plan, and time of applying the principal loading.

The compression tests shall be in accordance with JIS A 1108 (Test Methods for Compressive Strength

of Concrete).
The tension tests shall be in accordance with JIS A 1113 (Test Methods for Tensile Strength of Concrete).
The flexure tests shall be in accordance with JIS A 1106 (Test Methods for Flexural Strength of Concrete).

(2) The characteristic values of bond strength and bearing strength shall be established, as a rule, on the basis of the strength determined by appropriate testing.

(3) The characteristic values of flexural strength and tensile strength may be determined from the equations given in the Standard Specification-1991 [Design] Section 3.2, on the basis of the characteristic value of compressive strength (design strength), fck.

(4) The material coefficient for concrete, ? c, may be normally assumed to be 1.5 for the investigation of the ultimate limit state and fatigue limit state, and 1.0 for the investigation of the serviceability limit state.

[Commentary]

Regarding (3) above

It is accepted by past experimental results that the evaluations by Equations 3.2.1 and 3.2.2 given in the Standard Specification [Design], if applied to the strength range of this Recommendation (Draft), are equivalent to those in the range for normal strength concrete. Accordingly, the characteristic values of the flexural and tensile strengths are permitted to be determined from Equation 3.2.1 and Equation 3.2.2, respectively, on the basis of the characteristic value of the compressive strength, fck. The Equations 3.2.1 and 3.2.2 in terms of N/mm^2 are expressed as follows, respectively, for reference:

Flexural strength $fbk = 0.42\ fck^{2/3}$ (Commentary 9.1)
Tensile strength $ftk = 0.23\ fck^{2/3}$ (Commentary 9.2)

The characteristic values of bearing strength and bond strength are required to be determined, as a rule, by testing, due to the scarcity of test data regarding high strength concrete, though their tendency to increase with the compressive strength is acknowledged.

Regarding (4) above

Conventionally, when investigating the ultimate limit state, the compressive strength of concrete used for the design is required to be 0.85 times the design compressive strength obtained by dividing the characteristic value of the compressive strength, fck, by the material coefficient, ? c, in order to incorporate the effects of the difference between the strength of specimens and uniaxial compressive strength, as well as the effect of continued loading. Though these effects may all be incorporated more appropriately by means of material coefficients, the conventional approach of using the constant 0.85 was retained as it is in this Recommendation (Draft).

Recent studies indicate that a higher strength leads to a wider difference between the strength of concrete in the structure and the strength of specimens. Also, in the high strength range covered by this Recommendation (Draft), experimental data on full-scale specimens is limited, and so are applications to real structures, though there is a large store of experimental data on model specimens. In consideration of these facts, this Recommendation (Draft) adopts a more conservative value of 1.5 for the material coefficient, ? c, than for normal strength concrete, for the investigation of the ultimate limit sate and fatigue limit state. This is not applicable to the cases where safety is confirmed by appropriate testing.

Commentary Table 9.1 gives the design strengths determined by assuming ? c to be 1.5 and 1.0, for reference.

Commentary Table 9.1 Design Strength in N/mm^2

Limit State		Ultimate Limit State					Serviceability Limit State				
Specific Concrete Strength	f'_{ck}	60	70	80	90	100	60	70	80	90	100
Design Compressive Strength	f'_{cd}	40	47	53	60	67	-	-	-	-	-
Design Flexural Strength	f'_{bd}	4.2	4.6	5.1	5.5	5.9	6.3	7.0	7.6	8.2	8.8
Design Tensile Strength	f_{td}	2.3	2.6	2.8	3.1	3.3	3.5	3.9	4.3	4.6	4.9

9.2.2 Stress-strain curve

(1) A suitable stress-strain curve of concrete shall be assumed for each purpose of investigation.

(2) A modeled stress-strain curve as shown in **Fig. 9.1** may be employed for the investigation of the ultimate limit state for sectional failure of members subjected to bending moment with or without axial force.

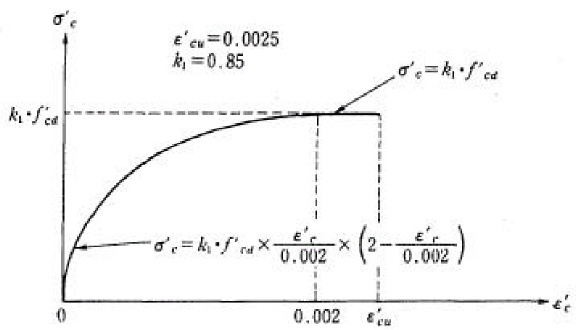

Fig. 9.1 Modeled Stress-Strain Curve of Concrete

(3) When investigating the serviceability limit state, the stress-strain curve of concrete may be assumed to be a straight line. The elastic modulus for this case shall be determined in accordance with Section 9.2.3.

[Commentary]

Regarding (1) above

The stress-strain curve of concrete widely varies depending on the type, strength, and age of concrete, stress conditions acting on the concrete, loading rate, and loading path. A suitable shape must therefore be assumed for a stress-strain curve of concrete to prevent under- or overestimation of the deformation and sectional load-bearing capacity.

It is generally known that a higher strength of concrete leads to steeper slopes of the ascending and descending portions of the stress-strain curve and a slightly larger strain at the maximum stress than normal strength.

Regarding (2) above

There are cases in which the differences of the shape of stress-strain curves have no appreciable influences on the calculated ultimate load-bearing capacity, as in the case of the ultimate load- bearing capacity of a bar member section. A stress-strain curve as shown in **Fig. 9.1** or a certain suitable shape, e.g., a rectangle, may be assumed for such cases. In the modeled stress-strain curve shown in **Fig. 9.1,** the ultimate strain is assumed to be smaller than that of normal strength concrete, to represent the brittle failure due to high strength. On the other hand, a suitable curve representing the actual relationship including the descending portion should be assumed in the case of investigating the deformation or ductility of a bar member to the ultimate state, where the influence of the stress-strain curve shape is significant.

9.2.3 Modulus of elasticity

(1) The modulus of elasticity of concrete to be used for the calculation of the elastic deformation or the redundant force shall be, as a rule, determined as follows: Obtain a stress-strain curve by testing in accordance with JSCE Standard "Test Methods for Static Modulus of Elasticity of Concrete (Draft)." The modulus shall be an average of test values of the secant modulus connecting the one third point of the compressive strength and the point of strain at 50×10^{-6} on the stress-strain curve.

(2) When the compression test results are not employed, the values given in **Table 9.1** may generally be used as the modulus of elasticity.

Table 9.1 Elastic Modulus of Concrete

f_{ck} (N/mm^2)	60	70	80	90	100
Elastic Modulus E_c(10^3 N/mm^2)	35	37	38	40	41

[Commentary]

Regarding (2) above

The values given in **Table 9.1** may generally be employed for the calculation of the elastic deformation or redundant force in the serviceability limit state. The values given in **Table 9.1** are established on the basis of a regression of about 1400 pieces of data that have been obtained so far, incorporating the excess strength added to the design strength for the actual use.

It is known that high strength concrete is more strongly affected by the type and quality of the aggregate than normal strength concrete, and that the fluctuation of elastic modulus of high strength concretes of the same strength is wider than that of normal strength concretes.

The influence of the elastic modulus of concrete on the safety of a structure is insignificant when compared with other characteristic values. However, where the elastic modulus has profound effects on the design calculations, it is desirable that a measured value be adopted, using the materials to be employed, if necessary.

9.2.4 Poisson's ratio

Poisson's ratio of concrete may generally be assumed to be 0.2 within the elastic range. However, it shall be assumed to be 0.0 in the case where the concrete is subjected to tension and cracking is permitted.

9.2.5 Shrinkage

(1) The shrinkage of concrete shall be established, as a rule, in consideration of the effects of the ambient humidity, cross-sectional shape and dimensions of the member, and proportions of concrete, and other factors.

(2) Both autogenous shrinkage and drying shrinkage shall be considered as the shrinkage of concrete.

[Commentary]

Regarding (1) above

Shrinkage of concrete is affected by various factors, such as the ambient temperature and humidity, cross-sectional shape and dimensions of the member, mix proportions of concrete, as well as the properties of aggregate, type of cement, consolidation conditions, and curing conditions of concrete. The shrinkage strain of concrete to be used for design is therefore required to be established, as a rule, in consideration of these factors.

Regarding (2) above

When the water-binder ratio is 40 to 60%, autogenous shrinkage is relatively small, while drying-induced shrinkage accounts for most of the total shrinkage. The effects of silica fume on the shrinkage are also considered to be small. Accordingly, the values for the drying shrinkage in Table 3.2.2 in Section 3.2.7 of the Standard Specification [Design] may be used as the value to be used for design.

On the other hand, when the water-binder ratio is 30% or less and the shrinkage from early ages is to be considered, the influence of autogenous shrinkage becomes predominant. The autogenous shrinkage is not only affected by the water-binder ratio, but also by the type of cement, type of silica fume, environment, and temperature. There have not been sufficient data to quantify these effects. It is therefore desirable to establish the value of autogenous shrinkage by sufficient testing.

9.2.6 Creep

(1) The creep strain of concrete may generally be determined by Equation 9.1, on the assumption that it is proportional to elastic strain caused by the applied stress:

e‘ cc== f ·s' cp/Ec (9.1)

where e`cc: compressive creep strain of concrete
f : creep coefficient
s'cp: applied unit compressive stress
Ec : elastic modulus of concrete

(2) The creep coefficient of concrete shall be established, as a rule, in consideration of the ambient

humidity, cross-sectional shape and dimensions of the member, mix proportions of concrete, curing conditions, and age of concrete when stress is applied.

(3) For prestressed concrete, the creep coefficient values given in Section 3.2.8, Table 3.2.2 of the Standard Specification-1991 [Design] may be used.

[Commentary]

Regarding (2) above

Creep of concrete is affected by various factors, e.g., the ambient temperature and humidity, cross-sectional shape and dimensions of the member, mix proportions of concrete, age of concrete when the load is applied, as well as properties of aggregate, type of cement, and consolidation and curing conditions of concrete. Accordingly, the values of the creep coefficient of concrete to be used for the design should be appropriately established referring to test results as well as records of past test results and measurements of real structures.

Regarding (3) above

Though there have been a lot of qualitative data indicating the general tendency of the creep coefficient to decrease as the strength of concrete increases, quantitative evaluations of the creep coefficient will require further accumulation of research efforts and confirmation by measurement. Accordingly, this Recommendation (Draft) permits the general use of the creep coefficient values given in Section 3.2.8, Table 3.2.2 in the Standard Specification [Design] as the creep coefficient for prestressed concrete.

Where the creep is considered to have significant influence on the design, it should be established on the basis of sufficient testing.

9.3 Investigation of ultimate limit state

9.3.1 Investigation of safety against bending moment and axial force

(1) For members subjected to an axial compressive force, the upper limit value of the axial compressive load-bearing capacity, N'oud, shall be calculated in accordance with the requirements of the Standard Specification-1991 [Design], Section 6.2.1, Subsection (1).
(2) When calculating the design sectional load-bearing capacity of a member subjected to bending moment with or without an axial force per section or unit width of the section of the member according to the direction of the sectional force, the calculation shall be based on Assumptions (I) through (IV) given below. In this case, the member coefficient, ? b, may generally be assumed to be 1.15.

(I) The strain is proportional to the distance from the neutral axis of the section.
(II) The tensile stress of concrete is disregarded.
(III) The stress-strain curve of concrete, as a rule, is as shown in **Fig. 9.1.**
(IV) The stress-strain curve of steel reinforcement, as a rule, is in accordance with the Standard Specification-1991 [Design], Section 3.3.3.

(3) With regard to the design sectional load-bearing capacity, the distribution of the unit compressive stress of concrete may be assumed to be rectangular (equivalent stress block) as shown in **Fig. 9.2,** excepting the case where all of the strains in the section of the member are compressive.

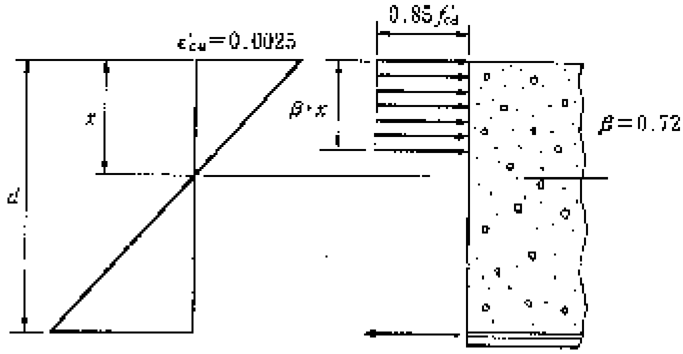

Fig. 9.2 Equivalent Stress Block

(4) If the influence of the bending moment is predominant in a bar member, the minimum reinforcement content shall be established in consideration of the properties of the member, so that reinforcement does not yield when flexural cracking occurs in the member.

(5) If the influence of the bending moment is predominant in a bar member, the content of axial tensile reinforcement shall be not more than 75% of the balanced reinforcement ratio.

[Commentary]

Regarding (3) above

The distribution of unit compressive stress generally tends to approach a triangle, as the strength of concrete increases. However, this Recommendation (Draft) requires a rectangular distribution to be employed similarly to the case of normal strength concrete. The tendency of high-strength is incorporated by reducing the coefficient ß for the effective depth of the equivalent stress block.

Regarding (4) above

The use of a high strength concrete increases the flexural cracking moment. This suggests that when flexural cracking occurs, the possibility of brittle failure of the member due to the yield or rupture of reinforcement becomes higher than with a reinforced concrete member made using normal strength concrete. To prevent such brittle failure, here the minimum reinforcement content is required to be calculated for each member, instead of the conventional requirement for the use of specified values.

Regarding (5) above

An excessive content of axial reinforcement may not only cause difficulty in the bar arrangement but also could lead to brittle failure, due to the failure of concrete in compression at the time of sectional failure. For this reason, the maximum tension reinforcement content is required to allow a margin for the balanced reinforcement ratio. The balanced reinforcement ratio of high-strength concrete in the ultimate state may be determined by Equation Commentary 9.3:

$$Pb = 0.61 \cdot (e'_{cu} /(e'_{cu} + f_{yd} / Es)) \cdot (f'_{cd} / f_{yd}) \qquad \text{(Commentary 9.3)}$$

where Pb : balanced reinforcement ratio

e'_{cu} : ultimate strain of concrete, generally 0.0025

f_{yd} : design yield strength of tension reinforcement (N/mm^2)

Es : elastic modulus of reinforcement, generally 2.0×10^5 N/mm^2

9.3.2 Confirmation of safety against shearing force

Safety against shearing force shall be investigated in accordance with the Standard Specification- 1991 [Design], Section 6.3.

[Commentary]

It has been confirmed by past experimental results that safety is comfortably assured when the equation for calculating the design shear strength (Eq. 6.3.2) given in Section 6.3 of the Standard Specification [Design] is applied to the high strength range covered by this Recommendation (Draft). The investigation of safety against shearing force in this Recommendation (Draft) is therefore required to be carried out in accordance with the Standard Specification [Design], Section 6.3.

It should be noted that the minimum content of shear reinforcement must be suitably established corresponding to the increased strength of concrete. Due to the scarcity of data to determine this value quantitatively, an appropriate minimum content of shear reinforcement should be established by testing.

9.4 Investigation of serviceability limit state

The serviceability limit state shall be investigated in accordance with the Standard Specification- 1991 [Design], Chapter 7 (Investigation of Serviceability Limit State).

[Commentary]

Various situations are conceived as the serviceability limit state depending on the service conditions, but generally it may be sufficient to establish the serviceability limit states for cracking, displacement/deformation, and vibration.

Past experimental results indicate a widening tendency of crack intervals of reinforced concrete members as the strength of concrete increases. However, in the range covered by this Recommendation (Draft), it has been confirmed that such crack intervals are practically the same as those of normal strength concrete. Accordingly, safety is sufficiently ensured by applying the equation for calculating flexural cracking (Eq. 7.3.1) given in the Standard Specification [Design], Chapter 7. The investigation of serviceability limit state is therefore required to be carried out in accordance with the Standard Specification [Design], Chapter 7.

9.5 Investigation of fatigue limit state

The fatigue limit state shall be investigated in accordance with the Standard Specification-1991 [Design], Chapter 8 (Investigation of Fatigue Limit State).

[Commentary]

The investigation of rupture of reinforcement subjected to repeated tensile stress is generally the only requirement regarding fatigue of beams and slabs. However, fatigue of concrete should also be investigated when the concrete is in a wet condition, which reduces the fatigue strength of concrete when compared with the air-dried condition.

The fatigue strength of concrete generally increases along with the compressive strength, but experimental data is scarcely available for the fatigue strength of concrete with a compressive strength of over 70 N/mm^2. Accumulation of such data to enable quantitative evaluation is awaited. Accordingly, fatigue of concrete is required to be investigated in accordance with the Standard Specification [Design], Chapter 8 (Investigation of Fatigue Limit State). This is applied to a range of f'ck of up to 70 N/mm in the case of compressive fatigue and to a f'ck range of up to 60 N/mm^2 in the case of flexural-compressive fatigue, in consideration of the fact that experimental data is limited for flexural-compressive fatigue, and that such data includes reports indicating that no marked increase in fatigue life is expected from an increase in compressive strength.

This is not applicable to the case where safety has been confirmed by appropriate testing.

9.6 General structural details

General structural details shall be in accordance with the Standard Specifications-1991 [Design], Chapter 10.

[Commentary]

Though the strength, durability, and watertightness of concrete containing silica fume are expected to be enhanced by the densified microstructure of hardened concrete, information on its material properties and reliability of construction are still insufficient. Accordingly, it is advisable that the values specified in Section 10.2 of the Standard Specification [Design] be applied to structural details, e.g., the minimum concrete cover.

This is not applicable to the case where the performance has been confirmed by appropriate testing.

CHAPTER 10 MARINE CONCRETE

10.1 Scope

This chapter provides the standards for matters specially required when incorporating silica fume in marine concrete.

[Commentary]

Silica fume is known to enhance the resistance of concrete to chloride ion penetration. Corrosion prevention of steel encased in marine concrete structures subjected to harsh environments is therefore a promising area for the effective utilization of silica fume. Silica fume has already been used for a number of marine concrete structures overseas, such as large platforms for petroleum excavation.

This chapter contains matters that require special considerations when using concrete containing silica fume for marine concrete structures.

10.2 General

When using silica fume for marine concrete, the replacement ratio of silica fume, mix proportions of concrete, and minimum concrete cover for reinforcement shall be established to impart the required load-bearing capacity and durability to concrete structures, while ensuring adequate workability during placing.

[Commentary]

Marine concrete structures are gradually damaged by various harmful actions, such as physical and chemical actions of seawater, weathering, and impact and abrasion by waves and drifting objects. Concrete used for such structures is required not only to be resistant to these actions but also have a high capability of protecting steel. Among these required qualities, those related to the former are resistance to frost damage, abrasion resistance, and chemical resistance to salts contained in seawater. Those related to the latter are resistance to chloride penetration, electrical resistance, resistance to water and air permeation, and resistance to carbonation.

Though the evaluation of the effects of silica fume on these qualities is still unsettled on some points, silica fume is proven to improve resistance to chloride ion penetration, electrical resistance, and resistance to water and air permeation significantly by increasing the strength and densifying the microstructure of hardened concrete. Resistance of concrete containing silica fume to chloride ion penetration is higher than concrete made using Ordinary Portland Cement without silica fume on the same compressive strength level, and the improving effect increases as the strength level increases. However, the use of silica fume can adversely affect the capability of protecting reinforcing steel, due to the reduced pH in pore water, when the replacement ratio is as high as 30% or when the unit cement content is low. Also, a large replacement ratio can slightly accelerate carbonation of concrete, though silica fume's effect on carbonation is normally marginal. For this reason, replacement ratios in the range of 5 to 15% are recommended when using silica fume for marine concrete structures, similarly to general concrete structures containing silica fume covered by this Recommendation (Draft). There are past examples in which a replacement ratio of less than 5% was adopted even for marine concrete structures, to improve the pumpability.

When using silica fume as well, the water-cement ratio, unit cement content, and air content shall conform to the requirements of the Standard Specification [Construction], Chapter 22 (Marine Concrete). The concrete cover depth should, as a rule, conform to the requirements of the Standard Specifications [Design], Section 10.2 (Cover). However, when a significant improvement is confirmed in the capability of protecting steel reinforcement by the use of silica fume and adoption of a low water-binder ratio, the minimum cover depth may be reduced accordingly.

10.3 Concreting work

When using silica fume for marine concrete, special care shall be exercised for the producing, conveying, placing, finishing, and curing of concrete, to prevent such defects as cold joints, honeycombs, and deleterious cracks.

[Commentary]

Well-organized concreting work is generally vital for marine structures with or without silica fume, as an interruption to the process can cause nonuniform weaknesses in concrete, such as cold joints, honeycombs, and deleterious cracking, from which deterioration easily propagates.

The scarce bleeding of concrete containing silica fume tends to cause plastic shrinkage cracking due to drying immediately after placing. It is important, beginning white placing, to provide a shade and windbreak and to speed-up the finishing to minimize the time before the start of curing, in order to protect concrete from such plastic cracking and ensure the resistance to chloride ion penetration, which is essential for marine concrete structures. Moist curing should be used, and the period of curing should be in accordance with the requirements of the Standard Specification [Construction], Section 8.2 (Moist Curing), according to the type of cement used. The concrete should be protected from being washed away at least during the period of moist curing.

Where long transportation time is expected, such as the case of carrying truck agitators on a verge, it is desirable that equipment and personnel for superplasticizing be arranged to ensure adequate workability for depositing and consolidating. When producing concrete containing silica fume on a concrete plant ship, storage equipment that will not allow moisture absorption of silica fume and appropriate batching equipment are required.

CHAPTER 11 PAVEMENT CONCRETE

11.1 Scope

This chapter provides the standards for matters specially required when incorporating silica fume for pavement concrete.

[Commentary]

The use of silica fume increases compressive strength of pavement concrete along with flexural strength and abrasion resistance. Concrete pavements are therefore a promising area for the effective utilization of silica fume.

This chapter contains matters that require special considerations when using silica fume for pavement concrete.

As to matters not specified in this chapter, the Standard Specification [Pavement] should apply.

11.2 General

When using silica fume for pavement concrete, the replacement ratio of silica fume and mix proportions of concrete shall be established to impart the required flexural strength, durability, and abrasion resistance to the pavement slabs.

[Commentary]

Concrete pavements are subjected to heavy duty compared with other structures. They are exposed to weather for a number of years, flexural stress from traffic loads, and cyclic stress from daily temperature changes. Concrete for pavements is therefore required to have such capabilities as high flexural strength, small drying shrinkage, and high abrasion resistance.

Concrete containing silica fume is known to have a higher compressive strength than ordinary concrete without it, and this leads to a higher flexural strength and abrasion resistance. For this reason, pavement concrete is a promising usage for silica fume. Whereas there have been few application examples in Japan, some examples have been reported overseas. In Norway, concrete containing silica fume with a 28-day compressive strength of 90 N/mm^2 was used for highway pavement with the aim of surface protection from abrasion by spike tires and salt damage by deicers. In the U.S., concrete containing silica fume with a 28-day compressive strength of 80 N/mm^2 was used as an overlay for pavement.

The mix proportions and replacement ratio should, as a rule, be established by testing, so as to obtain economically the qualities required of pavements. Maximum effects of improving flexural strength are reportedly obtained with a replacement ratio of slightly less than 10%. The drying shrinkage is said to be equivalent to or smaller than the case without silica fume, if the water-binder ratio is around 45% or lower. The abrasion resistance is reported to be improved significantly by using good-quality aggregate and adopting a compressive strength level of 80 to 90 N/mm^2. Accordingly, concrete containing silica fume is recommended where traffic stoppage should be minimized once the pavement is put into use, such as pavements in tunnels.

11.3 Concreting work

When using silica fume for pavement concrete, special care shall be exercised during consolidating, finishing, and curing of concrete, to assure the required flexural strength.

[Commentary]

The process of concrete paving after unloading of concrete generally includes spreading, consolidating, rough finishing, smoothing, and surface texturing.

When the water-binder ratio is high, entrapped air in concrete containing silica fume tends to remain entrapped, due to the reduced fluidity. When consolidating such concrete, sufficient vibratory consolidation should be carried out using a vibrator suitable for the slab thickness.

Concrete containing silica fume, with its scarce bleeding, is vulnerable to plastic shrinkage cracking from an early age after placing due to drying by wind and sunshine. Early drying also adversely affects the strength development and durability. For this reason, it is important to protect the concrete surface from drying while placing, carry out finishing quickly, and start moist curing immediately after finishing. However, it is difficult to maintain relatively large areas of pavement in a moist condition, beginning immediately after finishing. In such a case, coating the concrete surface with a membrane-forming curing compound is effective in preventing moisture loss. Such a membrane-forming curing compound should be sprayed sufficiently and uniformly at an appropriate time. The amount and method of spraying should therefore be examined by testing in advance. White-colored or other color compounds are useful for ensuring the coverage. Such membrane curing should also be followed by wet-cloth curing using wet curing mats or sheeting, or moist curing using water spray.

The moist curing should be continued until the flexural strength attains 0.70 fbr (fbr = specified strength of concrete), similarly to ordinary concrete without silica fume.

CHAPTER 12 SHOTCRETE

12.1 Scope

This chapter provides the standards for matters specially required when incorporating silica fume for shotcrete.

[Commentary]

This chapter provides the standards for the case of using concrete containing silica fume for shotcrete for lining tunnels and large-scale underground structures, protecting slopes and walls, patching deteriorated structures, etc.

12.2 General

When using silica fume for shotcrete, the materials, mix proportions, replacement ratio of silica fume, and shotcrete machinery and equipment shall be selected, and the application shall be carried out under an adequate control of these factors to obtain the intended effects.

[Commentary]

Shotcrete containing silica fume is used for tunnel lining and repair of deteriorated structures in Europe and the U.S. The purpose of using such concrete is, reportedly, to enhance the qualities of shotcrete and improve the work efficiency and work environment. Application experiments and trial applications are under way in Japan as well, exhibiting various improvements. Shotcrete is one of the promising fields for making the most of the advantages of silica fume.

In recent years, one-pass lining of tunnels, etc., as a permanent structure has been investigated using high strength and high durability shotcrete, in which the content of a set-accelerating agent is reduced by an addition of silica fume.

The capabilities of shotcrete improved by incorporating silica fume are as follows:

(1) Improvement of qualities: improvements in strength, watertightness, and resistance to frost damage
(2) Improvement of work efficiency: improvement inpumpability, reduction of rebound
(3) Improvement of work environment: reduction of dust

However, the evaluation of these improving effects still wavers on some points. The degree of improving effects is considered to depend on such factors as the method of application, application equipment, materials, and mix proportions. For this reason, when using silica fume for shotcrete, the application conditions, required qualities, and desired effects should be clearly identified, and the mix proportions and application method should be established to meet such requirements. The qualities of the shotcrete should also be controlled by appropriate procedures.

Ensuring an adequate content of entrained air, reducing the water-cement ratio, and increasing the unit binder ratio are said to be effective in improving freeze-thaw resistance also in the case of shotcrete containing silica fume.

The replacement ratio of silica fume should be selected according to the purpose of its use, so as to attain the required qualities of shotcrete. A replacement ratio in the range of 5 to 10% is generally adopted.

12.3 Materials

(1) Silica fume conforming to JSCE Standard "Silica Fume for Use in Concrete (Draft)" shall normally be used.

(2) Other admixtures shall be selected so that a concrete of the required qualities is obtained.

[Commentary]

Regarding (1) above

JSCE Standard "Silica Fume for Use in Concrete (Draft)" specifies the activity index and chemical components of silica fume on the premise that its use improves the strength and durability. Accordingly, when using silica fume for these purposes, silica fume conforming to this standard must be used. However, when the main purpose of using silica fume is to improve the work efficiency, i.e., to improve the pumpability, reduce the rebound and dust, etc., the use is out of the scope of the JSCE Standard. In such a case, silica fume not satisfying the requirements of the JSCE Standard may be used, if a concrete of the required qualities is ensured by testing.

Regarding (2) above

Chemical admixtures used for shotcrete are set-accelerating agents, dust-reducing agents, air-entraining and water-reducing agents, and high-range water-reducing agents (HWRA) or air-entraining and high-range water-reducing agents (AEHWRA). Those for which quality specifications by JIS or JSCE are available should conform to such specifications.

Also, when using these admixtures, their compatibility with silica fume, method of use, and the properties of concrete should be confirmed by testing in advance.

12.4 Concreting work

When using silica fume for shotcrete, special care shall be exercised as to the method of applying concrete and early curing.

[Commentary]

Shotcrete application methods are roughly classified into dry processes and wet processes. The former are processes in which concrete mixed in advance in a mixer is applied, and the latter are processes in which dry-mixed materials are mixed with water at the nozzle and applied. Silica fume disperses differently into the concrete matrices by different methods, affecting the qualities of the shotcretes. It is therefore necessary to examine the type of mixer, order of material charging, and mixing method according to the processes when using silica fume for shotcrete. Mixing to ensure sufficient dispersion, for instance, is required for a wet process, whereas the following is attempted as a dry process: a mixture of slurry silica fume and water is mixed with the dry-mixed materials just before the nozzle section.

In the wet processes, the increased viscosity of concrete containing silica fume increases the pumping load on the shotcrete equipment, and can cause pulsing of concrete and clogging of the piping. Care should therefore be exercised in selecting the shotcrete equipment as well

Concrete containing silica fume is said to undergo large early shrinkages. It is therefore desirable in the case of shotcrete as well that initial curing, e.g., moist curing, be started immediately after the application.

CHAPTER 13 CONCRETE PRODUCTS

13.1 Scope

This chapter provides the standards for matters specially required when incorporating silica fume for concrete products.

[Commentary]

This chapter provides the standards for the case of manufacturing concrete products using silica fume at a plant where the manufacturing process is systematically controlled. Accordingly, plain and reinforced concrete products as well as prestressed concrete products are covered. This chapter is not applicable to products produced in the yards near construction sites.

13.2 General

When using silica fume for concrete products, special care shall be exercised as to the materials, mix proportions, mixing, consolidating, and curing, so that the performance of silica fume is fully achieved.

[Commentary]

Concrete products are generally manufactured using stiff-consistency concrete with a low water-cement ratio, and their mix proportions tend to differ from those of cast-in-place concrete. Manufacturing processes also differ from ordinary concrete: each type of product requires its own consolidation conditions, such as centrifugal consolidation, and curing is in most cases accelerated using, e.g., steam.

As stated in earlier chapters up to Chapter 9, production of concrete containing silica fume generally requires more careful control than ordinary concrete with no silica fume. Incorporating silica fume in concrete products at precast concrete plants includes conditions different from ordinary cases of using silica fume for cast-in-place concrete, as a matter of course. For this reason, when manufacturing and placing concrete products containing silica fume, care should be exercised so that the purpose of using silica fume is fulfilled.

The manufacturing of concrete products has the following characteristics compared with in-situ placing:

(1) A better control of materials, mix proportions, production, and curing can be carried out systematically.

(2) Production is carried out by skilled workers, and the variability of qualities can be minimized by automated processes.

(3) Concrete products can be produced continuously under the same manufacturing conditions, and performance tests can be easily conducted using real products.

(4) Various production and curing methods can be adopted, to produce concretes with special features.

Consequently, silica fume is practicable, with its remarkable advantages being achieved, at precast concrete plants where good production control is excercised systematically. For instance, concrete having a very high compressive strength, which is one of the greatest advantages of using silica fume, can be produced relatively easily at plants where concrete with a low water-cement ratio can be controlled under special conditions.

It is desirable that qualified engineers, such as Chief Concrete Engineers and Concrete Engineers be assigned on a full-time basis at plants manufacturing concrete products containing silica fume, in order to exercise sufficient control over the production and placement thereof.

13.3 Quality of concrete

(1) Concrete used for concrete products shall possess the required strength and durability with minimum variability of qualities.

(2) The strength of concrete for concrete products shall normally be specified on the basis of the compression test values at 14 days.

(3) In the case where extremely high strength concrete can be produced constantly by special mix proportions and a special production method, the design of concrete products containing silica fume shall be in accordance with Section 9.1, Subsection (3), and the performance of such products shall be confirmed by testing.

[Commentary]

Regarding (1) above

The purposes of using silica fume for concrete products are to enhance the strength and durability, develop high early strength, reduce segregation, enhance the fluidity, inhibit efflorescence, change the color of concrete, or combinations thereof. Accordingly, when using silica fume for concrete products, the concrete should not only possess the qualities required for the purpose corresponding to the type and usage of the product, but also the basic qualities required of concrete, such as strength, durability, watertightness, capability to protect embedded steel, as a matter of course.

Regarding (2) above

Low water-cement ratios and accelerated curing are generally employed for concrete for manufacturing concrete products with the aim of developing high early strength and increasing the strength. The main purpose of using silica fume is also to develop high early strength and enhance the strength and durability. For this reason, 14 days was adopted as the standard age for specifying the compressive strength of concrete containing silica fume, as in the case of conventional concrete. Where autoclave curing or other special accelerated curing is applied, strength develops at early ages, and later strength development may be almost ignored. In such a case, an age earlier than 14 days, e.g., 7 days, may be used to specify the strength.

Strength of concrete products, for which the curing is not accelerated, gradually develops with age. Also, in the case of products with a relatively large thickness, the effects of accelerated curing may be weakened by the thickness. In such instances, it is desirable that the strength be specified based on the 28-day compressive strength.

Regarding (3) above

Concretes containing silica fume with a 91-day compressive strength in the order of 120 N/mm^2 are already placed on site overseas. There has so far been an example of placing a 100 N/mm^2 concrete in Japan. In the future, concretes with a higher strength are expected to become widely adopted, as concrete containing silica fume finds wider applications. To obtain very high compressive strength by using silica fume is considered to become one of the most significant uses of silica fume.

One way of obtaining so-called superhigh strength concrete using silica fume is to utilize special mix proportions and production methods under sufficient quality control of precast concrete plants. If, for instance, a concrete containing good quality aggregate with a silica fume replacement ratio of 20%, water-binder ratio of 25%, and a slump of 12 cm is steam-cured, its 14-day compressive strength can be higher than 100 N/mm^2. An example of a very high compressive strength in the order of 150 N/mm^2 is reportedly obtained by autoclave-curing of a mixture of the above- mentioned proportions.

Concretes covered by Chapter 9 are in the design strength range of 60 to 100 N/mm^2. If a concrete that meets a design strength of over 100 N/mm^2 can be constantly obtained with minimum variability of qualities using' the above-mentioned special mix proportions and production methods, the design values may be established differently outside the scope of Chapter 9. In such a case as well, appropriate design values should be established, as a rule, by conducting sufficient tests to confirm the mechanical properties of the high strength concrete and in consideration of the general design considerations provided in Chapter 9. It should also be confirmed that the required safety of the concrete products is ensured by confirming their performance by means of appropriate tests on real products.

13.4 Materials and mix proportions

(1) Silica fume shall, as a rule, conform to JSCE Standard "Silica Fume for Use in Concrete (Draft)".

(2) The mix proportions of concrete containing silica fume shall be appropriately established to provide the required qualities in consideration of the methods of fabrication and curing of the concrete products.

[Commentary]

Regarding (1) above

Strength enhancement and early strength development are the main purposes of using silica fume for concrete products among the many purposes stated in the Commentary regarding (1) of Section 13.3. In this case, it is essential to select the silica fume after sufficiently examining its quality, as the quality of silica fume directly affects the strength. For this purpose, silica fume conforming to JSCE Standard "Silica Fume for Use in Concrete (Draft)" shall, as a rule, be used. Particularly when the purpose of using silica fume is to enhance strength, it is vital to select silica fume with a high SiO^2 content and large specific surface area among those conforming to the Standard. It should be noted that the color of hardened concrete containing silica fume can vary widely depending on the type of silica fume and time of procurement. The color should be confirmed by testing in advance, and it is desirable to grasp the degree of the color variability.

Regarding (2) above

When using silica fume for concrete products, the mix proportions should be established in consideration of the quality and replacement ratio of silica fume, properties of fresh concrete, strength of concrete after hardening, etc., according to the purpose of the product, as a matter of course. The range of replacement ratios of silica fume to enhance the strength is generally 10 to 15%, but this can be increased to 20 to 30% when a very high strength is to be obtained using autoclave curing. The slump may vary widely depending on the method of fabrication: from 0 cm for pressure consolidation to 18 cm for centrifugal consolidation. Accordingly, the mix proportions of concrete should be established by testing, so that products of the required quality can be obtained, in consideration of the dispersibility of silica fume, consolidation conditions related to the fabrication methods, accelerated curing conditions using steam or an autoclave, and production conditions using other special processes.

13.5 Mixing

Concrete containing silica fume shall, as a rule, be mixed using a suitable batch-type mixer.

[Commentary]

While the degree of fluidity of concrete containing silica fume varies depending on the purpose of the product, the fluidity of concrete in which silica fume is contained to enhance the strength tends to decrease. Accordingly, the mixing time of concrete is generally extended. In some cases even 2 or 3 min of mixing may be necessary, and therefore forced mixing type mixers are suitable. In such a case, the type of mixer, product form of silica fume, order of charging, and mixing method, such as mixing time, should be examined in advance by testing, so that concrete in which silica fume is well-dispersed with the required workability is obtained efficiently.

13.6 Consolidation

Concrete containing silica fume shall be consolidated mechanically to obtain concrete products with the required qualities.

[Commentary]

Consolidation methods for concrete products are roughly classified into three categories: vibratory consolidation, centrifugal consolidation, and pressure consolidation. There are also combinations of these methods. The types of concrete products are closely related to their consolidation methods. Concrete containing silica fume for concrete products is normally consolidated and fabricated in a state with a relatively high viscosity. It is therefore necessary to select and properly execute a suitable consolidation method for the production of each type of concrete product, so that concrete is filled in all comers of formwork, entrapping minimum air.

13.7 Accelerated curing

Accelerated curing processes for concrete containing silica fume shall be such as to cause no deleterious cracks or other defects in the concrete, or to have no adverse effects on its long-term strength, durability, and other qualities.

[Commentary]

One of the major purposes of using concrete containing silica fume for concrete products is to obtain the required strength at an early age, in order to increase the form turnover, thereby enhancing the productivity, and to ship products early, thereby shortening the construction period. For this purpose, the process generally in practice is to accelerate the hardening of concrete by steam curing at a normal pressure. When performing steam curing, the following will cause cracking, scaling, and deformation of concrete: exposing concrete to steam immediately after being fabricated, drying concrete during initial curing, abrupt increase in temperature, curing at an excessively high temperature, and removing products while heated and cooling them abruptly. Also, a curing process with such sudden changes in temperature can adversely affect the long-term strength and durability of the concrete products. Accordingly, when establishing the curing method, a method suitable for concrete containing silica fume should be selected referring to JIS, etc., for steam curing methods of concrete products.

There are other curing methods whereby nearly the final strength of the concrete is attained at an earlier age even when silica fume is incorporated: autoclave curing, which uses high-temperature steam with a pressure of as high as 7 to 12 times the atmospheric pressure; and pressure curing, in which fabricated concrete products are cured with steam at a temperature of 100? under a pressure of 0.5 to 1.0 N/mm^2 . These processes are carried out at a temperature higher than those for steam curing under a normal pressure, and therefore require strict examination of the curing conditions, to avoid adverse effects on the concrete.

13.8 Quality control and testing

(1) When manufacturing concrete products containing silica fume, the materials, manufacturing process, and production equipment shall be controlled by establishing appropriate standards.

(2) Compression tests and other tests shall be conducted as required to judge the qualities of concrete products containing silica fume.

[Commentary]

Regarding (1) above

When manufacturing concrete products containing silica fume, it is important to exercise a more appropriate quality control over the entire production process, including the materials, manufacturing operation, and production equipment than the control practiced for conventional concrete products. This is because silica fume is mostly used to increase the strength of concrete, and the resulting concretes tend to have high viscosity with a low water-cement ratio. Such concretes require more careful control of the materials, mixing, consolidating, and curing. The control of the plant equipment is also important, as conveying and batching silica fume can be more difficult than in the case of cement.

Regarding (2) above

The quality of concrete products containing silica fume is affected by a number of factors in the manufacturing process from the materials through curing. To maintain the required quality of concrete products, it is important to grasp the state of quality control of concrete containing silica fume. To this end, necessary tests must be carried out, as a matter of course. The quality of products can be judged by testing the strength of real products, and this is an advantage of concrete products. Accordingly, concrete products should be tested according to methods using real products established for each product, to assure that they have the required qualities.

Standard Specification for Silica Fume for Use in Concrete (Draft) (JSCE-D 106-1995)

1. Scope

This specification covers the quality of silica fume to be used as an admixture for cement paste, mortar, and concrete.

2. Definitions

The meanings of certain terms used in this specification are defined as given in JIS A 0203 (Concrete Terminology) and as follows:

(1) Silica fume: Spherical ultrafine particles comprising amorphous SiO^2 generated during the production of metafile silicon and ferrosilicon.

(2) Reference mortar: Mortar produced from Ordinary Portland Cement and used as a reference in the quality tests of silica fume.

(3) Test mortar: Mortar produced from Ordinary Portland Cement and the silica fume to be tested at a mixing ratio of 9:1 by mass.

(4) Activity index: The ratio of the compressive strength of the test mortar to the compressive strength of the reference mortar expressed as a percentage.

3. Quality requirements

Silica fume shall conform to the requirements set forth in **Table 1** by the tests in accordance with Section 4.

Table 1 Quality requirements for silica fume

Quality		Requirement
Specific Surface Area (BET method)		≥10
Activity Indent %	7days	≥95
	28days	≥105
Silicon Dioxide (sio2) %		≥85
Magnesium Oxide (MgO) %		≤5.0
Sulfure Trioxide (SO3) %		≤3.0
Ignition Loss %		≤5.0
Hygroscopic moisture %		≤3.0

4. Tests

4.1 Sampling: Samples shall be prepared as follows:

(1) The amount and method of sampling shall be decided by consultation between the parties concerned.
(2) Samples shall be prepared in accordance with JIS R 5201 (Physical Testing Methods of Cement),

Section 4 (2).

4.2 Specific gravity

The specific gravity test shall be in accordance with JSCE-D 502 "Test Method for Specific Gravity of Silica Fume Using a Volumetric Flask (Draft)."

4.3 Specific surface area

The specific surface area shall be determined by the BET adsorption method using nitrogen gas.

4.4 Activity index

The activity index test shall be in accordance with Section 5.

4.5 Silicon dioxide

Silicon dioxide shall be determined in accordance with JIS M 8852 (Methods for Chemical Analysis of Silicastone), Section 7 (Determination of Silicon Dioxide).

4.6 Magnesium oxide

Magnesium oxide shall be determined in accordance with JIS R 5202 (Chemical Testing Methods of Cement), Section 12 (Determination of Magnesium Oxide), after being alkali-decomposed in accordance with JIS M 8852 (Methods for Chemical Analysis of Silicastone).

4.7 Sulfur trioxide

Sulfur trioxide shall be determined in accordance with JIS R 5202 (Chemical Testing Methods of Cement), Section 13 (Determination of Sulfur Dioxide), after being alkali-decomposed in accordance with JIS M 8852 (Methods for Chemical Analysis of Silicastone).

4.8 Ignition loss

The ignition loss shall be determined in accordance with JIS A 6201 (Fly Ash), Section 6.2 (Ignition Loss).

4.9 Hygroscopic moisture

The hygroscopic moisture shall be determined in accordance with JIS A 6201 (Fly Ash), Section 6.1 (Hygroscopic Moisture).

5. Activity index

The activity index shall be determined as follows:

5.1 Apparatus

The test apparatus shall comprise a mixer and molds to fabricate mortar specimens specified in JIS R 5201 (Physical Testing Methods of Cement), Section 10 (Strength Tests). The table vibrator for consolidation shall conform to ISO 679 (Methods of testing cements-Determination of strength).

5.2 Materials

(1) The cement shall be a blend of three brands, in equal parts, of Ordinary Portland Cements from different manufacturers arbitrarily selected. Each cement of the blend shall conform to JIS R 5210 (Portland Cement).

(2) The binder used for the test mortar shall be a blend of the cement and silica fume at a ratio of 9:1 by mass.

(3) The fine aggregate shall be ISO standard sand. Its grading shall be as given in **Table 2**.

Table 2 Grading of Fine Aggregate

Standard Sieve Opening (mm)	2.0	1.6	1.0	0.5	0.16	0.080
Accumulate Percentage Retained on the Sieve (%)	0	7 ± 5	33 ± 5	67 ± 5	87 ± 5	99 ± 1

(4) The mixing water shall be either purified or tap water.

5.3 Sampling

Silica fume shall be sampled in a manner to obtain its representative quality[1)]

Note 1): A back-up sample of at least 1 kg should be stored in a sealed container for retesting.

5.4 Test method

(1) Mix proportions of reference and test mortars

The mix proportions of the reference and test mortars shall be as follows: To 1.0 part of cement/binder, 3.0 parts by mass of fine aggregate are used. The water-cement ratio (water-binder ratio) is 0.50. The batch size shall be as follows [2)]:

Cement or binder: 450 g, fine aggregate: 1,350 g, and water: 225 g
Note 2): These amounts will provide 6 compression specimens or 2 flow tests.

(2) Mixing method for reference mortar

Set the mixing bowl and paddle at the mixing position, and charge water. Then add cement and mix for 30 sec. at a low speed. During the following 30 sec. ,charge sand at a constant rate with the mixer running. Switch to a high speed and mix the mortar for 30 sec. followed by a 90-sec. rest. Scrape off the mortar adhering to the paddle and wall of the bowl during the first 15 sec. ,Of the rest time. Cover the top of the bowl with a well-wrung damp cloth for the remaining rest time. Restart the mixer and mix for 60 sec. at a high speed. The overall mixing time including the rest timeis4min.

When the mixing is complete, remove the bowl from the mixer and remix the mortar 10 times with a spoon.

Remark - This mixing method conforms to ISO 679 (Methods of Testing Cements-Determination of Strength).

(3) Mixing method for test mortar

Prior to charging into the bowl, thoroughly dry-mix 405 g of cement with 45 g of silica fume. Set the mixing bowl and paddle at the mixing position, and charge water. Then add the mixture of cement and silica fume, and mix for 30 sec. at a low speed. During the following 30 sec. charge sand at a constant rate with the mixer running. Switch to a high speed and mix the mortar for 30 sec. followed by a 90 sec. rest. Scrape off the mortar adhering to the paddle and wall of the bowl during the first 15 sec. of the rest time. Cover the top of the bowl with a well-wrung damp cloth for the remaining rest time. Restart the mixer and mix for 120 sec. at a high speed. The overall mixing time including the rest time is 5 min..

When the mixing is complete, remove the bowl from the mixer and remix the mortar 10 times with a spoon.

(4) Measurement of mortar flow

Determine the mortar flow in accordance with JIS R 5201 (Physical Testing Methods of Cement), Section 10.7 (Flow Test).

(5) Preparation of test specimens

Place the mortar into the molds in two layers as follows: Deposit the mortar up to half of the depth of the mold, and distribute it evenly. Consolidate the first layer using a table vibrator. Deposit the second layer, level the top surface, and consolidate again with the table vibrator. Immediately after the consolidation, strike off the top surface with a metal straightedge. Spade the mortar once along each side and end of the mold with a suitable tool. Finally, flatten the top surface not by pressing but by smoothing down lightly. Mark the mold so that the specimen will be identifiable at the time of demolding. After a lapse of not less than 20 hr from the completion of placing, carefully remove the specimens from the molds and place them in a water tank, immersing them completely in water[3)].

Note 3) : The specimens used for testing at each age should be gathered from the widest variety batches.

(6) Compression test

Conduct compression tests in accordance with JIS R 5201 (Physical Testing Methods of Cement), Section 10.5 (Measurement) and Section 10.6 (Calculation). The portions of beams broken in the flexure tests shall be used as the specimens for each age. The number of specimens shall total six for each age, and each age group shall contain two or more specimens from each batch. The test ages shall be 7 and 28 days.

(7) Activity index

Calculate the ratio of the compressive strength of test mortar to that of the reference mortar at each specified age by the equation below, rounding off to an integer in accordance with JIS Z 8401 (Rounding off of values). The obtained integer shall be the activity index for the age.

$$A = c2/c1 \times 100$$

where
A = activity index (%)
c1 = average of compressive strengths of 6 specimens of reference mortar at each age (N/mm^2)
c2 = average of compressive strengths of 6 specimens of test mortar at each age (N/mm^2)

Test Method for Specific Gravity of Silica Fume Using a Volumetric Flask (Draft) (JSCE - D 502 -1995)

1. Scope

This test method covers the determination of specific gravity used in the calculation for mix design of silica fume used as an admixture in fresh concrete.

2. Apparatus

2.1 The balance shall have a capacity of 1 kg or more and sensitivity to 0.01 g or less.

2.2 The volumetric flask shall have a capacity of 500 ml and shall be calibrated to an accuracy of 0.15 ml at 20℃.

3. Sampling

3.1 Silica fume shall be sampled in a manner to obtain its representative quality. The minimum weight of a sample shall be 100 g.

3.2 The sample of 3.1 above shall be divided into two subsamples, each of which will be used for one test.

4. Procedure

4.1 Weigh the volumetric flask to the nearest 0.01 g (Wf). Introduce approximately 30 g of a subsample of 3.2 above to the flask and then re-weigh the flask with the sample to the nearest 0.01 g(Wa).

4.2 Fill the flask about half full with demineralized water. Shake the flask so that the sample is dispersed in the demineralized water. Fill with additional demineralized water to the mark. Roll and agitate the flask at an interval of 15 min until all air bubbles are eliminated. Alternatively, use a vacuum pump to eliminate air bubbles. Place the flask in a constant temperature water bath of 23±0.5 ? until the temperature of the flask and its contents is constant, and bring the water level in the volumetric flask to its calibrated capacity.

4.3 Wipe dry the outside of the volumetric flask, and determine the total weight of the flask, sample, and water to the nearest 0.01 g (Ws).

4.4 Remove the sample from the volumetric flask, and thoroughly rinse the flask. Fill the volumetric flask to its calibrated capacity with demineralized water at 23 ±0.5? , and determine the weight of the flask with water to the nearest 0.01 g (Wt).

5. Calculation

5.1 Calculate the specific gravity of silica fume determined with a volumetric flask (Dsf) by the equation given below, rounding off to three significant figures in accordance with JIS Z 8401 (Rounding off of values).

$$D_{sf} = (W_a - W_f)\{500 - [(W_s - W_a)/D_w]\}$$

where Dsf = specific gravity of silica fume determined with a volumetric flask

Wf = weight of empty flask (g)

Wa = weight of flask with approximately 30 g of sample (g)

Ws = weight of flask, sample, and demineralized water filled to the mark (g)

Wt = weight of flask with demineralized water filled to the mark (g)

Dw = (Wt - Wf)/500, density of demineralized water (g/cm^3)

5.2 Two tests shall be conducted on the two subsamples taken simultaneously, and the average shall be the test value.

6. Precision

The deviation from the average shall not be greater than 0.01.

7. Report

The report shall include the following:

(1) Name [1)], product form, and place of origin [2)] of silica fume,

(2) Sampled points and date and time of sampling, and

(3) Specific gravity determined with a volumetric flask.

Note 1) : The brand name may be reported for the name of silica fume.

Note 2) : The name of the producing country may be reported for the place of origin, in the case of imported silica fume.