Committee Report : JCI- TC104A

Technical Committee on Innovative Application of Fiber Reinforced Cementitious Composites

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Abstract

Despite the ability of fiber-reinforced cementitious composites to add value to structures by integrating elements of structural design and material design, a rational design method where both design elements are integrated (or seamless construction) has not been fully reviewed at present. Bearing in mind that fiber-reinforced cementitious composites can show their superiority by introducing a long-term performance design concept, this research committee established three working WGs, namely, (1) New Uses WG, (2) Performance Evaluation WG, and (3) Environmental Response WG, to propose new uses of fiber-reinforced cementitious composites.

Keywords: Fiber-reinforced cementitious composites, long-term performance design, material-structure seamless construction, crack width

1. Introduction

Just about 40 years have passed since short steel fiber-reinforced concrete technology was adopted in the 1970s. Short fiber-reinforced cementitious composites are, needless to say, concrete materials with which short fibers are mixed and, their ability to withstand external force with the support of fiber crosslinking even in the case of a cracks, can drastically increase bending strength and toughness compared to ordinary concrete. In particular, the merit of flexibility of selection of the kind of fiber as well as the mixing amount makes them attractive materials that can be freely designed to meet the performance required by a structure or its member. In other words, once seamless material-structure construction is put into practice and if materials are developed after the performance required for concrete structures is clearly identified, applications which exploit the merit of those materials may possibly be discovered.

As a project of the Japan Concrete Institute, activities contributing to the promotion of new high-toughness cementitious composites were undertaken in 2001 to 2003 by the “Task Committee on Ductile Fiber Reinforced Cementitious Composites (DFRCC) (chaired by Prof.

Keitetsu Rokugo from Gifu University)".[1)]

Table 1: Committee members

Chair	Yoshio KANEKO	Kyoto University
Secretary	Minoru KUNIEDA	Nagoya University
Secretary	Toshiyuki KANAKUBO	Tsukuba University
Secretary	Yusuke KURIHASI	Muroran Institute of Technology
	Takayuki ASAI	Nippon Expressway Research Institute Co., Ltd.
	Takahiko AMINO	Toa Corporation
	Seiichiro ISHIHARA	Asanuma Corporation
	Masato ISO	Fukui University
	Hajime ITO	Toyama Prefectural University
	Mitsuyasu IWANAMI	Port and Airport Research Institute
	Atsuhisa OGAWA	Kuraray Co., Ltd.
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	Akihiro SHIBA	Sumitomo Mitsui Construction Co., Ltd.
	Ryosuke SHIONAGA	IHI Corporation
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	Shigeki SEKO	Aichi Institute of Technology
	Kohei NAGAI	The University of Tokyo
	Satoru NAGAI	Kajima Technical Research Institute
	Takaaki HIRATA	Obayashi Technical Research Institute
	Kenichi HORIGUCHI	Taisei Technology Center
	Tokuichi MAEDA	Toyobo Co., Ltd.
	Nobuyuki MAEDA	Shimizu Corporation
	Yoichiro MUROGA	Hagiwara Industries Inc.
	Ken WATANABE	Railway Technical Research Institute
	Koji YAMANOBE	Shimizu Institute of Technology
Corresponding member	Yuichi SATO	Kyoto University
Observer	Kohei ASANO	Tsukuba University
JCI secretary	Kazuhisa INOUE	Japan Concrete Institute

This research committee was established for the purpose of providing information to help further expand the use of fiber-reinforced cementitious composites with the changing development and application of materials for fiber-reinforced cementitious composites in mind, and established three WGs to conduct two-year activities. **Table 1** shows the committee members.

WG1 (New Uses WG headed by Kurihasi) has sought and proposed new uses through the survey of papers published in the past decade.

WG2 (Crack Width Evaluation WG headed by Kanakubo), paying attention to smaller crack widths as one of the superiorities of fiber-reinforced cementitious composites, surveyed previous methods of crack width evaluation and, at the same time, made a proposal concerning the ideal method of evaluating crack widths for relevant materials.

WG3 (Environmental Response WG headed by Kunieda) pointed out the necessity to consider environmental loads of fiber-reinforced cementitious composites throughout their entire life span, first discussed $LCCO_2$, then proposed new uses from the viewpoint of environmental load mitigation, and reviewed the recycling efficiency of fiber-reinforced concrete.

A special aspect of review by all WGs was that it was based on the viewpoint of where in the stage of improving a structure's "long-term performance", the fiber-reinforced cementitious composites should show their superiority. Here, let us outline the activities of each WG.

2. Possibilities of fiber-reinforced cementitious composites for the purpose of improving the long-term performance of a structure (WG1)

To explore the ability of fiber-reinforced cementitous composites (FRCC) to improve the long-term performance of a structure, the trend of previous R&D and practical applications was surveyed, and approaches toward the development of new uses were suggested from four viewpoints. Finally, we proposed uses where the application of FRCC is inevitable to secure the long-term performance of concrete structures.

2.1 New uses where R&D and practical applications are under way

Here is an outline survey of papers on R&D and practical applications of fiber-reinforced cementitious composites for the purpose of improving long-term performance of concrete structures. The papers surveyed are those published from 2000 to 2011 including a collection of papers on concrete civil engineering, a collection of annual papers on concrete civil engineering, Proceedings of the Japan Concrete Institute (Concrete Journal/Concrete Technology Reports), a collection of papers of the Japan Society of Civil Engineers, the AIJ's Journal of Structural and Construction Engineering, the Journal of Structural Engineering, the ACI Materials Journal, and the ACI Structural Journal, totaling 646 papers. Applicable cases were compiled by hearings from members of this committee and concerned persons. These papers and applicable cases were sorted with reference to the matters listed below:

1) Target structures (newly built or existing structures)
2) Materials used (kind of fiber)
3) Applicable regions
4) Research objective
5) Review method
6) Review of long-term performance
7) Existing design guidelines, evaluation method
8) Standard test method used, etc.
9) Proposed evaluation method
10) Merits
11) Future review items
12) Literature cited

For reference, these data were, after classification into architecture (materials/structure) and civil engineering (materials/structure), included in the CD-ROM attached to this research committee’s report.

Moreover, these research papers were classified into 10 areas including prevention of delamination, prevention of cracks, load resistance improvement, earthquake resistance improvement, higher fatigue durability, impact resistance improvement, higher explosion resistance, fire resistance improvement, labor-saving construction, and long-term durability for use in newly built structures, and into 5 areas including prevention of delamination, cross-sectional repair, load resistance improvement, earthquake resistance improvement, and higher fatigue durability for use in existing structures, and analyzed such as for the kind of FRCC used in each category, applicable regions, the trend of research, and future problems to be reviewed. **Table 2** shows the number of research papers published each year by each area.

The table indicates that the most common objective in newly built structures was to improve load resistance, which is still the subject of a large number of studies. In the civil/structural engineering area in particular, most cases are intended to improve the shear capacity of beam members or the punching shear strength of slab members.

The second most common objective is labor-saving. Main uses are intended to improve the load and earthquake resistances of a member through the application of FRCC to reduce cross-sectional area for weight-saving, or to compensate for a shear strength shortfall of light-weight concrete RC/PC members by using FRCC so that weight-saving may be realized,

Table 2: Number of papers on new uses whose R&D and practical applications are under way

Publication year		'00	'01	'02	'03	'04	'05	'06	'07	'08	'09	'10	'11	Total
Newly built	Prevention of delamination				2	1	1						1	5
	Prevention of cracks	2	1	4	5	5	4	6	8	4	2	5	3	49
	Load resistance improvement	3	4	1	4	9	7	16	19	14	10	18	18	123
	Earthquake resistance improvement	3	2	10	6	3	8	10	9	8	8	6	1	74
	Higher fatigue durability	2		2	1		1		1		1	2	3	13
	Impact resistance improvement		2	2		1				1		1	3	10
	Higher explosion resistance								2	1		4		7
	Fire resistance improvement	1	2	1	1	3	3	4	10	5	4	4	1	39
	Labor-saving construction	1	3	6	5	14	7	7	6	14	5	6	3	77
	Long-term durability				1		1	5	5	3	4	5	2	26
Existing	Prevention of delamination				3	1	1						1	6
	Repairing materials		6	2	1		1		1	1	2		1	15
	Load resistance improvement					3		3	3	5	5	2	3	24
	Earthquake resistance improvement			1	2	5	3		5	2	6	3	2	29
	Labor-saving construction								3	1	2	3		9
	Higher fatigue durability			1							1	4		6

etc. These uses, therefore, lead to labor-saving by improving a member's load resistance/earthquake resistance. Other uses such as in buried frameworks and various joints were also found.

Many of the studies were also intended to improve earthquake resistance, and they tend to be found mainly in the architectural/structural engineering area. Other than applications in pillars, beam-column joints, and boundary beams, many cases relate to CES (Concrete Encased Steel) compositional structures consisting only of steel frames and FRCC. Long-term durability was also reviewed positively in terms of salt damage, freezing damage, neutralization, dimensional stability, wear resistance, and so on. Recently, research on the self-healing performance due to the effect of FRCC in limiting cracks is also under way.

On the other hand, the most common objective related to existing structures is to improve earthquake resistance. Applications are found in cases of using FRCC as a damping device in additional pillars, earthquake-resistant walls, structural bases, etc., as well as those of using

CES compositional structures in additional pillars, etc. The second most common objective is to improve load resistance, and application is found in shotcrete for repair/reinforcement purposes, concrete with increased thickness, post-installed panels, etc.

For each area's specific applications and other information, see committee reports.

2.2 Milestone for the development of new uses

The creation of new uses for fiber-reinforced cementitious composites (FRCC) and the expansion of their range of application will presumably require review of their design/construction by extending previous studies, and accumulating data and reviews of 1) any innovative concept for FRCC and 2) the development of new materials including improvement of existing materials.

As regards a new concept for FRCC, the committee focused on the application of a long-term performance design concept and mitigation of environmental loads. As for development of new materials including improvement of existing materials, it was decided to find solutions to problems of existing FRCC and approaches to the development of new FRCC. **Table 3** shows a list of points to which attention should be paid for each approach. They are outlined as follows:

Table 3: Milestone for the development of new uses

Approach to the development of new uses	Points to which attention shall be paid
From the viewpoint of long-term performance design	Long-term performance design concept
From the viewpoint of environmental load mitigation	Maintenance-free, semi-permanent structure
	Semi-permanent structure to be repaired/reinforced
	Cross-sectional reduction
	$LCCO_2$ evaluation
	Eco-materials
From the viewpoint of problem solution	Quality
	Economy
	Laws and regulations
From the viewpoint of new material development	New fiber materials
	New design concept materials
	Existing materials improvement

(1) Approach from the viewpoint of long-term performance design by taking time axis into consideration

In the area of architecture, long-term performance design is defined as a design which allows any structure to manifest its designed usability/security- and durability-related quality and performance during its in-service period. Also in the area of civil engineering, durability, as required performance, must meet the performance level for various parameters during the design durable period.

Furthermore, the adoption of a time axis in these performance designs enables structures to be managed while taking account of the social trend of their life extension/maintenance, based on a performance evaluation against a continual time axis (health monitoring). Therefore, extremely rational design may become possible.

On the other hand, since it is expected that FRCC will limit crack openings after cracking occurs, post-cracking tensile stresses give a gradually increasing characteristic or a gradually decreasing characteristic. Thus, unlike ordinary concrete and mortar, FRCC exhibits moderate post-peak behavior, so it is inferred that chronological change of crack widths can be estimated with relative ease. In designing a variety of structures using FRCC, if an estimated crack width-based long-term performance design concept is applied, then it may possibly lead to a structural design which makes the most of the advantages of FRCC.

At present, this remains only a concept described in Reference 2), and it is necessary in the future to review a concrete method of evaluating long-term performance. Since it is particularly important to estimate the chronological change of crack widths, it is expected that studies will be encouraged by the achievements of WG2 of this research committee.

(2) Approach from the viewpoint of environmental load mitigation

FRCC is characterized by its high ductility capacity since, even after cracks occur, the fiber's crosslinking effect limits crack openings. At the same time, however, more energy is required when demolishing the structure than ordinary concrete, and it is also expected that environmental loads will become heavier. On the other hand, if FRCC's kinetic property and durability are improved, it is also considered possible to design a semi-permanently serviceable structure. More specifically, a method of designing a maintenance-free or semi-permanent structure requiring repair/reinforcement is considered.

In addition, streamlining of substructure and foundation work brought about by weight reduction of superstructures due to the application of FRCC results in saving the amount of concrete used, as well as reduction of CO_2 emissions from cement making. Besides, by allowing FRCC to be composed of recycled materials, waste-mixed cement, etc., it may possibly mitigate environmental loads.

(3) Approach from the viewpoint of problem solution

Section **2.1** introduced new uses where R&D and practical applications are under way, but promotion is still slow as regards practical applications. One of the main reasons for this is the problem of qualitative instability. FRCC, in some cases, significantly fluctuates in terms of its fiber's dispersibility and orientation, often having a direct impact on kinetic property. Solutions to the problems include development of a means to stabilize fiber dispersibility/orientation, contrivance for construction, etc., but it is considered necessary as a first step to establish technology for secondary products of concrete.

Second is the problem of economy. This type of problem is mostly caused by an increase in initial costs due to application of FRCC. Several cases where this problem has been successfully solved are reported, including application to shield tunnel segments[3). New uses may, therefore, be possibly found by exploring any application method that has initial cost-effectiveness. Of course, it is also important in the future to propagate a design concept which examines not only initial costs but also cost- effectiveness from the viewpoint of life cycle costs (LCCs), taking advantage of the long-term performance of FRCC.

Here, as for FRCC, there are some cases where material performance is higher than required, which is a factor for higher costs not resulting in practical use. It is, therefore, assumed that, if a material design method corresponding to the performance required for a structure is established, it enables mix design which limits surplus performance as much as possible, presumably solving the problem of economy.

The problem to be taken up finally is that of laws and regulations. Particularly, in the case of architectural structures, when a material not complying with JIS like FRCC is used, it is necessary for each architectural structure to be separately accredited by the competent minister. As a solution, it seems important to keep advocating the merits of FRCC through research activities like those conducted by this committee, as well as to establish a seamless design/construction method where not only materials and structures but also the flow of construction is consistent.

(4) Approach from the viewpoint of new material development

Although a number of FRCCs have been developed so far, it is considered that any higher cost-effectiveness materials will enable creation of new applications. Here, let us introduce three points to which attention should be paid, and their present status.

First is the application of new fiber materials. Future technological innovation may result in the development of fiber materials whose kinetic properties and durability are better than ever before. And recently, it has become clear that application of iron sawdust (called steel chip) enable the manufacture of economical and high-performance FRCC.

Second is the development of new design concept-based materials. More specifically, it is fiber hybridization, although there appear to be several cases where this has already been reviewed. FRCC undergoes a substantial change in its kinetic property by changing the property of the mixed fiber and shape/size, which enables its performance to be changed by applying two or more kinds of fiber combined. There are, however, recent reports of the development of ultra high-strength mortar with curing characteristics, raising expectations that development of new design concept-based materials will be promoted in the future.

Third is the improvement of existing FRCC. For example, the range of application of UFC has been limited to only plain concrete members or post-tensioning PC members due to the inevitability of heat curing and sizable shrinking. However, recently, heat curing-dispensable and shrinkage-compensation UFC has been developed. Thus, it is also considered possible to create new uses through the improvement of existing FRCC.

In this section, we have outlined each approach. For further details of the matters reviewed here, see committee reports.

2.3 Proposal for inevitable applications of fiber-reinforced cementitous composites

Up to the preceding section, this report has mentioned a number of merits of FRCC, and approaches to develop uses of FRCC. On the other hand, looking at the present state of concrete structures, their manufacture, transportation, construction, curing, and in-service processes still retain a number of problems. Regarding problems of a great post-service impact on third parties in particular, there are many cases where measures have already been taken such as by applying FRCC, but there are many cases where no measures have been taken.

Hence, in this section, let us discuss the regions where the application of FRCC is deemed inevitable, and how it should be used.

(1) Prevention of concrete fragments from spalling

Since concrete fragment spalling accidents occurred one after another in and after 1999, anti-spalling measures have come to be taken in numerous concrete structures. At present, however, some local governments and structural administrators have neither taken adequate measures nor prepared sufficient guidelines, etc., as yet.

With respect to the prevention of concrete fragments from spalling, therefore, it is important to improve methods of handling and maintaining newly built structures.

Particularly, since the application of FRCC is extremely effective in preventing concrete fragments from spalling, we should like to propose that the application of FRCC should be made compulsory in concrete structures very likely to cause damage to third parties like tunnels, elevated bridges, and rock sheds,.

(2) Prevention of brittle fracture

Bridge maintenance is indispensable not only for saving LCC due to the life extension of a bridge, but also for safe running of vehicles, etc. Recently, however, cases of cave-in from punching shear fracture due to the fatigue of floor slabs, etc., are increasing. Looking at the present state of architectural structures, the use of ultra high-strength concrete tends to be promoted due to latter-day Manhattanization. However, it needs to be taken into full consideration that ultra high-strength concrete is liable to extremely brittle fracture at the time of compression failure.

Considering that the application of FRCC is quite effective in inhibiting such brittle fracture, we should like to propose that the application of FRCC should be made compulsory in areas where this kind of fracture is assumed to occur.

3. Evaluation of crack widths（WG2）

As for fiber-reinforced cementitious composites, since fibers crosslink cracks in a matrix even after cracking and transmit stresses, crack width extension is limited to a greater extent than in a matrix containing no fiber. In this chapter, we attempt to quantitatively evaluate fiber-reinforced cementitious composite crack widths, and discuss relevant information as well as information for the expansion of uses.

3.1 Long-term performance design and crack width evaluation for concrete members

As regards a structure, not only material degradation over time but also, in the long run, time-related deterioration in structural resistance can be expected. This report proposes a concept of “long-term performance design”, based on the application of fiber-reinforced cementitious materials as a new construction method which permits seamless design of the relationship between material properties and structural performance, as shown in **Fig. 1**[2),4)]. Here, in-service years were set on the horizontal axis as time axis and performance indicators to quantify the structural performance of a structure, on the vertical axis. In the figure, the performance indicator is defined as an indicator giving a measure to evaluate the structural performance of a structure, the required long-term performance is defined as the long-term performance required during the in-service period, and the targeted performance is defined as the minimum long-term performance necessary to meet the required long-term performance during the set in-service period. It shows that, if the performance of an actual structure is below the targeted performance, the required long-term performance cannot be obtained during the in-service period. For an ordinary structure, repair and/or reinforcement becomes necessary to meet the targeted performance. Fiber reinforcement will probably slow the deterioration of structural performance, and may also reduce the extent of damage due to short-term disturbance. As for long-term performance design with the time axis taken into account, fiber reinforcement seems to be effective for the performance of concrete (or cementitious) structures.

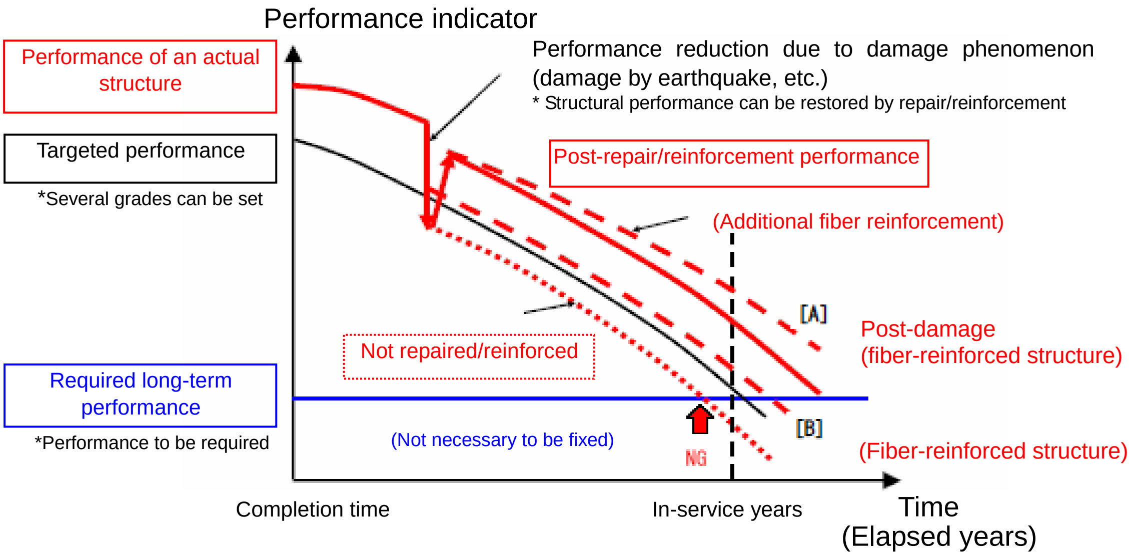

Fig. 1: "Long-term performance design" concept

3.2 Information relating to strain hardening-type materials

(1) Materials design technology for ECC

As for ECC (Engineered Cementitious Composite) with expectation of multiple cracks and deformation behavior up to several-percent tensile strain under tensile stress after initial cracking, it is said that structural behavior can be evaluated on the level of ECC-based members by using the micro-level performance of constituent materials[5)]. **Fig. 2** shows an outline of material design technology for ECC[5)]. Level 1 shows the behavior of pull-out from a single fiber matrix, by using the micromechanics parameter which shows the micro-level performance of fiber and matrix. Level 2 shows the crosslinking law for crosslinking cracks by multiple fibers based on the pull-out behavior of single fiber. Level 3 shows the stress-strain relationship as a macro-dynamic behavior of materials by using the crosslinking law. Level 4 shows the reflection of the stress-strain relationship of materials on the structural behavior of members.

This means that, if micro-level material parameters are used, even structure- and member-level crack widths can be evaluated. There are, however, problems to be solved by evaluation on each level, and some evaluation variables (for example, single fiber-matrix interfacial shear stress=bond stress) which need to be experimentally determined.

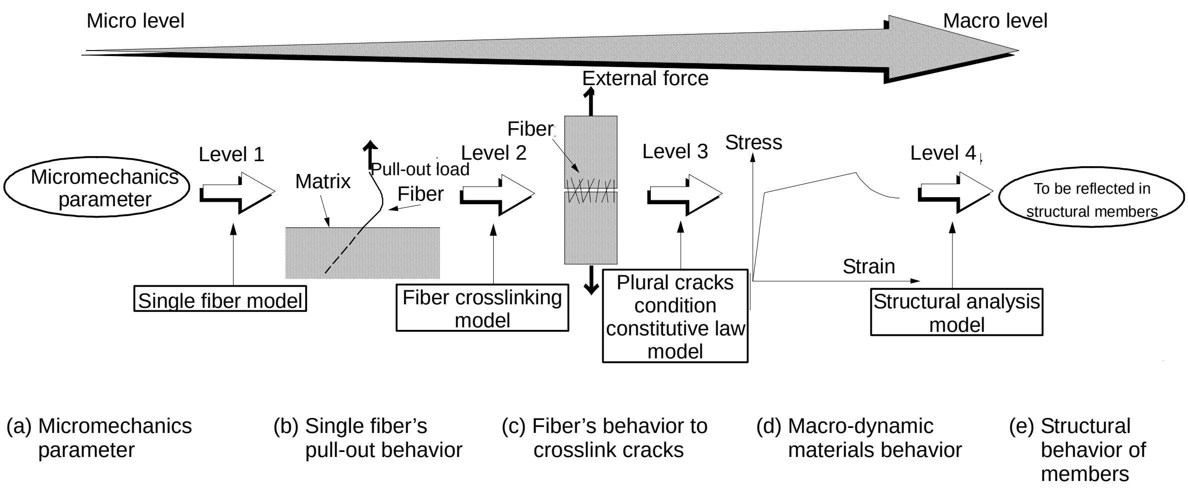

Fig. 2: Materials design technology for ECC[5)]

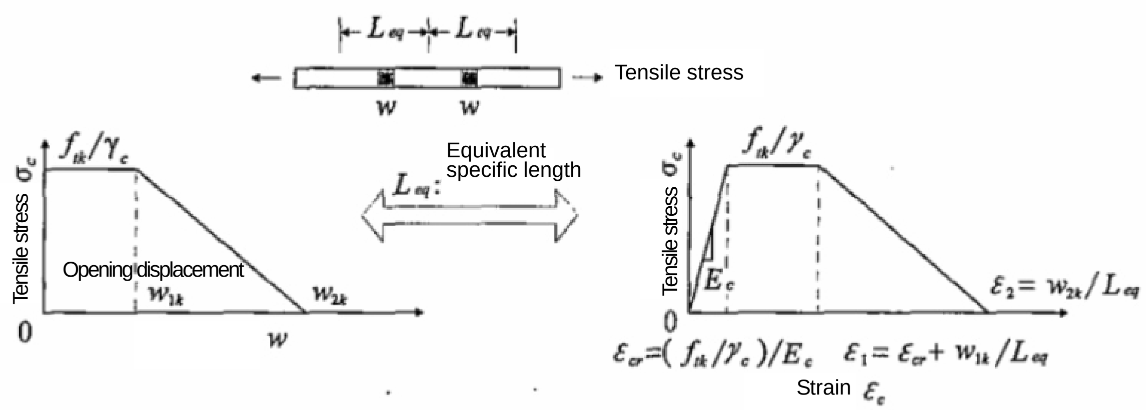

Fig. 3: Relationship between tension softening diagram and tensile stress-strain curve[6)]

(3) Crack width evaluation for UHP-SHCC

In recent years, UHP-SHCC (Ultra High-Performance Strain-Hardening Cementitious Composite) having the characteristics of ultra-high strength and high toughness has been developed, and research on it is under way[7)]. The material demonstrates its strain hardening capability under working tensile stress by refining the matrix with the water cementitious material ratio of 0.22 and through silica fume blending, and then by mixing it with high-strength PE fiber (**Fig. 4**). Research is still now under way on this material's single fiber bond behavior[8), 9)], stress-strain-crack width relationshipse.g., [9),10)], and member-level evaluatione.g.,[11)].

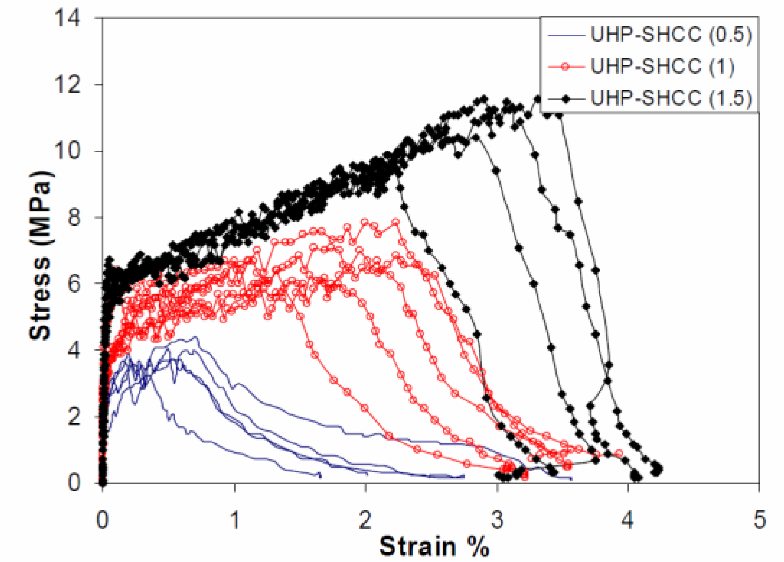

Fig. 4: UHP-SHCC tensile stress-strain relationship[7)]

3.3 Information relating to tension softening-type materials

In the case of FRC (Fiber-Reinforced Concrete), the effect of mixing short fiber is demonstrated as performance to retain tensile force after concrete cracking. To quantitatively indicate this performance, a "tension softening diagram" generally plotted as a relationship between tensile stress and crack opening displacement is used. If this property is adopted in nonlinear FEM analysis, etc., as a material composition law of FRC itself, it enables numerical evaluation of the deformation, proof stress, average crack width, etc., of columns, beams, and other members in which short fibers are used.

As far as the tension softening diagram of FRC is concerned, in the case of SFRC (Steel Fiber Reinforced Concrete), the shape, mixing ratio, and orientation of steel fiber affects its softening characteristics. Moreover, as for nonmetallic fibers (including aramid, vinylon and polypropyrene fibers) whose development has been promoted in recent years, softening characteristics are systematically defined for each material by using a tension softening diagram obtained such as from a three-point bending test (**Fig. 5**)[12)]. Also from the viewpoint of evaluating the crack width of FRC structural members, the influence of the kind of short fiber and the fiber mixing ratio on bending crack width has been reviewed for bending crack widths of different fiber-mixed ferroconcrete beam members (**Fig. 6**)[13].

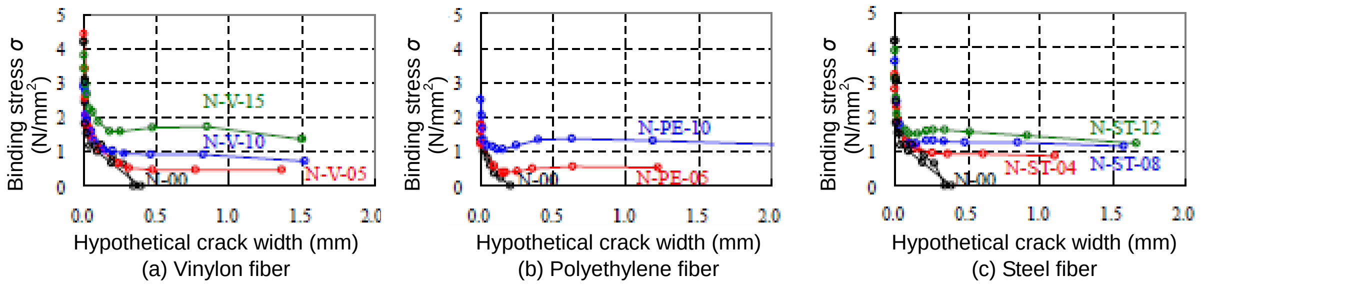

Fig. 5: Different fiber-mixed concrete tension softening diagram comparison[12]

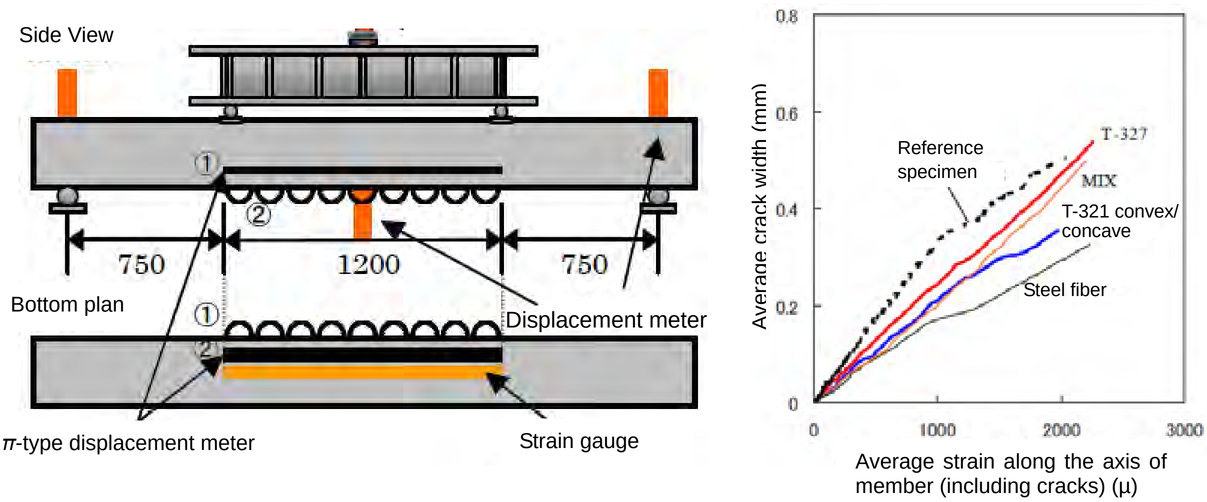

Fig. 6: Evaluation of average crack width of different fiber-mixed ferroconcrete members[13]

3.4 Information relating to shear property in the crack plane

The shear property of fiber-reinforced cementitious composites in the crack plane can presumably be identified by considering not only stress transmission due to contact in the crack plane, as systematized by research concerning shear transmission within a concrete structure, but also the crosslinking effects of fiber. There is still no unified theory, however, since there are diverse affectors such as the amount of aggregate and characteristics of fiber (length, shape, adherability, rigidity, etc.). Here, let us introduce the factors to be taken into account for the quantification of shear property in the crack plane and relevant previous research.

Since fiber-reinforced cementitious composites generally contain no aggregate or contain little coarse aggregate, their crack planes are smoother than normal concrete. Therefore, the matrix does not seem to transmit shear much. The contribution by fibers is added in, and the share of tension to be borne by fibers arranged at random independently from gaps as well as the resistance of fibers due to their rigidity, need to be identified. Hence, the phenomenon is complex if fiber characteristics are classified individually as a main factor, and then snubbing and group effects of multiple fibers are considered. But the contribution by fibers is a factor similar to that in the tensile model. Therefore, if a model inclusive of fiber direction pull-out behavior is built, it can probably be applied to shear performance.

Most current research about shear transmission in the crack plane is done to identify each material's characteristics, and direct shearing tests are attempted in the same way as in the case of fiber-free concretee.g.,[14),15)] (**Fig. 7**). Here, since the tensile force of randomly arranged fibers induces a force at angles to the crack plane, it is difficult to maintain the state of pure shear, raising the problem of secondary cracking. In recent years, a study has been attempted by Suryanto, et al., by spatial averaging measurement and modeling of the shear property of plural crack-type fiber-reinforced cementitious composites[16)] (**Fig. 8**). Based on experimental tests to revolve the principal axis for loading after adoption of initial cracking into a thin plate, the existing concrete shear transmission model is modified to identify the shear property, implementing panel-/member-level verification.

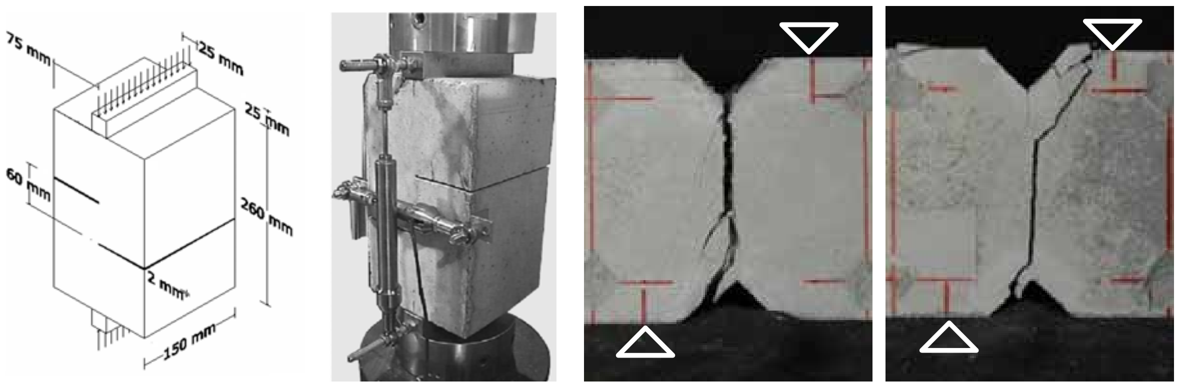

Fig. 7: Direct shear test example[14, 15)]

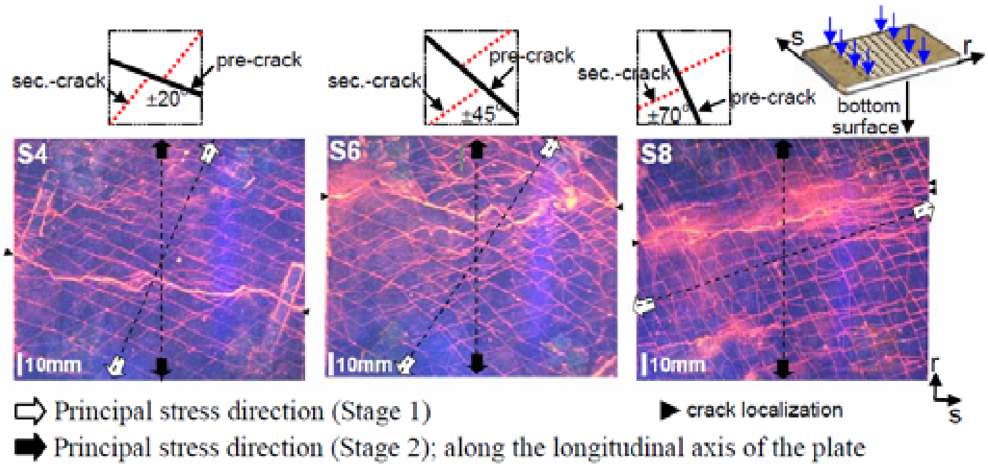

Fig. 8: Multidirectional cracking due to revolution of principal stress axis[16)]

3.5 Single-fiber/matrix attachment test method

It is indispensable to adopt fiber crosslinking laws (fiber crosslinking stress-crack width relationship) for the evaluation of crack widths in fiber-reinforced cementitious composites. It is, however, difficult to experimentally derive a crosslinking law. The crosslinking law depends greatly upon the interfacial properties of the single fiber embedded in the matrix, but key factors governing interfacial properties are fiber-matrix adhesive properties and fractures of fiber. Such factors also include a snubbing effect in which the orientation angle of the fiber improves pull-out resistance. As an effective method of directly grasping these factors, single fiber pull-out tests are performed to propose a variety of specimen production methods and loading methods[17),18)] (**Fig. 9** and **Fig. 10**). When conducting delicate mezzo-scale tests like these, experimental results are also affected by specimen production and loading methods.

3.6 Simplified method of evaluating crack widths

Consider the situation where single fibers have been embedded in the matrix and tensile loads are occurring. If the fiber volume fraction is taken as V_f , the number of fibers per length as N_f, and the initial gradient of a single fiber adhesive stress-pull-out volume curve as K_b, the volume s_f of fibers pulled out when new cracking occurs in the cross-section A_m matrix (under the tensile strength of f_t) is determined from the following equation:

$$N_f \cdot v_f \cdot \frac{1}{2} \cdot \phi_f \cdot K_b \cdot s_f^{\ 2} = f_t \cdot A_m \tag{1}$$

where the valid coefficient of the fiber’s tensile load is v_f and the fiber’s peripheral length is Φ_f .

If the crack width w_{cr} is taken as twice the amount of fiber pulled out and the fiber’s cross section is perfectly round with its diameter of d_f, the following equation is obtained:

$$w_{cr} = \sqrt{\frac{2 \cdot f_t \cdot d_f}{V_f \cdot \nu_f \cdot K_b}} \tag{2}$$

Equation (2) gives crack widths independently of fiber length and cracking space if it is construed that, with the fiber's balanced tensile load taken as the matrix's tensile strength, the fiber's adhesive stress has been perfectly established within the range of the fiber axis. Since the balanced condition is represented as the tensile strength of the matrix, it may well give the largest crack width obtained in the process of cracking.

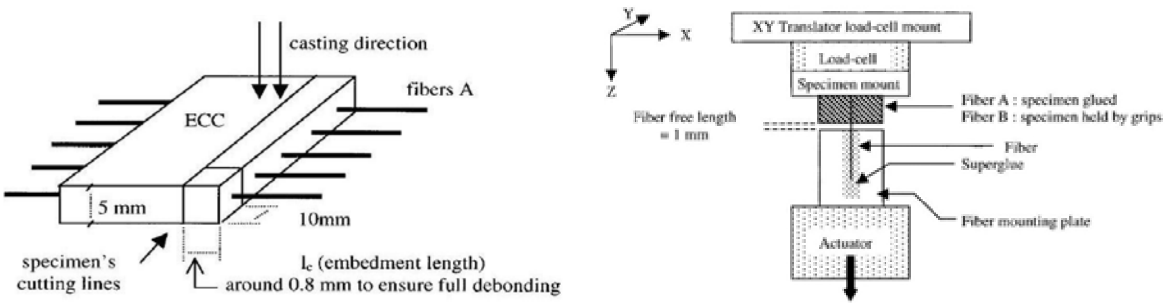

Fig. 9: Single fiber attachment test method[17)]

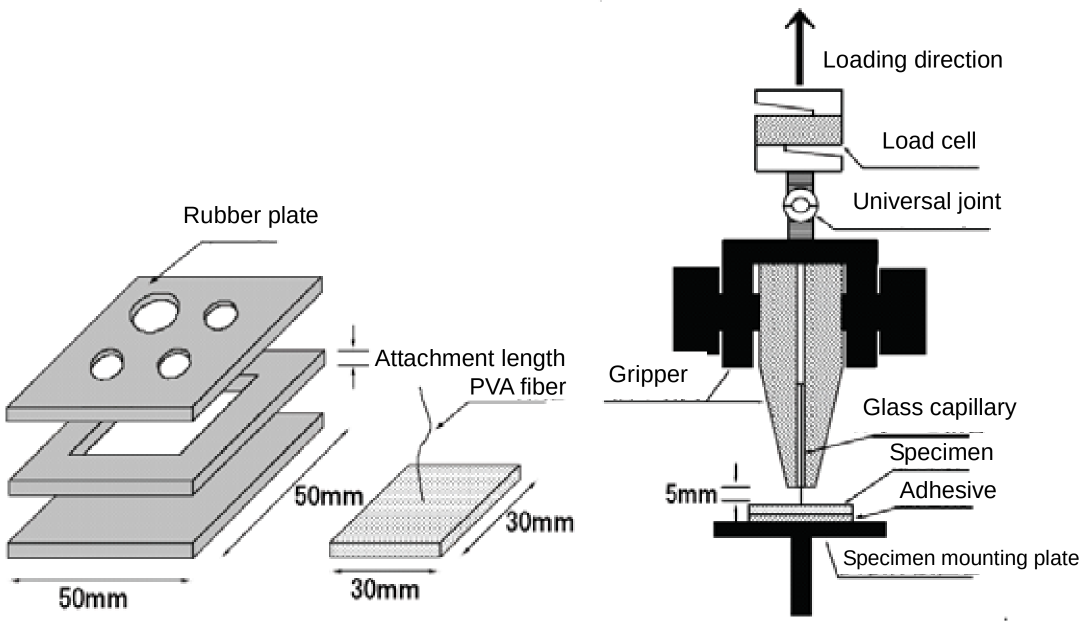

Fig. 10: Single fiber attachment test method[18)]

4. Desirable fiber-reinforced cementitious composites for environmental needs (WG3)

4.1 Overview

Chapters **2** and **3** introduced case study-based reviews and crack width evaluation methods in order to realize a long-term performance design of structures using fiber-reinforced cementtious composites. In a model, the effects of fiber mixing are expected to contribute to the extension of a structure's life. At present, on the other hand, the extension of a structure's life cannot be discussed without consideration of recent environmental problems.

As for the concrete structure-targeted environmental impact evaluation by JCI, the "Technical Committee on Minimization of Global Warming Substrances and Wastes in Concrete Sector" and the "Sustainability Committee" are now engaged in a variety of tests and the accumulation of data. On the other hand, an evaluation of fiber-reinforced concrete from the environmental aspect has yet to be made. And if the environmental load of fiber-reinforced cementitious composites (with some 1% fiber) is compared with that of ordinary concrete, that of fiber-reinforced cementitious composites is expected to be particularly larger at the time of material procurement as well as that of abandonment.

For the purpose of providing basic information to review uses similarly to those of normal concrete (e.g., road base material, recycled aggregate), assuming the situation where a structure using fiber-reinforced cementitious composites is demolished, the fractural characteristic of strain softening-type fiber-reinforced concrete (FRC) was identified.

In addition, FRCs each using either steel or polypropyrene fiber were prepared, and the influence of short fibers on the fractural characteristic of FRC was reviewed by comparing with that of normal concrete through sieve analysis/water absorption testing.

4.2 Recycling efficiency of fiber-reinforced concrete

(1) Materials used

The concrete used in this experiment was roughly divided into normal concrete (NC) and 5 FRC which were different as to type of fiber and mixing ratio. Normal concrete was ready-mixed concrete (W/C=42%), and FRC was normal concrete with added polypropyrene (PP) fiber- or steel fiber (SF). Steel fiber was 30mm-long two end-hooked fiber of the focusing type. PP fiber was 48mm long indented straight type. The compressive strength of concrete was 56MPa in the case of normal concrete, and ranged from 44 to 50MPa for fiber-reinforced concrete.

This experiment used 20 cylindrical test pieces of φ150×300-mm for each kind of concrete. The test pieces prepared were fractured when they became 28 days old. They were fractured only once, using a commercially available self-propelled jaw crusher (38-ton/h throughput, 55-mm outlet opening).

(2) Sieve analysis test results

Fig. 11 shows the grading curve of each concrete obtained from the sieve analysis test. In the case of PP fiber-mixed FRC, it is found that the more fibers are mixed in, the more concrete fragments pass each sieve. This indicates that the post-fracture size of concrete fragments is relatively small. In case of 0.2% fiber mixing, no definite difference from normal concrete (NC) was found. It is inferred that the reason why the size of concrete fragments discharged was smaller for FRC is that the fibers crosslinked cracks at the time of fracture, inducing local destruction such as destruction of mortar attached around original aggregate, but further observations are required. Also with respect to the kind of fiber, SF-mixed FRC exhibits a little less grading in the grain size distribution than that in which 1.0% of PP, at the same fiber mixing rate, was mixed, but the overall trend is similar.

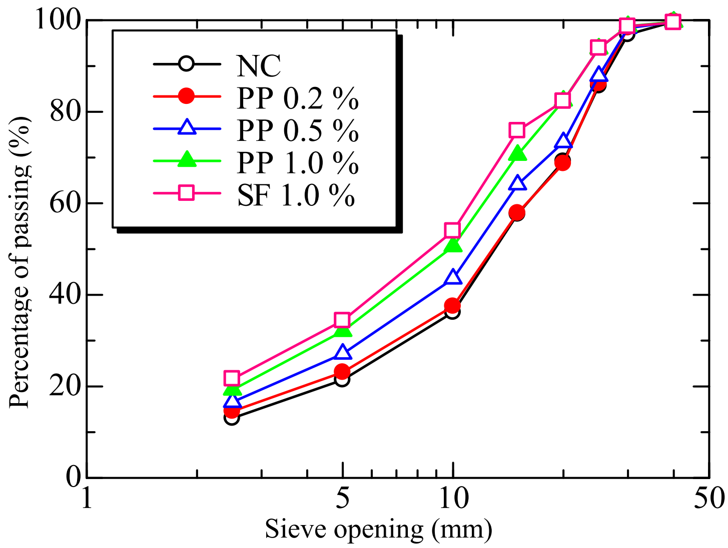

Fig. 11: Grading curve

Photo 1 shows the appearance of concrete fragments that stayed on top of the sieve with a nominal diameter of 10mm in the sieve analysis of each FRC test piece. More concrete fragments than those that stayed on top of 40-mm or 20-mm sieves were found to have no fiber attachment. This implies that, as for the concrete used in this research, most short fibers can be removed by fracturing it into fragments that stay on top of a 10-mm sieve.

(a) Concrete fragments in which 0.2% PP fiber is mixed

(b) Concrete fragments in which 0.5% PP fiber is mixed

(c) Concrete fragments in which 1.0% PP fiber is mixed

(d) Concrete fragments in which 1.0% SF is mixed

Photo 1: Concrete fragments stay on top of 10mm sieve

5. Conclusion

The research committee, aiming to discover new uses of fiber-reinforced cementitious composites, not only reviewed previous technologies, particularly those of the past decade or so, but also crack width evaluation methods and the mitigation of environmental loads. Model-based evaluation and utilization of short fiber effects are expected to permit wider and wider applications in future. It is our pleasure if this review helps you in your search for uses.

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