I. RECOMMENDATION FOR DESIGN AND CONSTRUCTION OF STEEL FIBER REINFORCED CONCRETE

CHAPTER 1. GENERAL

ARTICLE 1. Scope

This recommendation presents the general standards which are particularly required for design and construction of steel fiber reinforced concrete. Items not specified in this recommendation shall be in accordance with JSCE "Standard Specifications for Non-Reinforced and Reinforced Concrete".

(Commentary)

Steel fiber reinforced concrete (SFRC) is a composite material aimed to improve tensile strength, flexural strength, resistance to cracking, toughness, shearing strength, shock resistance, etc. by distributing discontinuous short steel fibers uniformly in concrete.

In general, the steel fibers used are 25 ∿ 40 mm in length, 0.3 ∿ 0.6 mm in diameter and approximately 50 ∿ 80 in aspect ratio (ratio of length to diameter), and the range of steel fiber content is 0.5 ∿ 2.0% by volume (approximately 40 ∿ 160 kg/m^3).

Since the steel fibers restrict the development of existing inner cracks in concrete, SFRC has excellent resistance to the formation of cracks. Tensile strength of concrete is correspondingly larger as steel fiber content increases. Also, since the balance of force is maintained even after the formation of cracks by the transmission of tensile force to the steel fiber which runs across the cracks, the apparent plastic deformation increases, and as a result not only the flexural strength but also flexural toughness increases to great extent.

Roughly speaking, SFRC is used in two cases, i.e. in non-reinforced concrete structures and also in reinforced concrete members using steel bars. But there are also cases where SFRC alone is used in place of reinforced concrete using steel bars, such as concrete pipes formed by centrifugal force.

This recommendation, however, shall apply only to those cases where an non-reinforced concrete structure is constructed using SFRC and where it is used in combination with reinforced concrete members using steel bars as above mentioned. They shall not be applied to those cases where SFRC alone replaces the design usually be considered as reinforced concrete using steel bars. The reason for this is that the reinforcement effect on concrete of using steel fibers and that of using steel bars in reinforced concrete members are essentially different, and that it is extremely rare for the latter to be replaced by the former except for their members.

When SFRC is used for an non-reinforced structure, flexural strength, shearing strength, fatigue strength, etc. are improved depending on steel fiber content and, therefore, it is possible to reduce the thickness of pavement and tunnel lining. The durability of structures using SFRC is also improved along with resistance to cracks and freezing and thawing.

On the other hand, if it is used in combination with steel reinforcing bars, the shearing strength of members can be increased, making it particularly effective for use in structures where seismetic resistance is required.

In recent years, SFRC has been used for lining concrete in tunnels in large underground caverns and for slope protection, most of which are constructed by shotcrete method. In general, the quality of shotcrete is largely influenced by the type of spray gun used and SFRC is no exception in this regard. To attain the required quality when shotcreting with SFRC, special consideration must be given to the materials used, its mix as well as design and construction considerations. This recommendation cannot cover all these subjects, therefore, they are specified separately in the "Guideline for Construction of Steel Fiber Reinforced Shotcrete".

ARTICLE 2. Definitions

Terms used in this recommendation shall have the meanings assigned to them as follows:

Steel fiber-shall be defined as a reinforcing material for concrete or mortar which is produced in the form of discontinuous short fibers using steel as its raw materials.

Steel fiber reinforced concrete-shall be defined as a mortar or concrete in which steel fibers are included in the mix.

Steel fiber content-shall be defined as volume percent of steel fibers contained in 1 m^3 of SFRC.

Orientation of steel fibers-shall be defined as the orientation of steel fibers distributed in concrete toward a certain direction.

Toughness-shall be defined as the energy required to deform a prescribed size of steel fiber reinforced concrete to a prescribed amount, that is a ratio indicating the magnitude of ductility of concrete.

CHAPTER 2. QUALITY OF STEEL FIBER REINFORCED CONCRETE

ARTICLE 3. General

Steel fiber reinforced concrete shall have the required strength, toughness, durability, watertightness, and workability suitable for construction and shall not vary widely in its quality.

(Commentary)

In case steel fibers are not distributed evenly in SFRC or if their distribution is oriented toward one direction, SFRC may not attain its required strength or toughness. Hence, sufficient care must be exercised during mixing and construction.

Strength. Tensile strength, flexural strength, shear strength and toughness of SFRC increase in proportion to steel fiber content, but compressive strength does not vary much. Therefore, it is desirable to use either tensile strength or flexural strength as an index of quality of SFRC. As it is difficult to test tensile strength, the flexural strength is used as an index to indicate the quality of SFRC. On the other hand, durability and watertightness are influenced by the quality of the concrete matrix, that is, the water-cement ratio. From the viewpoint of assuring durability and watertightness of SFRC, it is specified in this recommendation that the water-cement ratio in the concrete matrix should not exceed the prescribed value. In SFRC, changes in the water-cement ratio may be confirmed by the compressive strength. This recommendation describes the use of both the flexural strength and compressive strength as indices to the quality of SFRC.

Toughness. One of the excellent properties of SFRC which could not be obtained by ordinary concrete is its toughness due to the fact that even after cracks have occurred the concrete reaches the point of rupture only gradually maintaining considerable strength, thereby sharply reducing its brittleness.

In order to fully utilize the advantages of SFRC, it is desirable to use SFRC on structures where its toughness can be introduced into the design. For this purpose, it is necessary that the provisions for design in this recommendation must incorporate toughness as well as strength. However, the design technique for structures to utilize the toughness of the material used has not yet been established to date, and there are no examples available. Therefore, the design method of this recommendation is based on allowable strength method as shown in the existing JSCE "Standard Specifications for Non-Reinforced and Reinforced Concrete", by treating toughness as a characteristic value of the material and SFRC is specified to have the toughness corresponding to its strength.

Durability. The resistance against freezing and thawing actions of SFRC in which AE concrete is used in the concrete matrix, was found to improve remarkably compared to that of AE concrete itself.

According to the exposure test data on SFRC in a corrosive environment, such as marine condition, it was found that the corrosion of steel fiber in SFRC is extremely slow and the durability of SFRC is better than that of ordinarily reinforced concrete in a severe corrosive environment, such as under the severe wave splash. In spite of the fact that the section of steel fiber is considerably small as compared to that of steel bars, the reason for its excellent durability shown under the severe corrosive environment can be summarized in the following three items:

1) Because the reinforced concrete members use reinforcing steel bars in such a way that they are concentrated, and once the corrosion starts from cracks of concrete, it progresses without stopping, reducing effective section of steel bars and the durability of members is lowered rapidly. On the other hand, since steel fibers are distributed randomly in SFRC, even though the part of steel fibers which are exposed on the surface start to corrode, the corrosion is restricted within that particular steel fibers and the speed with which such corrosion propagates into inner fibers is very slow.

2) In ordinary reinforced concrete members, cracks are caused due to the expansion pressure from ferrous oxide developed as a result of corroded steel bars, which accelerates the progress of corrosion and in turn the cracks become larger, but in the case of steel fiber, the expansion pressure caused is not so large as that of the steel bars and acts in such a way as to restrict the cracks themselves.

3) In case of steel reinforced members, gaps tend to occur below the steel bars due to bleeding, which become the cause of corrosion of the steel bars. On the contrary, since steel fiber has smaller section and even though gaps occur around them due to bleeding, such gaps are filled by cement hydrate (in particular $Ca(OH)_2$) easily, making the resistance to corrosion rather strong.

Workability. SFRC can be constructed with the ease of the same degree as long as it has the same consistency as that of ordinary concrete. Also, SFRC has a possibility of having varied quality as compared to the ordinary concrete. This is because the distribution condition of discontinuous steel fibers and orientation in the concrete affect the quality of SFRC, such as strength, toughness, etc.. To reduce the variation in quality of SFRC, it is necessary that sufficient care be exercised in its construction as previously mentioned. Particularly in the selection of construction machinery a proper investigation is required.

ARTICLE 4. Strength

(1) The strength of steel fiber reinforced concrete shall be based on flexural and compressive strengths of the concrete at the age of 28 days.

(2) Flexural strength test and compressive strength test of steel fiber reinforced concrete shall be in accordance with the JSCE Standards of "Method of Tests for Flexural Strength and Flexural Toughness of Steel Fiber Reinforced Concrete" and "Method of Tests for Compressive Strength and Compressive Toughness of Steel Fiber Reinforced Concrete."

CHAPTER 3. MATERIAL

ARTICLE 5. General

Material used shall be of good quality.

ARTICLE 6. Admixtures

(1) Air-entraining agent and air-entraining water reducers used shall be those which are in conformity with JIS A 6204 "Chemical Admixtures for Concrete", and they shall not contain detrimental amount of Chloride.

(2) Corrosion-inhibiting agent used shall be in conformity with JIS A 6205 "Corrosion-inhibiting Agent".

(3) Admixtures used other than (1) and (2) above shall be tested, confirmed and method of use shall be thoroughly investigated before use.

ARTICLE 7. Steel Fiber

Steel fiber shall be in conformity with JSCE Standard "Specification of Steel Fibers for Concrete".

(Commentary)

JSCE Standard "Steel Fiber for Concrete" specifies that steel fiber below the length of 30 mm may be used for both placing and shotcreting SFRC. However, the longer the steel fiber of SFRC the larger the reinforcement effect is. Therefore the steel fiber of above 30 mm is recommended for use in case of placing of SFRC. Provided that if the length of steel fiber exceeds 40 mm, sufficient care shall be exercised on mix, design, mixing, placing, compaction, etc.

ARTICLE 8. Aggregate

Aggregate shall be clean, strong, durable and of suitable size and shall not contain detrimental materials, such as dust, dirt, inorganic impurities, chloride, etc..

ARTICLE 9. Water

(1) Water used shall not contain detrimental amounts of oil, acid, chloride, organic material, etc. which affect the quality of the concrete.

(2) Water used for mixing shall not contain chloride ion of more than 200 ppm.

CHAPTER 4. MIX PROPORTION

ARTICLE 10. General

Mix proportion of steel fiber reinforced concrete shall be designed so as to reduce the unit water content as much as possible within the required strength, toughness, durability, watertightness and suitable workability of SFRC.

(Commentary)

Similar to that of ordinary concrete, it is extremely important for SFRC to be designed to reduce the unit water content as much as possible within the required properties. Since it is not possible to specify the quality of SFRC by the compressive strength alone, the mix proportion shall be designed on the basis of the compressive strength, flexural strength and toughness.

As SFRC requires large amount of water, it is desireable to make it an AE concrete using good quality AE agent, AE water reducer, etc. similar to that of ordinary concrete.

ARTICLE 11. Mix Designed Strength

Mix designed strength σ_r of steel fiber reinforced concrete shall be the proportionally increased value of the design standard strength σ_k multiplied by a suitable factor.

(Commentary)

There is a controversy as to how the factor "p", proportionally increased factor, is to be determined. Taking into consideration the fact that SFRC has high resistance to cracks and toughness compared to ordinary concrete and that quality control is carried out thoroughly, there can be no particularly inferior points compared to ordinary concrere. However, since there is not enough data to date which is required to change the proportional increasing factor quantitatively, it was decided that the required average strength to be in conformance with ordinary concrete. It is then specified to satisfy the two conditions that the test value of compressive strength and flexural strength of the concrete at site shall not be less than 80% of the design standard strength σ_k at the probability of more than 1/20, and that it shall not be less than the design standard strength σ_k at the probability of more than 1/4.

ARTICLE 12. Steel Fiber Content

Steel fiber content shall be determined taking into account the required flexural strength and toughness of the steel fiber reinforced concrete.

(Commentary)

The superior mechanical properties of SFRC, which ordinary concrete could not attain, are such as crack arrest, toughness, flexural strength, shearing strength. However, these properties are determined depending, not on the water-cement ratio, but on steel fiber content.

As the steel fiber content is increased, flexural strength, shearing strength, bonding strength of steel bars and toughness increase, but these increases differ depending on the type of steel fiber used, and the toughness is the property that is affected the most. That is, when the steel fiber differs, there are cases to change the steel fiber content in order to obtain the same toughness.

The steel fiber content is specified to be determined taking into account the flexural strength and toughness. Properties of SFRC, such as flexural strength, shearing strength, bonding strength with steel bars, etc. can be represented by strength and based on the principle that SFRC has the required toughness.

Although the toughness required differs depending on the structure which becomes the subject of application, the flexural toughness obtained by JSCE Standard "Methods of Tests for Flexural Strength and Flexural Toughness of Steel Fiber Reinforced Concrete" shall be used.

The standard values shall be as shown in the commentary Table - 1 depending on the design standard flexural strength. It is desirable that the relationship between the steel fiber content and the flexural strength and toughness should be determined by tests as it varies greatly depending on the material used, method of construction, etc..

When the steel fiber content is below 0.5%, distinctive features of SFRC are difficult to be demonstrated depending on the type of steel fiber. When it is above 2%, fiber balls tend to form and, therefore, the steel fiber content of SFRC is specified to be within the range of 0.5% and 2%.

Commentary Table-1 Flexural Toughness Factor of SFRC

Design Standard Flexural Strength	Flexural Toughness Factor
above 55 kg/cm^2	above 35 kg/cm^2
above 70 kg/cm^2	above 55 kg/cm^2
above 90 kg/cm^2	above 70 kg/cm^2

ARTICLE 13. Water-Cement Ratio

The water-cement ratio shall be determined taking into account the required compressive strength and durability of the steel fiber reinforced concrete. The water-cement ratio of the steel fiber reinforced concrete shall be not larger than 55%.

(Commentary)

Similar to ordinary concrete, the compressive strength of SFRC is closely related to the water-cement ratio. Therefore, it is decided that the water-cement ratio be determined based on the compressive strength and durability. As it is not advantageous from the viewpoint of economy to utilize SRRC as a compressive material alone, efforts shall be made to utilize other properties such as the flexural strength, shearing strength, toughness, restrictive nature against cracks, etc. For this reason, it is not desirable to make the water-cement ratio too large, and the water-cement ratio of SFRC is determined to be below 55%.

When determining the water-cement ratio based on the durability for the pavement concrete, the water-cement ratio shall be below the values shown in Commentary Table-2.

Commentary Table-2 The Maximum Water-Cement Ratio (%) when Determining the Water- Cement Ratio Based on the Durability of the Concrete

(1) When freezing and thawing are to occur repeatedly under particulary severe weather conditions	45
(2) When freezing and thawing are to occur occasionally	50

ARTICLE 14. Water Content

The water content shall be determined by tests so that it is as small as possible within the workable limit.

ARTICLE 15. Maximum Size of Coarse Aggregate

The maximum size of coarse aggregate shall be not larger than 2/3 of the length of the steel fiber and shall not exceed 1/5 of the minimum size of members to be placed or 3/4 of the minimum clear horizontal distance between reinforcing bars.

(Commentary)

In SFRC, the relationship between the maximum size of coarse aggregate and the length of steel fiber has a great effect on the flexural strength and toughness. According to the results of research to date, it is shown that when the maximum size of coarse aggregate is about 1/2 of the length of steel fiber, the largest flexural strength and shearing strength are attained, and the strength is lowered when the value becomes either larger or smaller. As the maximum size of coarse aggregate obtainable in practice is limited economically, it is specified that the maximum size of coarse aggregate shall be below 2/3 of the length of steel fiber.

ARTICLE 16. Fine Aggregate Ratio

The fine aggregate ratio, percentage of total aggregate by solid volume, shall be determined by tests so as to make the water content as small as possible within the range that the workability and strength required can be obtained.

(Commentary)

In the mix design of SFRC, the fine aggregate ratio shall be suitably determined. If the optimum fine aggregate ratio is determined in consideration of the workability alone, the required strength cannot necessarily be obtained, if its value is below 60%. Therefore, it is specified that the strength must also be examined.

Commentary Table-3 and 4 are reference tables to be used when the mix proportion is obtained based on consistency. An approximate value can be obtained using this table. When specially-shaped and sized steel fiber is used, however, it must be noted that the values shown in the table may not be applicable. Examination with regard to the strength shall be carried out separately.

Commentary Table-3 Reference Table in Determining Mix Proportions of SFC

Values as shown in this Table are determined under the following conditions:

1) Shape and size of steel fibres: 0.5 x 0.5 x 30 mm

2) Steel fiber content: 1.5 % by volume

3) Fine aggregate shall be with finess modulus of 3.00, and coarse aggregate used shall be crushed stone with water reducing agent of good quality.

4) Water-cement ratio: 50%, Slump: 8 cm

Maximum size of coarse aggregate Gmax (mm)	AE Concrete (Air content 5%)		Concrete without AE agent		
	Fine aggregate ratio s/a (%)	Unit water content W(kg/m³)	Entrapped air (%)	Fine aggregate ratio s/a (%)	Unit water content W(kg/m³)
10	68	214	3.0	70	225
15	65	208	2.8	68	221
20	60	200	2.5	63	215
25	55	191	2.1	58	208

Corrections required in case the conditions differ from above:

Changes in the conditions	Fine aggregate ratio (%)		Unit water content(kg/m³)
For increase or decrease of 0.5 % in steel fiber content	Gmax: 10, 15 mm	±10	±10
	Gmax: 20 mm	±8	
	Gmax: 25 mm	±5	
For increase or decrease of 0.05 % in water-cement ratio	±1		±2.5
For increase or decrease of F.M. 0.01 in fine aggregate	±0.5		no correction
For increase or decrease of 1 cm in slump	no correction		±3
For increase or decrease of 1 % in air content	∓1		∓6
For increase or decrease of 10 in aspect ratio of steel fibre	±3		±10

Note 1) This Table will only be applicable to SFRC using with norminal converted diameter of 0.3 ∿ 0.6 mm steel fibers.

Commentary Table-4 Reference Table in Determining Mix Proportions of SFRC Pavements

Values as shown in this Table are determined under the following conditions:

1) Shape and size of steel fibres: 0.5 x 0.5 x 30 mm

2) Steel fiber content: V_f = 1.5 % by volume

3) Fine aggregate shall be with finess modulus of 2.76, and coarse aggregate used shall be crushed stone with water reducing agent of good quality.

4) V.B. test time: 30 seconds

5) Air content: 4 %

Maximum size of Coarse aggregate (Gmax) (mm)	Unit coarse aggregate volume (V_G)	Unit water content Note 1) (kg/m^3)
25	0.59	165(172)
15	0.51	174(180)
10	0.46	185(191)

Corrections required in case the conditions differ from above:

<table>
<tr><th>Changes in the conditions</th><th colspan="2">Unit coarse aggregate volume (V_G)</th><th colspan="2">Unit water content (kg/m^3)</th></tr>
<tr><td rowspan="2">For increase and decrease of 0.5 % in Steel fiber Content (V_f)</td><td>Gmax: 10, 15 mm</td><td>±0.08 V_G</td><td colspan="2" rowspan="2">±11</td></tr>
<tr><td>Gmax: 25 mm</td><td>±0.13 V_G</td></tr>
<tr><td rowspan="2">For increase and decrease of 10 seconds in V.B. test</td><td colspan="2" rowspan="2">no correction</td><td>V_f=1%</td><td>∓3.5</td></tr>
<tr><td>V_f=2%</td><td>∓5</td></tr>
<tr><td>For increase and decrease of 1 % in air volume</td><td colspan="2">no correction</td><td colspan="2">∓3.5</td></tr>
<tr><td>For increase and descrease of F.M. 0.1 in fine aggregate note 2)</td><td colspan="2">∓0.01 V_G</td><td colspan="2">no correction</td></tr>
</table>

Note 1) Figures in parentheses indicate unit water content when AE agent is not used.

Note 2) This Table will only be applicable to SFRC using fine aggregate with F.M. 2.50 ∿ 3.30.

ARTICLE 17. Consistency

The consistency of steel fibre reinforced concrete shall be as small as possible within the range of suitable workability.

(Commentary)

Testing method for consistency of SFRC shall be as the same method as ordinary concrete. The slump of SFRC becomes smaller compared to ordinary concrete due to the bulk effect of steel fibers, in the mix proportioning, therefore, it is better to determine the slump 1 ∿ 2 cm smaller than usual.

The relationship between slump and settling velocity of SFRC differs slightly from that of ordinary concrete. The slump equivalent to the standard settling velocity of 30 seconds by V.B. test for pavements is about 2.5 cm in case of the ordinary concrete, but it is about 1 cm in case of SFRC.

ARTICLE 18. Expression of Mix Proportion

(1) Expression of the mix proportion shall be as shown in Table-1.

Table-1 Table of Mix Proportion

Shape and size of steel fiber (mm)	Steel fiber content (%)	Maximum size of coarse aggregate (mm)	Range of slump (cm)	Range of air volume (%)	Water cement ratio w/c (%)	Fine aggregate ratio s/a (%)	Unit volume (Kg/m^3)							
							Steel fiber SF	Water W	Cement C	Fine aggregate S	Coarse aggregate G		Admixture	
											mm ~ mm	mm ~ mm	Admixture	Chemical Admixture

(2) Specification for mix proportion shall be such that 100% of fine aggregate shall pass through 5 mm sieve and 100% of coarse aggregate shall remain in 5 mm sieve, and shall be expressed as all being in surface-dry condition.

(3) When converting the specified mix proportion to the field mix, water content of aggregate, amount of fine aggregate which remains in 5 mm sieve and amount of coarse aggregate which passes through 5m sieve, etc. must be taken into consideration.

CHAPTER 5. BATCHING AND MIXING

SECTION 1. Batching

ARTICLE 19. General

Component materials of steel fiber reinforced concrete shall be properly batched so as to obtain required quality.

ARTICLE 20. Batching Facilities

Batching method and device of steel fiber shall be subject to approval of the supervisory engineer prior to their use.

ARTICLE 21. Batching of Steel Fiber

(1) Steel fiber shall be batched (individually for each mix) by weight.

(2) Boxed steel fibers may be directly induced to the mixer provided they are used as a unit of box.

(3) Tolerance in batching of steel fibers shall be less than 2% per one batch.

SECTION 2. Mixing

ARTICLE 22. General

Steel fiber reinforced concrete shall be thoroughly mixed so as to obtain required quality.

ARTICLE 23. Mixer

(1) Mixer shall be tilting type or pan type mixer.

(2) Continuous mixer shall be subject to approval of the supervisory engineer prior to use.

(Commentary)

Regarding (1) Mixing time of SFRC becomes comparatively longer than that of ordinary concrete because of addition of the steel fibers takes time. When pan type mixer is used, it is necessary that a well maintained mixer be used, as the mortar may leak from the discharge gate of the mixer and the quality of SFRC may be adversely affected.

The mixing torque of mixer, in case the pan type mixer is used, normally becomes larger than that of the ordinary concrete. The tests with the pan type mixer of 1.5 m^3 proved that the mixing was satisfactorily accomplished even when the mixing volume of SFRC was 100% of the capacity of the mixer at the slump of around 10 cm, but the mixing torque was approximately twice that of ordinary concrete. As the slump become around 5 cm, the torque reached up to four times that of ordinary concrete at the maximum, suggesting that in case of mixing dry mix of SFRC the mixer capacity including the mixing volume must be checked beforehand.

There also is an example where the required quality of SFRC was obtained simply by adding the steel fibers directly from the loading receiver to a truck agitator. However, method of addition of steel fibers, mixing conditions, etc. using this method have not yet been verified, so it may be used on small scale jobs only when the approval of the supervisory engineer is obtained.

Regarding (2) In case of using the transportable continuous mixer, there are some examples where repair work have to be carried out in a hurry and when transportation takes time. For the continuous mixer, however, there is no governing JIS, and there are considerable heterogeneous features as compared to that of the batch mixer, such as batching of materials and mixing itself, etc.. Therefore, it is specified that the approval for use must be obtained from the supervisory engineer.

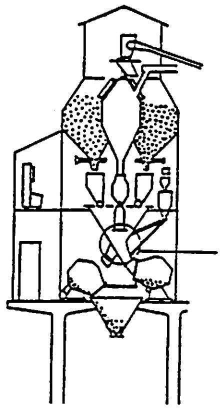
The points which have to be taken into consideration in the production of SFRC using continuous mixer are that SFRC discharged is comparatively unstable in the beginning of the mixing including resumption of mixing operation after an interruption, and a considerable number of steel fibers are bent when mixing SFRC with slump of 2 ∿ 3 cm. Therefore, it is necessary that careful calibration of weighing various materials be carried out and the difference between the design mix proportion and actural mix proportion be thoroughly checked in order to avoid producing SFRC of unstable quality. Also, when the quality becomes unstable in the beginning of the mixing, measures such as, making the mix richer in order to stabilize the quality, receiving the mixed SFRC by the agitator truck once and performing the remixing, or discarding about 100 ℓ of SFRC produced in the beginning of the mixing, etc.

ARTICLE 24. Addition of Steel Fibers

Addition of steel fibers shall be carried out in such a way so as to have uniform mix.

(Commentary)

In order to obtain SFRC of the required quality, it is most important to disperse the steel fibers into the concrete uniformly, without fiber balls being generated. The method of adding the steel fibers to the mixer, becomes the most important of all in the production of SFRC, in which thorough care must be exercized.



Commentary Figure - 1

The method which is used the most at present, is the one in which a dispenser of steel fibers is installed on the top of the mixer and add steel fibers into the mixer so as to prevent forming fiber balls when mixing. Another example is the one in which an aligned package of steel fibers is used to uniformly disperse the steel fibers without using any dispenser. But, in this case care must be taken not to generate fiber balls.

In case of using a tilting mixer, it must be noted that even though the dispenser is used the steel fibers may block the passage near the bifurcation distribution device in the mixer.

ARTICLE 25. Mixing

Mixing time shall be determined by tests.

(Commentary)

As there is not yet an established method of adding the required volume of steel fibers in the mixer in a short time, this can be accomplished in many cases using a dispenser with the capacity of about 40 kg/min. Consequently, with one dispenser, the time required for the steel fibers to be added is about 4 minutes when steel fiber content is 2%, during which time there is a fear that the volume of entrapped air may increase depending on the type of the mixer.

For this reason it is specified that the mixing time shall be determined by tests to assure the concrete quality.

There are many examples where about 30 seconds mixing is performed after the steel fibers have been added to the mixer.

CHAPTER 6. READY MIXED CONCRETE

ARTICLE 26. General

When the ready mixed concrete is used in construction, it shall be purchased from a JIS authorized plant where either a chief concrete engineer or a concrete engineer who has sufficient experience in SFRC is permanently stationed.

ARTICLE 27. Designation Regarding Quality

When the ready mixed concrete is to be ordered for procurement, such as materials, quality of SFRC, method of transportation, method of inspection, etc. shall be agreed upon in advance.

CHAPTER 7. TRANSPORTATION AND PLACING

ARTICLE 28. General

Before the construction commences, transportation and placing of ready mixed concrete shall be carefully planned and the approval thereof shall be obtained from the supervisory engineer in advance.

ARTICLE 29. Transporting Machinery and Equipment

(1) Vehicles used for transporting SFRC shall be those in which loading and unloading can be easily carried out.

(2) In the selection of the type of concrete pump to the used, quality of SFRC, location of placing, volume to be placed, etc. must be taken into consideration.

(Commentary)

Regarding (1) In many cases the type of vehicle used is determined depending on the mix of SFRC. That is because, in case of using an agitator truck, the entrance of the truck may be blocked by SFRC when the mix is too dry or an entire volume of SFRC cannot be discharged.

When a dump truck is used, SFRC has to be transported in such a manner as to prevent segregation of materials to the minimum by using a truck with watertight bed, because its mortar content is rich as compared to ordinary concrete even though it is of a comparatively dry mix.

Regarding (2) Since there are a variety of concrete pumps available and differences in performance, it is essential that a proper type of pump be selected for the job condition. When SFRC is pumped under pressure, the steel fibers tend to orient to the direction of flow. Therefore, at the location where the orientation of the steel fibers are to be effectively used, it is beneficial to examine the direction of the tip of the concrete pump in advance so as to obtain the highest reinforcement effect after the hardening of SFRC.

ARTICLE 30. Placing

(1) SFRC shall be placed so that it is not required to be moved, once it is placed into the formwork.

(2) When placing SFRC into one location, it shall be continuously placed.

(Commentary)

Regarding (1) It is extremely difficult to insert a shovel into SFRC or move SFRC manually. And to move SFRC by using an inner vibrator should be avoided as much as possible as it not only causes material segregation, but also adversely affects direction and dispersion of the steel fibers.

Regarding (2) If the placing of SFRC in the predetermined location is interrupted and a construction joint has to be provided, that portion of the concrete loses the continuity of SFRC.
Therefore, SFRC must be continuously placed until the placing of the location is completed.

ARTICLE 31. Consolidation

SFRC shall be thoroughly consolidated immediately after it is placed.
A vibrator shall be used for consolidation.

(Commentary)

Methods of consolidation and type of vibrator used for consolidation shall be selected depending on the type of structure, shape, size of structure and mix of SFRC. These, however, must be thoroughly examined as they can greatly influence the distribution and orientation of the steel fibers and the quality of SFRC after it is hardened.

In general, steel fibers tend to be oriented two-dimensionally within the plane which is vertical to the direction of the placing of SFRC. But locally they tend to orient along the vibrator or within the plane along the formwork. Also, if SFRC is subjected to too long duration of vibration, the steel fibers tend to settle. Therefore, it is better that too much vibration be avoided.

CHAPTER 8. QUALITY CONTROL AND INSPECTION

ARTICLE 32. General

Materials, steel fibers, machinery and equipment, operation, etc. shall be properly controlled so as to produce steel fiber reinforced concrete of the required quality.

ARTICLE 33. Testing of Steel Fiber Reinforced Concrete

(1) Before the construction is commenced, testing of materials and testing of steel fiber reinforced concrete to determine the mix shall be performed in compliance with the instructions of the supervisory engineer, and performance of machinery and devices shall be confirmed.

(2) The following tests shall be carried out during the time of construction in compliance with the instructions of the supervisory engineer:

(a) Tests for aggregates

(b) Slump test

(c) Test for air content

(d) Unit volume weight test

(e) Compressive strength test

(f) Flexural strength test

(g) Test for steel fiber content

(h) Flexural toughness test

(i) Other tests

(3) To determine whether or not curing is proper and when to remove the formwork or to confirm whether or not it is safe to load the concrete, the concrete strength test shall be carried out using test pieces which are cured under the same conditions as that of the concrete at site. In case the strength obtained is remarkably smaller than the strength of test pieces which are cured under the standard condition, the method of curing of the concrete at site shall be improved as directed by the supervisory engineer.

(4) After the completion of the construction, if required, non-destructive test or the tests using core samples taken from the structure shall be performed in compliance with the instruction of the supervisory engineer.

(Commentary)

Regarding (1) Flexural toughness test must be carried out to ensure that SFRC of the required quality is obtained.

Regarding (2) Strength tests of the concrete is necessary to confirm its quality. In case of SFRC, hoever, it is difficult to judge other strengths from the compressive strength. For this reason, the quality of concrete matrix is confirmed by the compressive strength, and other strengths of SFRC is confirmed by the flexural strength. Also, the toughness of SFRC should be examined by the flexural toughtness test, but they may be checked more simply by measuring the steel fiber content of the concrete.

ARTICLE 34. Test Methods

Of the tests of steel fiber reinforced concrete, compressive strength test, flexural strength test, shearing strength test, toughness test and test for steel fiber content shall be in compliance with the methods as specified by the standards of the Japan Society of Civil Engineers. Other tests shall be performed by the methods as specified by JIS.

ARTICLE 35. Control of Concrete

Control of SFRC shall be carried out by means of strength and toughness or steel fiber content. Test pieces shall be taken so as to represent the concrete of the structure.

(Commentary)

Since the strength of SFRC is controlled by the compressive strength and flexural strength of the concrete at the age of 28 days, it is proper to perform the compressive strength and flexural strength tests of the concrete at the age of 28 days to confirm that the concrete strength is as required. In case, however, if it is able to confirm that the compressive strength becomes more than the required value when the concrete has the required flexural strength, the control by using compressive strength may be omitted in compliance with the instruction of the supervisory engineer. In case an early strength control is carried out, either an interrelation with the 28 day strength or it shall be confirmed that the concrete attains the required strength by performing the strength test at the age of 28 days, as required.

It is desirable to perform the flexural toughness test at the age of 28 days to know the toughness of SFRC, but to examine more simply, it may be confirmed by means of testing steel fiber content.

ARTICLE 36. Quality Inspection of Concrete

(1) When inspecting quality of concrete based on the test values, all test values and a part of continuous values obtained shall be inspected in compliance with the instruction of the supervisory engineer.

(2) In case the water-cement ratio is determined based on the compressive strength, quality of concrete inspected shall be considered as having the required quality if it may be inferred that the test value of the compressive strength shall not be less than 0.8 σ_{ck} at the probability of more than 1/20 nor shall not be less than σ_{ck} at the probability of more than 1/4 with a suitable risk factor. In general this inspection shall be carried out based on the compressive strength of the age of 28 days. Timing and number of times and number of test pieces to be taken for the test shall be in compliance with the instruction of the supervisory engineer.

(3) In case the water-cement ratio is determined based on the durability and water-tightness, quality of concrete inspected shall be considered as having the required strength if the average value of test values exceeds the required water-cement ratio or the compressive strength equivalent thereto.

(4) In case the steel fiber content is determined based on the toughness, the quality of concrete shall be inspected using the test value of the toughness or the steel fiber content.

(5) As a result of the test, if the quality of concrete is found unsuitable, proper measures, such as correction of the mix proportion, performance inspection of machinery and equipment, improvement of job methods, etc. shall be taken at the same time confirming whether or not the concrete placed in the structure would serve the required objective and taking proper measures as required.

CHAPTER 9. PLANT PRODUCTS OF STEEL FIBER REINFORED CONCRETE

ARTICLE 37. General

SFRC used to produce plant products shall have the required strength, toughness, durability, water-tightness, etc., and its quality shall not vary widely.

ARTICLE 38. Strength of Concrete

(1) Concrete strength of the plant products shall be determined on the basis of the compressive strength or flexural strength or combination of both.

(2) The age of concrete to qualify the strength shall be determined in consideration of the type of cement, type of admixture, method of curing, method of construction, etc.

(3) Compressive strength test and flexural strength test shall be in accordance with JSCE Standards for "Methods of Tests for Compressive Strength and Compressive Toughness of Steel Fiber Reinforced Concrete" and "Methods of Tests for Flexural Strength and Flexural Toughness of Steel Fiber Reinforced Concrete". Specimens shall be of the size as prescribed in the Standards and shall be prepared as much as possible with the consolidation and curing conditions equivalent to those of the plant product.

ARTICLE 39. Distribution and Orientation of Steel Fibers

Plant products of steel fiber reinforced concrete shall be produced considering the effect of distribution and orientation of fibers due to the method of placing and consolidation.

CHAPTER 10. GENERAL MATTERS ON STRUCTURAL DESIGN

ARTICLE 40. General

(1) Concrete structures of steel fiber reinforced concrete shall be analyzed in accordance with the theory of elasticity.

(2) Strength of members shall be ascertained by examining that the stresses of steel bars and concrete are below allowable stresses.

(3) Tensile stress of steel fiber reinforced concrete without reinforcing steel bars may be taken into consideration.

(Commentary)

Regarding (1) In the analysis of concrete structures of SFRC, the method of analysis used for ordinary non-reinforced and reinforced concrete shall be followed, that is the theory of elasticity.

Regarding (2) In the design of members, it is totally the same as in the case of ordinary non-reinforced and reinforced concrete without steel fibers that the stress is to be examined whether it exceeds the limit of allowable stress or not.

Regarding (3) In case tensile stress of ordinary concrete without steel fibers is considered, not only the approval of the supervisory engineer has to be obtained, but also it has to be ascertained that no cracks will occur due to drying, shrinkage, settlement, etc. In consideration of the good properties of SFRC, such as toughness and restriction of cracks, it is prescribed that design may be performed considering tensile stress.

ARTICLE 41. Unit Weight of Concrete

The unit weight of concrete to be used for design calculation shall be the value which has been ascertained by tests.

(Commentary)

The unit weight of concrete varies depending on method of construction, steel fiber content, type of aggregate, mix proportion, method of compaction, etc. The unit weight of placed concrete is around 2.30 $\sim$ 2.45 t/m^3 and therefore, the unit weight of concrete for design calculation may be determined as 2.35 t/m^3. The unit weight of shotcreted concrete is around 2.20 $\sim$ 2.30 t/m^3.

The unit weight test of placed concrete may be performed on unhardened concrete in accordance with JIS A 1116 "Testing Methods of Unit Weight of Concrete and Air Volume by" Weight. The unit volume weight to be used for design calculations is based on an air-dried state value; the difference with an air-moist state value is negligible. The value of unhardened concrete is close to that for an air-moist state.

ARTICLE 42. Modulus of Elasticity

(1) Young's modulus of steel fiber reinforced concrete for calculations of statically indeterminate stress or elastic deformation, may be the values as shown in Table-2 below:

Table-2 Young's Modulus

Design Standard Compressive Strength	σ_{ck}(kg/cm^2)	240	300	400
Young's Modulus	(kg/cm^2)	2.7×10^5	3.0×10^5	3.5×10^5

(2) For calculations in determining sectional area or stress of member, Young's modulus ratio "n" of steel bars and concrete, shall be 15.

(3) Poisson's ratio of steel fiber reinforced concrete shall be 0.2

(Commentary)

Regarding (1) Young's modulus to be used for elastic calculations is not affected by steel fibers if the steel fiber content is below 2%. Therefore, Young's modulus may be the same value as that of ordinary concrete without steel fibers.

Regarding (2) and (3) For reasons similar to (1) above, "n" value to be used for elastic calculations may be assumed as 15 and Poisson's ratio as 0.2.

ARTICLE 43. Drying Shrinkage and Creep

(1) For the design of structures, effects of drying shrinkage and creep of concrete must be taken into consideration, as required.

(2) The drying shrinkage to be used for design calculations of statically indeterminate structures, shall be the values as shown in Table-3 below:

Table-3 Drying Shrinkage

Type of Structure		Drying shrinkage
Rigid frame		15×10^{-5}
Arch	Reinforcing steel bar volume more than 0.5%	15×10^{-5}
	Reinforcing steel bar volume less than 0.5% and more than 0.1%	20×10^{-5}

Note: Arch herein is the arch structure which has reinforcing steel bars in an axial direction 4 cm^2 per meter of width in upper and lower sides, respectively, and has the total reinforcing steel bar volume of more than 0.1% of the arch section.

(3) In case an effect of drying shrinkage is required to be taken into consideration for the design of non-reinforced concrete structures, the standard value of drying shrinkage used for calculations shall be 25×10^{-5} for members without having direct contact with ground under the normal atmospheric conditions. For members having direct contact with ground, this value shall be reduced depending on the actual circumstances.

(4) The creep strain shall be in proportion to elastic strain. The creep modulus of concrete shall be 3.0 in case of indoors and 2.0 in case of outdoors, for the statically indeterminate structure under normal atmospheric conditions, with no loading in the early age.

(Commentary)

Regarding (2), (3) It is known from results of experiments that steel fibers restrict drying shrinkage of SFRC, and that shrinkage rate decreases as steel fiber content increases.

In case of SFRC, however, the same value as that of ordinary concrete may be used for design calculation in consideration of the fact that the unit water content of SFRC is higher as compared to ordinary concrete.

Regarding (4) From results of the experiments on compressive creep, strain and creep modulus are known to be slightly smaller compared to those of ordinary concrete. The same values as those of ordinary concrete may be used for design calculations.

ARTICLE 44. Allowable Stresses of Steel Fiber Reinforced Concrete

(1) The allowable stresses of steel fiber reinforced concrete shall be determined according to the design standard strength which is obtained based on flexural strength and compressive strength of concrete at the age of 28 days.

(2) The allowable flexural compressive stress (including when it is accompanied by the axial force) shall be calculated according to the formula as shown below:

$$\sigma ca \leqq \sigma ck/3$$

Where, σck ; design standard compressive strength.

(3) For the allowable shear stress, the values used for ordinary concrete may be increased by the premium rates as shown in Table-4, provided the effective height of members is below 20 cm and the design standard compressive strength is above 300 kg/cm^2.

Table-4 Premium Rates of Allowable Shearing Stress τ_{al}

	Design Standard Flexural Strength (σ_{bk})	Premium Ratio of Increase of Allowable Shearing Stress τ_{al} to Concrete without Steel Fibers
In case of beam and slab	above 55 kg/cm^2	1.1
	above 70 kg/cm^2	1.2
	above 90 kg/cm^2	1.3

(4) The allowable adhesive stress shall be below the values as shown in Table-5 below:

Table-5 Allowable Adhesive Stress τ_{oa} (kg/cm^2)

	Design Standard Flexural Strength (σ_{bk})	
	above 70 kg/cm^2	above 90 kg/cm^2
Deformed Bar	20	22

(5) Allowable Stress of Steel Bar

In case of a general structure where effects of cracks are to be considered, the allowable stress of steel bars used for steel fiber reinforced concrete may be the values as shown in Table-6 below:

Table-6 Allowable Stress of Steel Bar σ_{sa}(kg/cm^2)

Type of Steel Bar	SR24	SR30	SD24	SD30	SD35	SD40
Allowable Tensile Strength	1400	1800	1400	1800	2000	2200

(Commentary)

Regarding (1) Reference is made to Articles 3 and 10.

Regarding (2) Since the compressive strength of SFRC does not vary according to steel fiber content, it is assumed to be equivalent to that of the ordinary concrete with the same water-cement ratio.

Regarding (3) The shearing properties of SFRC may be improved as compared to those of reinforced concrete without steel fibers and the ultimate load capacity and toughness at the time of repeated loading. This tendency is particulary remarkable when the effective height of members is small.

The tests performed to date, however, are mostly with regard to members with effective height of smaller than 20 cm and, therefore, premium increase of allowable stress is limited to the cases smaller than 20 cm.

In case where a thin member is to be constructed using SFRC, test results show that the larger values of allowable stress may be allowed. Reference may be made to the "National Railways Design Standards for Structures" in which the premium increase of the allowable stress is allowed by using the modulus as shown in the following formula:

$$\alpha = 1.6 - d$$

where, α: Modulus of premium increase of allowable shear stress in case of a thin member $(\alpha \geqq 1)$

d: Effective height of members (unit: m)

The allowable shear stress τ_{a1} shall be obtained from both σ_{ck} and σ_{bk}, but in case the value equivalent to 300 kg/cm² of σ_{ck} is used, quality control need not be carried out from viewpoints of both compressive and flexural strength; flexural strength alone will suffice. This is because the condition of σ_{ck} = 300 kg/cm² can be met with the exception of the extreme case where water-cement ratio is made below 55% in SFRC. Even though the value of τ_{a2} is not shown for calculations of diagonal tensile steel bar, it is dealt with by making it the same as that of the ordinary concrete, as the compressive strength does not vary greatly due to steel fiber content.

Regarding (4) There is little data available with regard to the adhesive strength of steel bar which is embedded in SFRC. But with regard to SFRC using deformed bar, the data shows that the adhesive strength increases and also an experiment on a beam shows that the adhesive shearing rupture seldom occurs. For these reasons, it is specified that the unit adhesive strength ot SFRC to be τ_{oa} = 20 kg/cm² in case σ_{bk} = 70 kg/cm² and τ_{oa} = 22 kg/cm² in case σ_{bk} = 90 kg/cm².

Regarding (5) As a result of reinforcement by steel fibers, the relationship between crack width and steel bar stress in reinforced concrete may be improved and therefore the crack width may be narrowed for the same steel bar stress. Consequently, it is specified that the allowable stress of steel bar is not necessarily taken to be lower as in the case of ordinary reinforced concrete even when effects due to cracks have to be considered. The tendency, in recent years in particular, has been that the allowable stress is reduced in the case of the ordinary concrete paying attention to the steel bar stress with dead load alone. However, there is no reason to reduce the values shown in Table-6 in case of using SFRC.

ARTICLE 45. Allowable Stresses of Steel Fiber Reinforced Concrete without Reinforcing Steel Bars

(1) Allowable compressive stress (including the case where it is subjected to an eccentric axial loading)

$$\sigma_{ca} \leqq \sigma_{ck}/4$$

where, σ_{ck} is design standard compressive strength of concrete

(2) Allowable Flexural Tensile Stress

$$\sigma_{ba} \leqq \sigma_{bk}/4 \quad \text{and}$$

$$\sigma_{ba} \leqq \bar{\sigma}_b/2$$

where, σ_{bk} : design standard flexural strength of concrete

$\bar{\sigma}_b$: flexural toughness factor of concrete

(3) Allowable Bearing Stress

$$\sigma_{ca} \leqq 0.3\ \sigma_{ck}$$

In case of a local loading, allowable bearing stress σ_{ca} may be obtained from the following formulae, where loading area is A' and distribution area is A:

$$\sigma_{ca} \leqq (0.5 + 0.05\ \frac{A}{A'})\ \sigma_{ck} \quad \text{and}$$

$$\sigma_{ca} \leqq 0.5\ \sigma_{ck}$$

where, σ_{ck} : design standard compressive strength of concrete

(Commentary)

Regarding (1) The same idea used in non-reinforced concrete without steel fibers is followed. Since SFRC excels in toughness and resistance against cracks, the allowable compressive stress is not limited to 55 kgf/cm².

Regarding (2) In case of a member with thickness of smaller than about 15 cm, flexural strength of SFRC increases as steel fibers content becomes higher, and capacity of deformation is higher after the maximum loading is reached. These properties of SFRC cannot be seen in ordinary concrete. For this reason, the reliability with regard to flexural tensile strength of SFRC may be higher compared to that of ordinary concrete without steel fibers.

In consideration of this, it is specified that allowable stress is to be calculated from design standard flexural strength. The upper limit is 1/2 of flexural toughness factor as shown in Commentary Table-1 in the Commentary for Article 12.

The thickness of members already produced using SFRC is mostly smaller than about 15 cm. But, if the thickness of members is larger, allowable flexural stress must be examined separately.

Regarding (3) The same idea used in non-reinforced concrete without steel fibers is followed.