JSCE Recommendations for Design and Construction of High Performance Fiber Reinforced Cement Composite with Multiple Fine Cracks

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SUMMARY

High performance fiber reinforced cement composite with multiple fine cracks is a cement-based material on which worldwide active research has been conducted and particular attention has been focused in recent years. The Japan Society of Civil Engineers (JSCE) published the recommendations for design and construction of this material in March 2007, which is the first-released recommendations in the world. This material shows strain-hardening tensile stress-strain behavior like steel and has a capability of controlling the width of crack within a permissible range because of the formation of multiple fine cracks under the tensile stress condition. Appropriate use of these unique characteristics can work out a structural component excellent in both durability and mechanical performance. This paper introduces the JSCE recommendations for design and construction of high performance fiber reinforced cement composite with multiple fine cracks.

Keywords: *HPFRCC; multiple fine crack; strain hardening; design; execution; recommendations.*

INTRODUCTION

High Performance Fiber Reinforced Cement Composite with multiple fine cracks (referred to HPFRCC in this paper) is a cement-based composite material on which worldwide active research has been conducted and particular attention has been focused in recent years. HPFRCC shows strain-hardening tensile stress-strain behavior like steel and exhibits an excellent capability to control the width of crack. These characteristics under tensile stress conditions are realized by forming multiple fine cracks [Naaman and Reinhardt, 1995]. Some structures using HPFRCC have been started to construct in Japan [Japan Concrete Institute, 2004], for which the JCI Technical committee on performance evaluation of highly ductile cementitious composite (chairman: K. Rokugo) played a very important role from 2001 to 2004 [Kanda et al. 2006].

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Inheritance of the JCI technical committee was to organize a new committee in 2005 for drafting the recommendations for multiple fine cracking type fiber reinforced cement composite in JSCE (chairman: K. Rokugo and secretary general: H. Yokota) which led to the publication of world's first recommendations for design and construction of HPFRCC [JSCE, 2007]. The outline of the recommendations is described in this paper.

OUTLINE OF THE RECOMMENDATIONS

The JSCE committee was organized with commission of consultants, construction companies, and construction materials manufacturers, who have been involved and interested in the application of HPFRCC to civil structures. Active discussions on materials and design and construction technologies were made, and then reflected in the recommendations.

The table of contents of the JSCE recommendations is presented in Table 1. The JSCE recommendations specifies the methodology of structural performance, serviceability, and durability verifications according to the performance-based concept. Test methods for determining tensile strength, tensile strain capacity, and crack width are also specified because the tensile characteristics are very important for the structural design of HPFRCC. The test results provide designers and engineers with material properties such as yield strength, ultimate tensile strain capacity, and maximum crack width for given HPFRCC for material and structural designs. The recommendations allows to occur cracks not only at the ultimate limit state but also in the service conditions. The serviceability limit state design is required to assure the durability throughout the design service life on the basis of the calculated tensile strain or crack width induced in HPFRCC members.

Table 1 Contents of the JSCE recommendations

Chap. 1	General
Chap. 2	Basis of Design
Chap. 3	Design Values for Materials
Chap. 4	Load
Chap. 5	Structural Analysis
Chap. 6	Verification of Structural Safety
Chap. 7	Verification of Serviceability
Chap. 8	General Structural Details
Chap. 9	Verification of Durability
Chap. 10	Casting Construction
Chap. 11	Direct Spraying Construction
Test method 1.	Method of making and curing specimens
Test method 2.	Test method for tensile properties of HPFRCC
Test method 3.	Determination of maximum and average crack widths
Test method 4.	Determination of variation in crack widths
Appendices I to VI (informative)	

The recommendations is provided for synthetic short fiber reinforced cement composites that exhibit pseudo strain-hardening behavior and form multiple fine cracks under uniaxial tensile stress conditions. More specifically, the target composite is limited with that the average ultimate tensile strain capacity is larger than or equal to 0.5 % and the average crack width is smaller than or equal to 0.2 mm as determined with the test methods in the recommendations. The scope of application of the recommendations includes steel reinforced HPFRCC members (R/HPFRCC) and an existing RC structure covered with HPFRCC layers (HPFRCC-covered RC), but excludes monolithic use of HPFRCC in members.

The appendices provide very useful information for using the recommendations, which include general characteristic values of HPFRCC on mechanical and durability-related properties, bases of the recommendations, examples of design and construction, and so on.

CHARACTERISTICS OF HPFRCC

HPFRCC covered in the recommendations is a composite material with synthetic short fiber such as polyvinyl alcohol (PVA) or polyethylene (PE) at a fiber-volume fraction of less than around 2 %. The features of HPFRCC in relation with other fiber reinforced cementitious materials are illustrated in Figure 1. Characteristics of HPFRCC are best manifested when compared with ultra high-strength fiber reinforced concrete (UFC) [JSCE, 2006] in this figure. The design strengths of UFC are 150 N/mm^2 for compressive strength and 5 N/mm^2 for tensile strength, which are characteristics of UFC far greater than those of HPFRCC. However, UFC shows multiple fine crack formation like HPFRCC only under bending and not under uniaxial tension, which leads to a limitation in reflecting the multiple fine crack performance into structural design as a material property. Unlike HPFRCC, UFC does not show the strain-hardening or plastic type tensile stress-strain behavior but shows so-called quasi-brittle behavior where early-stage damage concentration takes place at the initial cracks. These differences in materials properties lead to different principles of designing structural members between HPFRCC and UFC. UFC is designed so that cracks are not allowed to occur in the service conditions while HPFRCC allows cracks to draw the best characteristics. Construction methods of HPFRCC are divided into two types: casting and spraying. The former is mostly applied for new constructions while the latter is applied for repair.

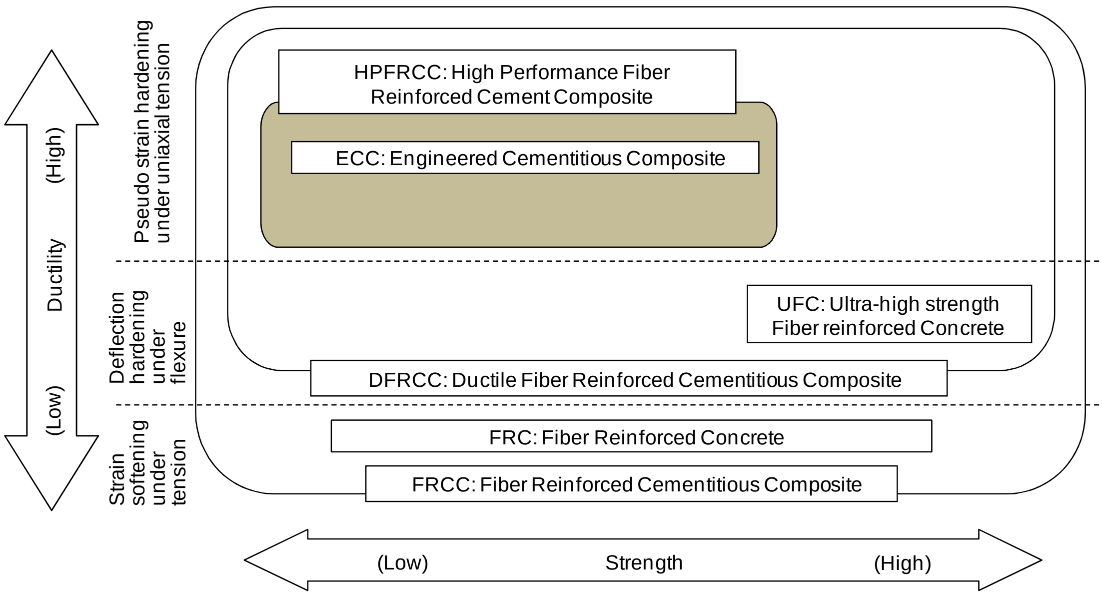


Figure 1 Classification of materials

ADVANTAGES IN APPLYFING HPFRCC

Tensile and shear load carrying capacities of R/HPFRCC members are deducible by superimposing those of reinforcing steel and HPFRCC. This contribution of HPFRCC is originated from the fact that the tensile characteristics of HPFRCC can be maintained at a region exceeding the yield strain of steel reinforcement. This contribution results in improvement of cost effectiveness and structural performance, which appears more significant in case that the serviceability limit state governs the structural section design.

Unlike other structural systems, an HPFRCC member also shows a unique feature in protecting steel reinforcement. When a crack forms in conventional reinforced concrete (RC) members, the crack allows corrosive factors to transport more easily, which may result in the corrosion-induced deterioration of steel reinforcement. In R/HPFRCC or HPFRCC-covered RC members, however, the crack width in HPFRCC becomes smaller and hence the carbonation rate and chloride migration rate are suppressed obviously exhibiting higher corrosion protection capability than those of RC members. Therefore, those HPFRCC members can be expected to have a longer design service life owing to their protective capability against corrosion-induced corrosion of steel reinforcement and other environmental actions.

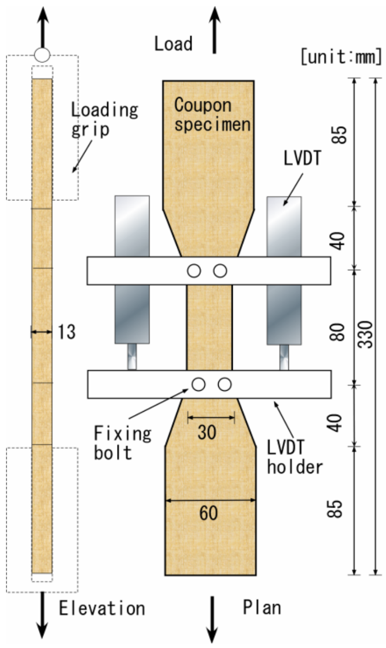


Figure 2 Test method for determining tensile characteristics

MATERIAL PROPERTIES AND DESIGN VALUES

Another unique feature of HPFRCC lies in tensile characteristics including pseudo strain-hardening tensile stress-strain behavior and crack width controlling capability, while compressive performance is not very different from that of the normal concrete. Three major material properties such as tensile yield strength, ultimate tensile strain capacity, and maximum crack width are defined to reflect the tensile characteristics in structural design.

The first two characteristics can be determined by the uniaxial direct tensile test [Inakuma et al. 2006] proposed in the recommendations (Test method 2) as shown in Figure 2. When the tensile stress-strain relationship is determined with the proposed method, tensile yield strength, f_{ty} and ultimate tensile strain capacity, ε_{tu} can be obtained as shown in Figure 3, and their characteristic values are to be determined taking into account their variations. Examples of variation in the tensile yield strength and the ultimate tensile strain capacity are shown in Figures 4 and 5, respectively. A schematic representation of the characteristic tensile yield strength, f_{tyk} and characteristic ultimate tensile strain capacity, ε_{tuk} are shown in Figure 6 together with an example of actual stress-strain relationship.

The characteristic value of crack width is defined as the maximum crack width for which the test method is proposed in the recommendations (Test method 3). In this test method, crack widths as shown in Figure 7 are measured under the tensile loading performed in the same way as that shown in Figure 2. The crack width can be measured either with direct microscope observation or indirect estimation based on the number of cracks and the tensile strain. When the crack width is obtained, the maximum crack width is determined taking into account the variations as shown in Figure 8.

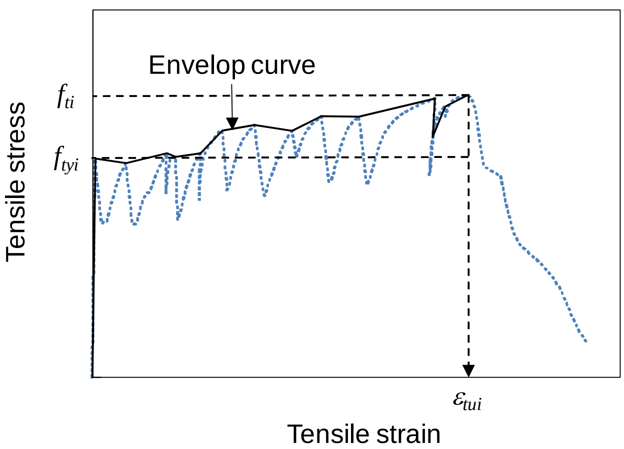


Figure 3 Method of tensile characteristics evaluation

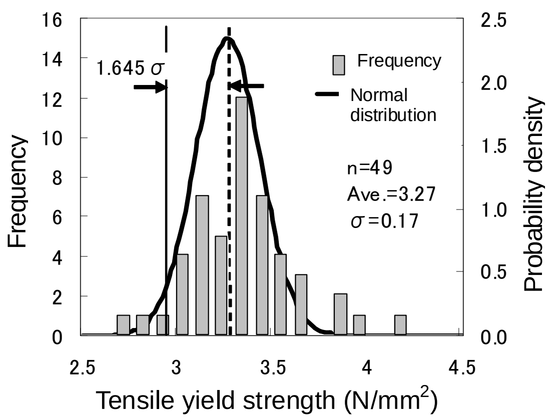


Figure 4 Variations in measured tensile yield strengths

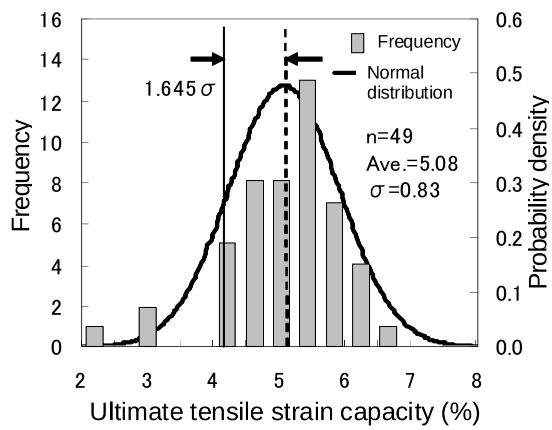


Figure 5 Variations in measured ultimate tensile strains

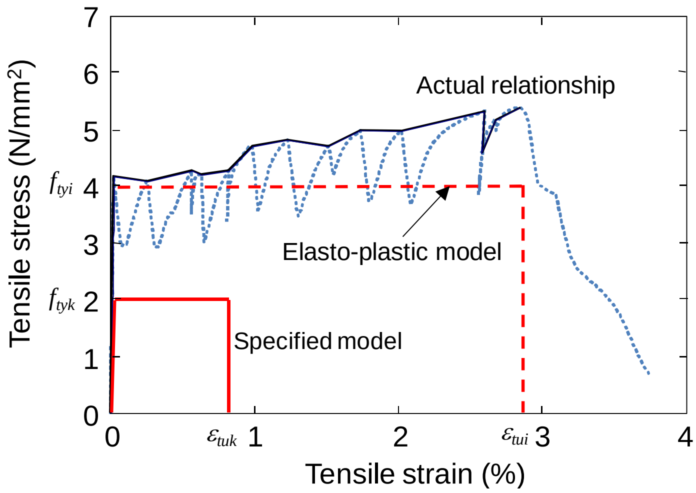


Figure 6 Models expressing tensile stress-strain relationships

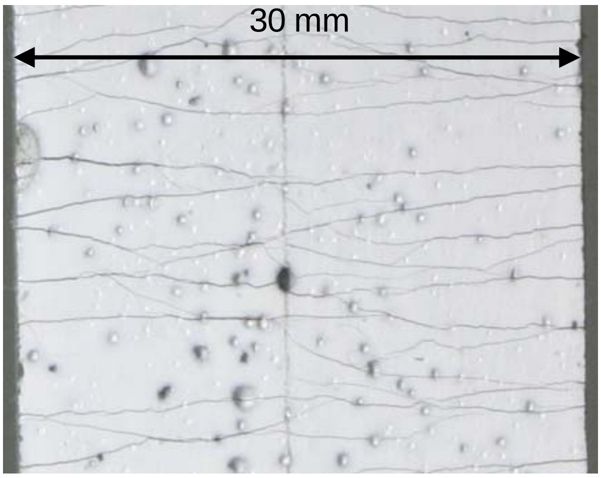


Figure 7 Multiple fine cracks in ECC

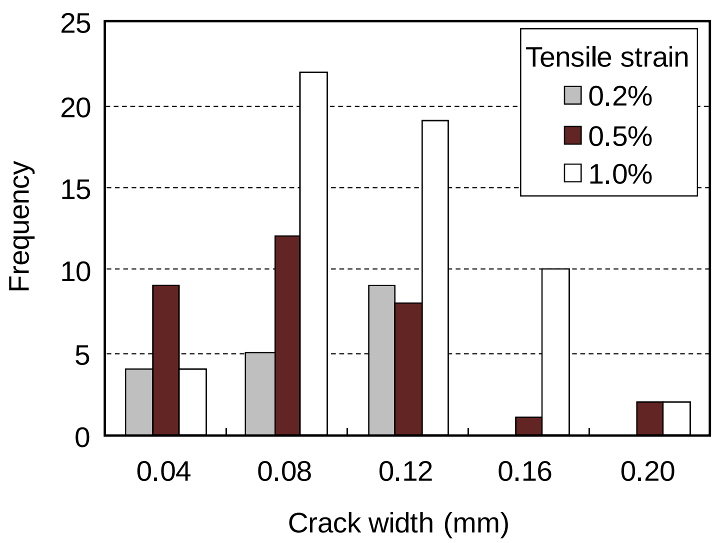


Figure 8 Distribution of measured crack widths at different tensile strain levels

VERIFICATION FOR STRUCTURAL PERFORMANCE

Structural Safety for Bending Moment

Regarding the structural safety verification of HPFRCC members in bending, design capacity of cross-section can be determined reflecting the contribution of the design tensile yield strength of HPFRCC to the steel reinforcement within the range of design ultimate tensile strain of HPFRCC. These design values for material performance are determined taking into account the safety factors. Assumption in stress and strain distribution in the section of an R/HPFRCC member is shown in Figure 9, where the tensile stress of HPFRCC is added as a component of tensile stress resultant unlike RC members. Since the design ultimate tensile strain capacity of HPFRCC normally exceeds the yield strain of steel, it is possible in the calculation of design flexural moment capacity of members to superimpose the tensile yield strength of HPFRCC on the tensile yield strength of steel.

Estimating design capacity of member cross-section normally adopts so-called fiber model to calculate a moment-curvature relationship, where the elasto-plastic model, as shown in Figure 6, is used to represent the tensile stress-strain relationship of HPFRCC. The results of the design calculation and experiment for the flexural behavior of beams are compared in Figure 10, where ECC is a variation of HPFRCC as shown in Figure 1. The characteristic (average) values of tensile yield strength and ultimate tensile strain capacity of HPFRCC are used for the calculation; that is, no safety margins are taken into consideration. As shown in Figure 10, the calculated and the experimental results show good agreement. Therefore, Figure 10 demonstrates the appropriateness of the assumption made for flexural moment capacity design, although the moment-curvature relationship is presented using the load-displacement relationship instead in the figure.

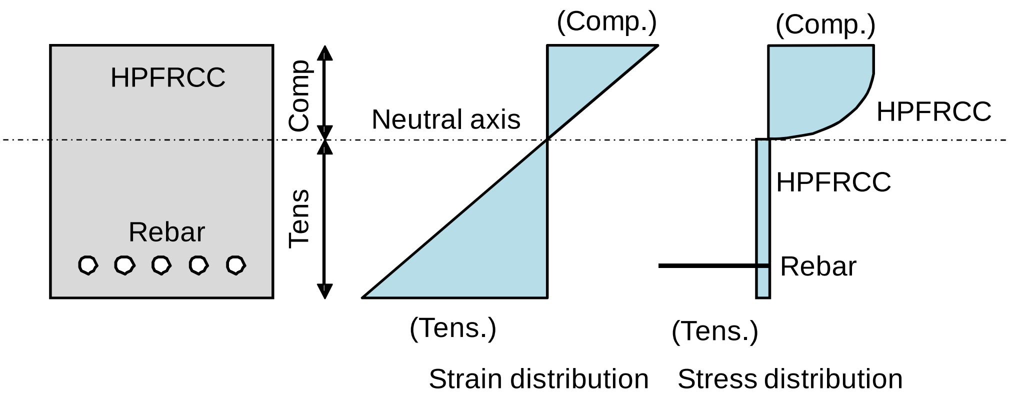


Figure 9 Schematic diagrams of strain and stress distributions for flexural capacity

Structural Safety for Shear Force

Structural safety verification for shear forces can be performed by calculating the design shear capacity, V_{yd} with the following equation:

$$V_{yd} = V_{cd} + V_{sd} + V_{fd} + V_{ped} \quad (1)$$

where V_{cd} : design shear capacity of linear member without shear reinforcing steel, excluding the contributions of fibers in HPFRCC; V_{sd} : design shear capacity of shear reinforcing steel; V_{fd} : design shear capacity of fibers in HPFRCC; and V_{ped} : effective tensile force of axial tendon in parallel to shear force. The resulting design shear capacity has a fiber contribution term V_{fd} in addition to V_{cd}, V_{sd} and V_{ped} comprising the shear capacity of RC member. In Equation 1, values of V_{sd} and V_{ped} are the same as those for conventional RC member while a reduction of 70 % is applied to V_{cd} because cracks are allowed to occur in the service conditions. Although V_{fd} is a function of β_u, an angle made by the crack plane with the axis, it is fixed at $\beta_u = 45°$ to keep the safe side.

The results of calculation with Equation 1 and the experimental results are compared in Figure 11, in which the design tensile yield strength of HPFRCC is replaced by the average value of measured tensile yield strength that is larger than the design value. This figure shows that the calculation with Equation 1 may provide the safe-side estimation.

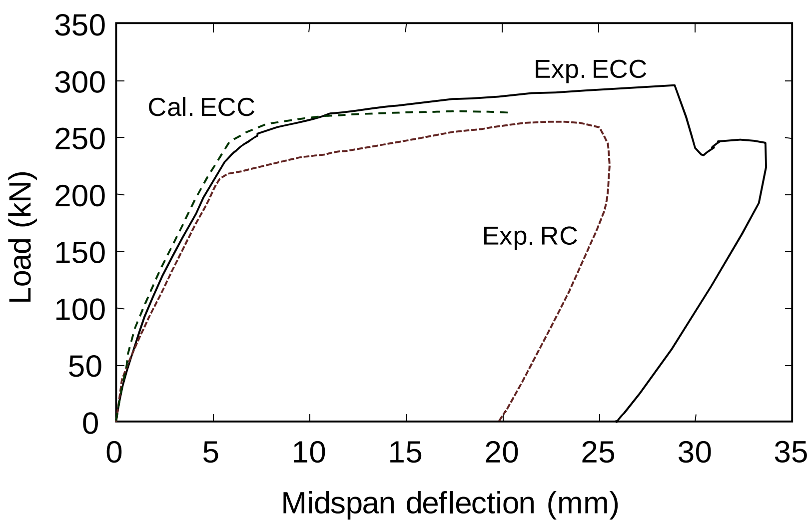


Figure 10 Examples of load-displacement curves

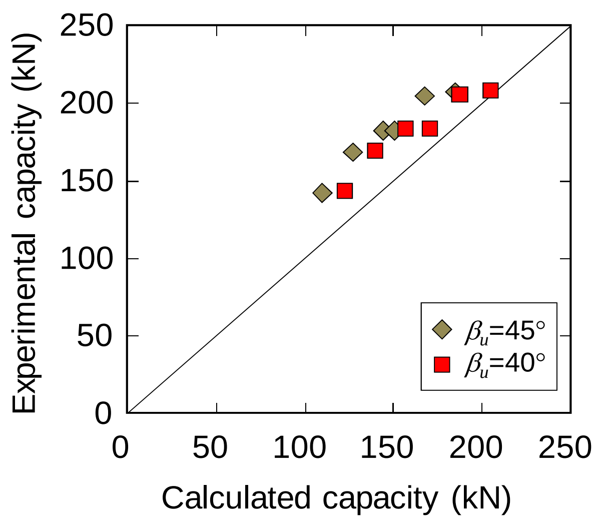


Figure 11 Comparison of experimental and calculated shear capacities

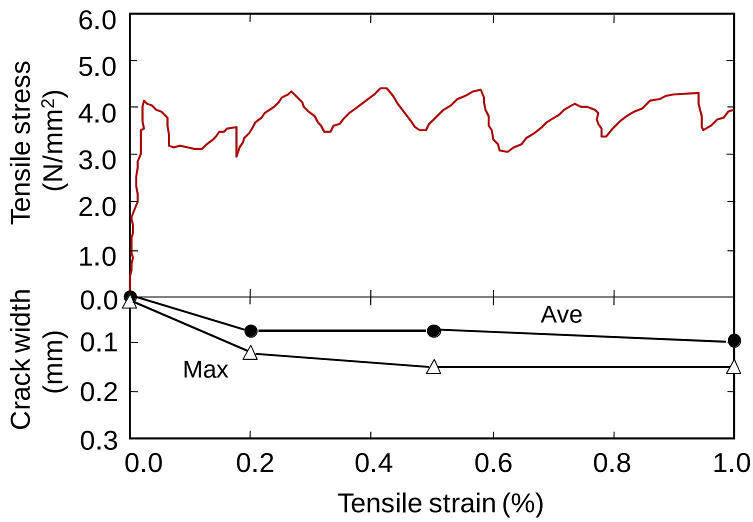


Figure 12 Effects of tensile strain on crack width

Serviceability

Serviceability verification in the recommendations is featured by (i) cracks are allowed to occur in the service condition and the crack width is treated as a material property not as structural performance, and (ii) limitations in stress or strain in service condition are set not only for steel stress but also for tensile strain in HPFRCC. As stated in (i), crack width in HPFRCC is not greatly affected by structural design parameters such as tension reinforcement ratio and cover thickness but by the material property before reaching ultimate tensile strain capacity, while that in normal RC member is controlled by the structural design parameters. This concept is manifested in Figure 12. This figure shows the relationship between tensile strain and crack width, where the mean crack width refers to the averaged width of multiple cracks that occur at a tensile strain and the maximum crack width refers to a characteristic value of crack obtained stochastically taking into account the variations as stated above. As shown in this figure, variations in crack width are small even though the tensile strain develops. In other words, the developed crack width may be regarded nearly constant until the tensile strain reaches the ultimate state except for small strain ranges. Therefore, HPFRCC can control crack width without the help of steel reinforcement. To guarantee the design, serviceability verification requires the tensile strain of HPFRCC in service condition has to be smaller than the ultimate tensile strain capacity.

VERIFICATION FOR DURABILITY

Advantage of Multiple Fine Cracks

It is of great importance to guarantee the durability of materials for use in constructions. HPFRCC shows such performance that a crack is controlled its width, as mentioned earlier. This causes high durability of HPFRCC against environmental actions. As shown in Figure 13, deterioration causing factors cannot be transported easily through cracks because of very narrow crack openings. Also the mechanism of steel corrosion is shifted from the macro-cell corrosion to the micro-cell corrosion because of the formation of lots of cracks at short intervals.

Verification for Carbonation-Induced Corrosion of Reinforcement

Carbonation generally develops faster at a cracked region as in RC structures where corrosion of steel reinforcement embedded occurs around the carbonated/cracked regions. However, crack width of HPFRCC can be controlled to be smaller than that of RC members and it is experimentally verified that the development of carbonation at the cracked region is not significant compared to a region without cracks. Table 2 summarizes the results of accelerated carbonation test. Therefore, corrosion of steel reinforcement embedded can be verified in the same way as the case without cracks by defining a permissible crack width below which the crack width of a member in service is controlled.

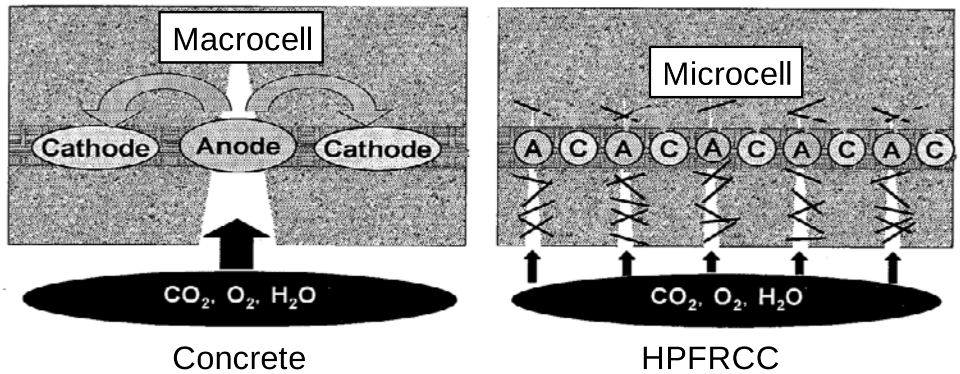
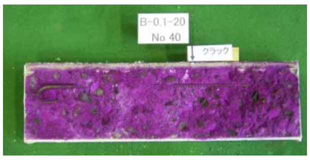
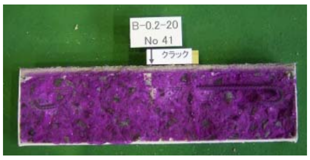
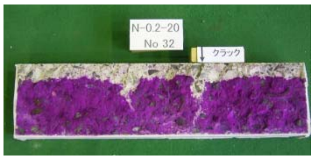
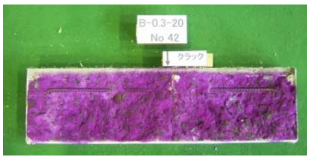
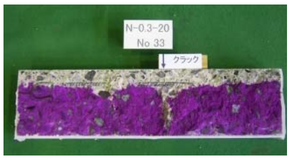
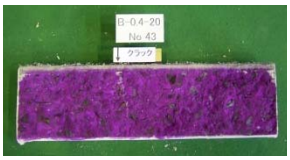
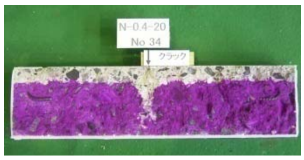


Figure 13 Differences of corrosion mechanism due to crack formation

Table 2 Effects of cracks on carbonation depth

Maximum crack width	HPFRCC-covered concrete (cover: 10 mm thick)	Normal concrete
0.1 mm		
0.2 mm		
0.3 mm		
0.4 mm		

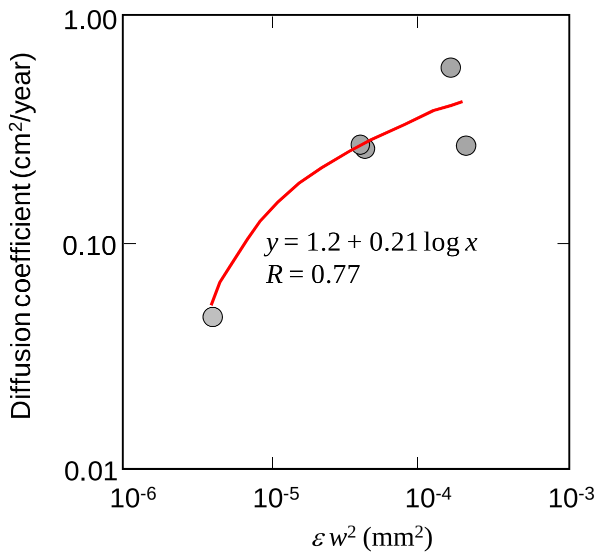


Figure 14 Example of measured chloride ion diffusivity

For carbonation related verification, confirmation is needed whether a calculated depth comprising designed carbonation depth plus remaining depth corrected with a structure factor exceeds the cover depth or not, as performed in RC members [JSCE, 2005]. The characteristic value of carbonation rate factor for HPFRCC has to be set properly on the basis of testing but, as confirmed, the value may be equal to that of concrete when water-to-cement ratio is the same. Crack width should be examined by confirming that the maximum crack width, as explained in the serviceability verification, is less than the permissible crack width.

Verification for Chloride-Induced Corrosion of Reinforcement

Verification regarding the chloride ingress is performed with the workflow as summarized in Table 3 in which it has to be confirmed that the designed chloride ion concentration at the location of steel reinforcement is lower than the threshold value of chloride concentration for onset of steel corrosion at the specified cover depth during design service life. The design value of diffusion coefficient of chloride ions in HPFRCC employed in this verification has to be determined taking into account possible tensile strain and crack width in service condition. Verification of RC members takes crack width and crack interval as the parameters [JSCE, 2005] and verification in HPFRCC members principally follows this concept. A formula for estimating the diffusion coefficient of chloride ions taking into account the above factors is newly proposed on the basis of experimental results as shown in Figure 14.

$$D_d = D_k + D_0 \log (\varepsilon w^2) \tag{2}$$

where D_d : design value of diffusion coefficient of chloride ion in HPFRCC (cm^2/year); D_k : characteristic value of diffusion coefficient of chloride ion (cm^2/year); D_0 : a constant to represent the effect of cracks on transportation of chloride ions in HPFRCC (cm^2/year); ε : tensile strain which is resulted by service load; and w : characteristic value of the maximum crack width (mm).

The threshold value of chloride concentration for onset of steel corrosion is 1.2 kg/m^3. This threshold value is the same as that of normal concrete, while the value may be set higher according to experimental data as shown in Figure 15. This appears due to the higher chloride ion binding capability of HPFRCC originated from its high unit cement content and various admixtures mixed. The advantage of HPFRCC is demonstrated in Figure 15. It is shown in this figure that the fraction of free chloride ion in HPFRCC after immersion test in 10 % NaCl solution ranges from 0.2 to 0.4 while that in normal concrete with a water-cement ratio of 0.5 ranges from 0.6 to 0.8 proving the higher chloride ion binding capability of HPFRCC.

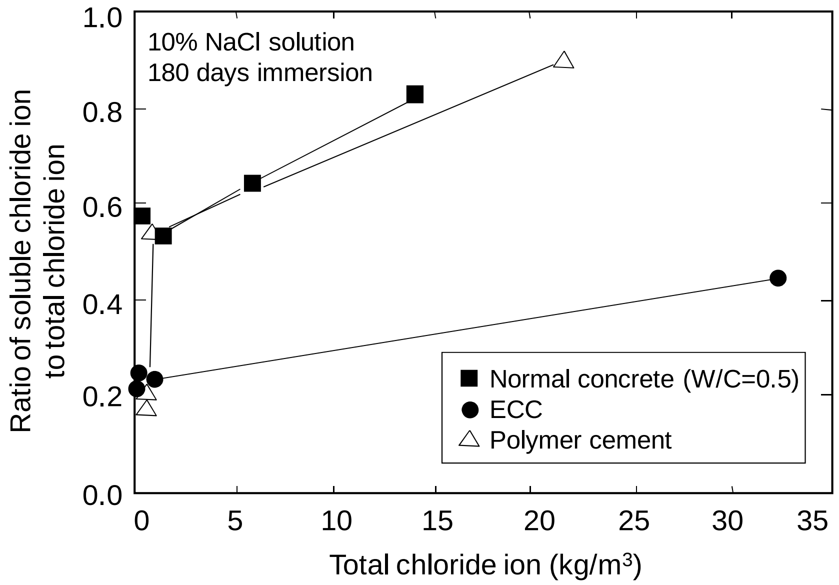


Figure 15 Example of permissible chloride ion concentrations for steel corrosion

Table 3 Verification procedure for chloride-induced corrosion in HPFRCC

Stage	Estimation	Input	Output
0	Calculation of strain	–	Tensile strain at extreme tension fiber due to service loads
1	Calculation of maximum crack width	Design value of tensile strain	Characteristic value of maximum crack width
2	Determination of diffusion coefficient of chloride ion	Maximum crack width Tensile strain	Design value of diffusion coefficient of chloride ion in HPFRCC
3	Calculation chloride ion concentration at steel reinforcement	Design value of diffusion coefficient of chloride ion Design service life Design cover thickness	Chloride ion concentration at steel reinforcement during design service life
4	Verification of steel corrosion	Chloride ion concentration at steel reinforcement Threshold value of chloride concentration for onset of steel reinforcement corrosion	Result of verification Comparison between the calculated chloride concentration and the threshold value

SELECTION OF MATERIALS, PRODUCTION, AND CONSTRUCTION

The constituent of HPFRCC has to be sufficiently stable and durable during the design service life of structures. In particular, selection of the synthetic fibers that has never been present in the normal concrete has to be confirmed by testing its stability over the design service life. The confirmation test methods including high temperature accelerated test under alkali environment are compiled in the appendix of the recommendations.

Production and construction of HPFRCC members are described in Chapters 11 and 12 of the recommendations. Bases of mix design and mixing are presented and the confirmation of performance of HPFRCC by inspection is emphasized. Examples of inspection items of casting construction are listed in Table 4 in which the principal inspection items are tensile characteristics and crack width.

Conventional construction methods of concrete may be applicable to HPFRCC. Because the tensile characteristics of HPFRCC are important in the design consideration, basic cautions are given on the layered placement and placing joints that greatly affect the performance of the completed structures. Methods of performance confirmation for placing joints are compiled in the supplemental section of the recommendations.

Table 4 Inspection items of HPFRCC

Item	Test method	Timing and frequency	Criteria
Mix proportion	Weighing of each material	All batches	Within a permissible range of error
Fresh state	Inspection by experts	Occasionally	Good workability, stability and uniform quality
Fluidity	Flow value conformed to JIS A 1150	At the start of construction At sampling In case of any changes in quality	Adoptable to conditions required by the construction methods
Segregation resistance	V-funnel test		
Unit mass	JIS A 1116		
Mixing temperature	Temperature measurement		
Compressive strength	JIS A 1108	Once a day or every 20 to 150 m^3 depending on the importance of structure and on construction scale	Probability of lowering the design value has to be less than 5 %,as estimated with appropriate consumer's and producer's risk
Tensile yield strength	Uniaxial direct tensile test (Test method 2)		
Ultimate tensile strength and strain			
Maximum crack width	Crack width measurement (Test methods 3 and 4)		

CONCLUDING REMARKS

Application of HPFRCC is still in incunabula and associated with problems to be solved, while it poses a unique feature that has never been presented by the existing cement-based materials. A worldwide active research and development of HPFRCC imply a possibility to realize concrete structures with excellent safety, serviceability, and durability. It is our anticipation that the publication of the recommendations would contribute to the realization of building excellent concrete structure. The English edition of the recommendations is now in progress, which will be published in 2008.

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