RHEOLOGICAL EVALUATION AND CONSTITUTIVE DESIGN OF HIGH PERFORMANCE FIBER REINFORCED CEMENTITIOUS COMPOSITE

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ABSTRACT: This paper evaluates the rheological performance and proposes a constitutive design method for high performance fiber reinforced cementitious composite (HPFRCC) in the fresh state. It first proposes methods for evaluating the fluidity and segregation resistibility as well as fiber aggregation of HPFRCC based on slump test and ring penetration test. It then experimentally investigates the fluidity limit of matrix mortar to ensure no aggregation and segregation of fiber and the quantitative relations between the fluidity of HPFRCC and its matrix mortar for different polyvinyl alcohol fiber content. Finally, it suggests a constitutive design method of HPFRCC based on the experimental results.

KEYWORDS: fresh HPFRCC, rheological evaluation, constitutive design method, segregation, fiber aggregation.

1. INTRODUCTION

HPFRCC, which exhibits extremely ductile pseudo strain-hardening performance and lower damage characteristic in the hardened state, has been developed in recent years. By making it practicable in various structural elements, a new structural system can be expected that has desirable safety, restoration and durability [1].

At present, HPFRCC is mostly made by adding fine fibers (polyvinyl alcohol fiber, steel fiber, etc.) or a large number of thicker fibers to mortar or cement paste [1]. Dry matrix mortar or cement paste can't fully disperse fiber bundles, so some of the fibers form hard aggregations. However, if the mortar has too high fluidity, its lower segregation resistibility will cause flocculation of fibers, and even cause hard aggregations of fibers. Therefore, the flow resistibility and the segregation resistibility, which are closely related to its filling in the casting stage and its uniformity in the hardened stage, are two compatible performances of fresh HPFRCC, as for other cementitious materials. Quantitative evaluation and harmonious design of fluidity and segregation resistibility are very important in realizing HPFRCC.

This paper proposes methods for evaluating the fluidity and segregation of HPFRCC and the fiber's degree of aggregation. The relation between the fluidity of HPFRCC and its matrix mortar, and the limit fluidity of matrix mortar in the absence of the segregation and aggregation of fiber are investigated experimentally for different contents of polyvinyl alcohol fiber (PVA fiber). A constitutive rheological design method of HPFRCC is thus suggested.

2. EXPERIMENTAL PROGRAM

2.1 MATERIALS AND SPECIMENS

Besides Ordinary Portland Cement and polycarboxylate-based superplasticizer, JIS No.7 silica sand was employed as aggregate material in accordance with precedent [2]. The PVA fiber used has 40.0μm nominal diameter and 15mm length. The mix proportions of each series of matrix mortar and the measured results of their consistency are shown in **Table 1**, in which the yield stress and plastic viscosity were measured with a Model-B8L Viscometer [3]. The 42 series of HPFRCC specimens were mixed by adding the PVA fibers to the 14 series of mortars with a volume ratio of 1.0%, 1.5% and 2.0%. The fabrication procedure is shown in **Fig.1**.

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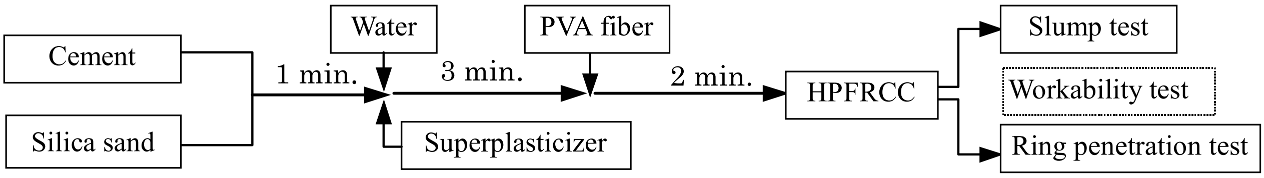

Fig. 1 Fabrication procedure of HPFRCC specimen

2.2 TEST METHODS FOR EVALUATING RHEOLOGICAL BEHAVIOR

(1) Slump test

Right after the HPFRCC was mixed, part of the specimen was used in a slump test. The slump cone used in this study was 1/2 the size of a standard one, as shown in **Fig.2**. The test results show that when the specimen's fluidity is too high, it is estimated more sensitively by the slump-flow value (*mSf*) than the slump value (*mSl*) because of the approach of *mSl* to its limit value (150mm). However, when the specimen is stiff, since *mSf* is close to 100mm, the sensitivity of *mSl* is inversely higher.

If the segregation resistibility of the specimen is lower than a certain limit, with its flow during slumping, part of the matrix mortar separates from the fibers and goes ahead (Fig.2). Grievous segregation will cause the fibers to pile up within the central range and the measured *mSl* is small. The graver the segregation is, the larger the distance ΔS is, which is from the edge of the central specimen containing fibers to that of the whole specimen. Here, the segregation degree (S_d), of HPFRCC is defined by $S_d = 2\Delta S_m / mSf$, in which ΔS_m is the mean value of ΔS on four directions, measured 5 minutes after the slump cone is drawn up.

Hence, as a simple and practical evaluation method, *mSl* can be used to estimate the fluidity of dry type HPFRCC (*mSl* <80mm), and *mSf* and S_d may describe the fluidity and segregation, respectively, of the flowing type specimen.

Table 1 Mix proportions and consistency of matrix mortar

No.	Mix proportions			Consistency			
	W/C	*S/C*	*Sp* (C×%)	mSl_m (mm)	mSf_m (mm)	τ_{ym} (Pa)	η_m (Pa·s)
14	0.33	0.40	0.00	40	100	15.10	6.70
3		0.50		28	100	-	-
8	0.35	0.40		65	100	10.50	4.50
12			0.50	130	350	3.22	1.50
2			0.75	147	380	2.00	0.65
5			1.00	150	510	1.03	0.30
13	0.40	0.50	0.00	95	140	6.40	3.50
6	0.45			135	230	4.52	2.24
7		0.60		110	200	4.90	2.48
10		0.50	0.50	138	450	2.10	0.50
11		0.60		140	370	2.86	0.53
1	0.50	0.40	0.00	136	285	3.60	1.36
9	0.60	0.50		140	360	1.73	0.43
4	0.65			145	390	1.30	0.25

[Notes] *W/C*: Water-cement weight ratio; *S/C*: Silica sand-cement weight ratio; *Sp*: Dosage of super-plasticizer; mSl_m: 1/2-size slump value; mSf_m: 1/2-size slump flow value; τ_{ym}: yield stress; η_m: plastic viscosity.

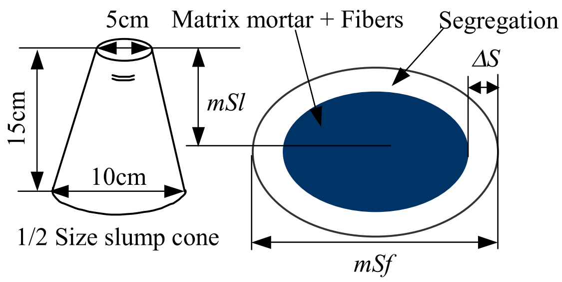

Fig.2 Flow and segregation of slumping fresh HPFRCC

(2) Ring penetration test

A ring penetration test has been used to evaluate the segregation resistibility of coarse aggregate and the gap-passability for high fluidity concrete. It was reported that the sinking velocity (V_s) of ring increases with decrease in coarse aggregate content. There is nearly no coarse aggregate on the passage of the ring and V_s is a constant after about the 4th penetration [4]. In this study, the ring penetration test is employed to estimate the aggregation degree of fiber in HPFRCC. The device is shown in **Fig.3**. In order for it to apply to dry type specimen, the ring is made up of a circular and wedge-shaped band rather than a circular steel bar, as shown in Fig.3.

As shown in **Fig.4**, when there are already hard fiber aggregations in an HPFRCC specimen at the beginning of the penetration test, V_s of the first time penetration is smaller. However, after that, V_s increases owing to the decrease of aggregations on the passage of the ring, and finally approaches a constant. In this case, the ratio between the first time velocity to the stable velocity, called relative sinking velocity (V_{rs}), is less than one, and decreases with increase in the amount or the dimension of fiber aggregation. If there is no hard

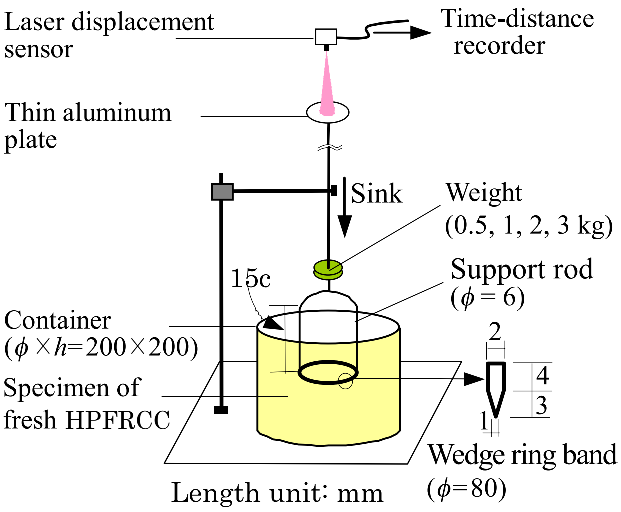

Fig.3 Ring penetration test device

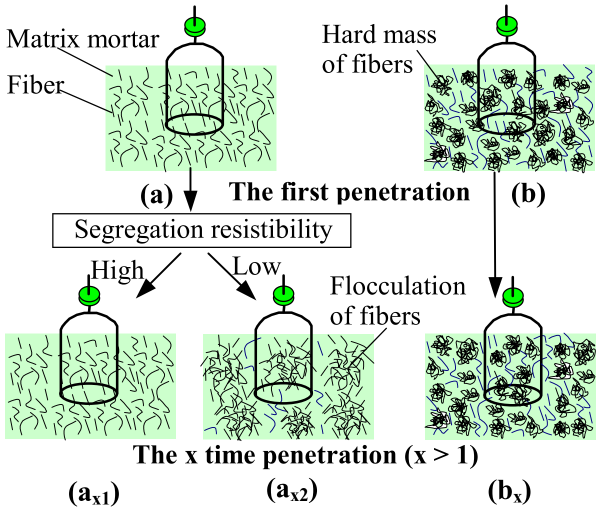

Fig.4 Distribution of fibers after the penetrations

fiber aggregation and the segregation resistibility is high, V_s is almost unvarying with number of the penetrations, and V_{rs} is near to one. According to the preliminary examinations, in these two cases, the mean ring sinking velocity in HPRFCC of 80mm depth becomes stable after the 4th or 5th penetration. V_{rs} is less than 0.9 when there are hard PVA fiber aggregations, and in the range of 0.9~1.1 when there is no aggregation or segregation of PVA fibers.

However, when the segregation resistibility is low, the ring penetration may cause flocculation of fibers. The velocity of the first penetration is inversely more than that of the following penetrations. A large number of penetrations are necessary to reach a stable sinking velocity, and the relative sinking velocity (V_{rs}) from the first time to the 5th time is greater than one. Hence, if the measured value of V_{rs} is more than 1.1, it may be assumed that the specimen has no hard aggregations at the beginning, but that fiber flocculation occurs during the test.

3. TEST RESULTS AND DISCUSSION

The following discusses the effects of the rheological behaviors of mortar and PVA fiber content on the rheological performances of HPFRCC on the basis of slump test and ring penetration test results.

Fig.5 shows the relationship between mSl and mSf of the HPFRCC specimens and the rheological constants of matrix mortar for different PVA fiber contents. The fluidity of HPFRCC drops with increasing fiber content or declining matrix mortar fluidity. The smaller the τ_{ym} or η_m of the matrix mortar is, the larger the mSf of the HPFRCC is. Through regressive analysis of the data shown in Fig.5, the relational expressions of HPFRCC fluidity and its matrix mortar toward any PVA fiber content are obtained as shown in Eq.1.

$$mSl = a_1 mSl_m^2 + b_1 mSl_m + c_1 \,,\ mSf = a_2 mSf_m^2 + b_2 mSf_m + c_2$$

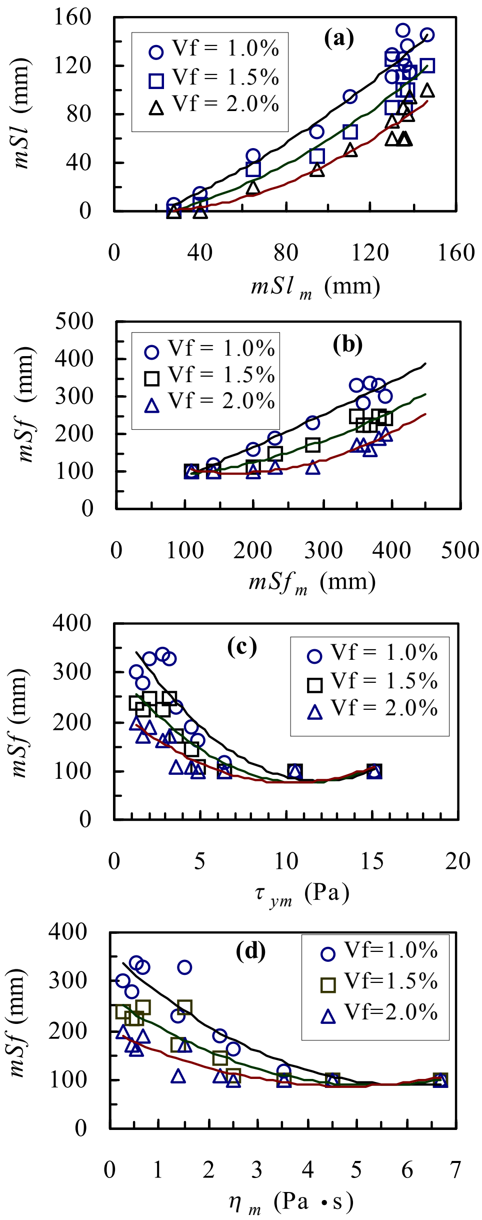

Fig.5 Relationships between rheological constants of HPFRCC and its matrix mortar.

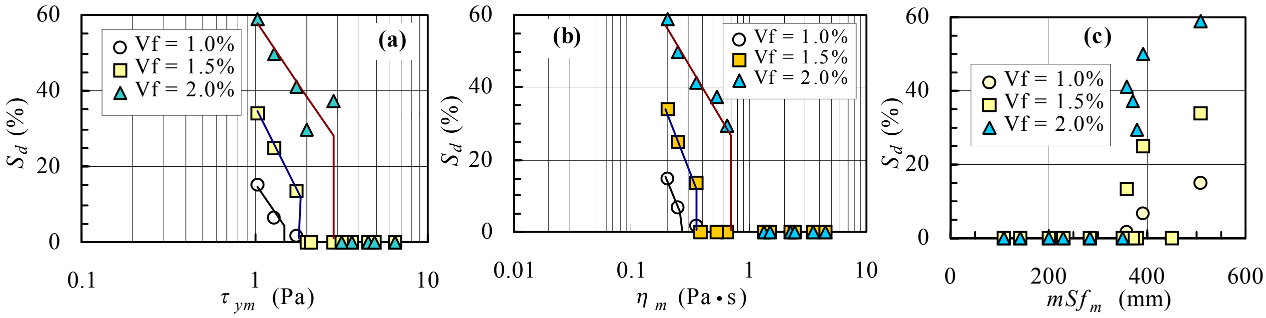

Fig.6 Effects of matrix mortar consistency on the segregation degree of HPFRCC.

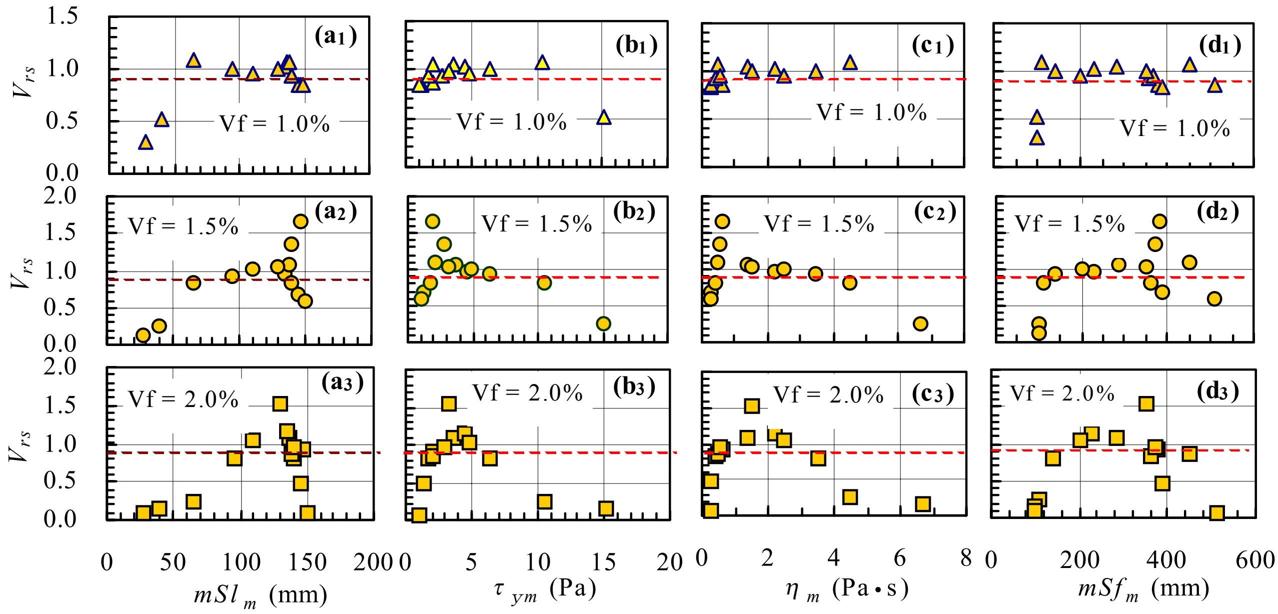

Fig.7 Relations between V_{rs} of HPFRCC and rheological constants of its matrix mortar.

$$mSf = a_3\tau_{ym}^2 + b_3\tau_{ym} + c_3\ ,\ mSf = a_4\eta_m^2 + b_4\eta_m + c_4 \tag{1}$$

in which all coefficients are dependent on the PVA fiber content *Vf* (vol. %), and are given as follows:

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} = Vf \cdot \begin{bmatrix} 0.0020 \\ 0.0014 \\ -0.874 \\ -2.254 \end{bmatrix} + \begin{bmatrix} 0.0011 \\ 0.0009 \\ 3.204 \\ 9.827 \end{bmatrix},\ \begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = Vf \cdot \begin{bmatrix} 0.747 \\ -1.193 \\ 25.747 \\ 42.100 \end{bmatrix} + \begin{bmatrix} 1.386 \\ 1.729 \\ -81.06 \\ -130.49 \end{bmatrix},\ \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \end{bmatrix} = Vf \cdot \begin{bmatrix} 0.0020 \\ 112.65 \\ -181.78 \\ -158.79 \end{bmatrix} + \begin{bmatrix} 0.0011 \\ -7.55 \\ 587.75 \\ 512.02 \end{bmatrix} \tag{2}$$

Fig.6 shows the relations between segregation degree S_d and rheological constants of the matrix mortar. It indicates that S_d of HPFRCC is related clearly to τ_{ym} and η_m of the matrix mortar for any PVA fiber content, and increases with decrease in τ_{ym} or η_m under a certain limit. A large fiber content results in a great segregation degree for a certain high fluidity matrix mortar. This is because, to move a larger number of fibers, a greater adhesive force is necessary between the fibers and the mortar.

The specimens that have large mSf_m but no segregation or small S_d, are found in Fig.6(c). S_d is not clearly correlated with mSf_m even for the same fiber content. This is because the correlation between slump-flow value and viscosity of mortar is not very clear, but the latter depends on the segregation resistibility of HPFRCC.

Fig.7 shows the effects of the matrix mortar's rheological performance on hard fiber aggregation in HPFRCC for three PVA fiber contents. For the specimens with fiber aggregations, the relative velocity V_{rs} of the ring when sinking in an 80mm depth specimen is closely related to mSl_m for the dry type specimen, and to τ_{ym} and η_m for all specimens. V_{rs} decreases with decreasing mSl_m, τ_{ym} or η_m under a certain limit (called the lower limit here), or increasing mSl_m, τ_{ym} or η_m above a certain limit (called the upper limit here). With increasing fiber content, the lower limits increase, but the upper limits decrease. This means that the higher or lower the matrix

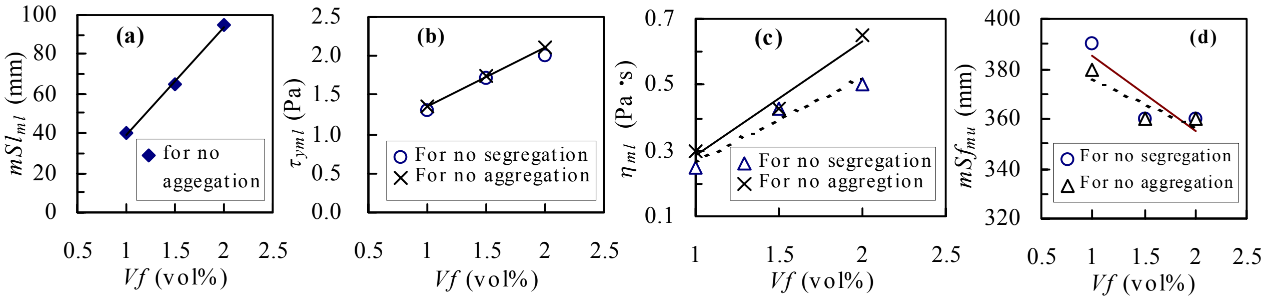

Fig.8 Consistency limits of matrix mortar for no segregation or aggregation for different fiber contents.

mortar's fluidity is beyond a certain limit, the greater the fiber aggregation degree is, and for a certain PVA fiber content, there is a specific mortar fluidity range within which hard fiber aggregation is absent from HPFRCC. Owing to the segregation and the flocculation of fibers during the test, some high fluidity specimens gain large V_{rs} values of more than 1.1, even though their matrix mortars have small τ_{ym}, η_m and large mSf_m, mSl_m.

Hard fiber aggregation in flowing specimen results from excessive fiber segregation. It is uncertain whether fiber aggregation occurs in an HPFRCC specimen whose matrix mortar has a large mSf_m, because large mSf_m does not definitely mean that fiber segregation occurs. This occurs only when η_m is also less than the lower limit, as shown in Fig.7 ($d_{1\sim3}$), i.e. only when the matrix mortar viscosity is so low that excessive fiber segregation occurs.

The upper and lower limits of the mortar's rheological constants to avoid segregation or hard fiber aggregation in HPFRCC at three PVA fiber contents determined from Figs.6 and 7, are plotted in **Fig.8**. Although the aggregation or segregation is not closely related to mSf_m, as the relevant information, the limits of mSf_m are also presented in Fig8 (d**)**. According to Fig.8, with increasing fiber content, each lower limit increases by contrast to the decrease of the upper limits of mSf_m. The lower limit of τ_{ym} or η_m for no segregation is smaller than that for no fiber aggregation, but the upper limit of mSf_m for no segregation is greater than that for no fiber aggregation.

In theory, τ_{ym} and η_m may characterize the mortar's consistency, but they are difficult to measure for dry type mortar. Hence, in practice, the lower fluidity limit of matrix mortar for the absence of segregation and fiber aggregation is described by the lower limit (mSl_{ml}) of mSl_m, but the upper limit is characterized by the lower limits (τ_{yml}, η_{ml}) of τ_{ym} and η_m exactly or the upper limit (mSf_{mu}) of mSf_m sketchily. These limits for any PVA fiber content are calculated by Eq.3, which is obtained through regressive analysis of the data shown in Fig.8.

$$mSl_{ml} = 55Vf - 15.8,\ \tau_{yml} = 0.75Vf + 0.61,\ \eta_{\mathrm{ml}} = 0.35Vf + 0.065,\ mSf_{mu} = \text{-}20Vf + 396.7 \quad (3)$$

4. RHEOLOGICAL DESIGN OF MIXTURE

The following proposes a constitutive rheological design method for HPFRCC mixed with PVA fibers, and the method is summarized in **Fig.9**.

Step1: The indexes (mSl and mSf) of HPFRCC fluidity are determined according to the conditions of production, transportation and structural element or member cast etc., and the fiber content Vf (and usually W/C) to meet the mechanical performance requirements in hardened stage is set up.

Step2: The rheological constants (mSl_{mp}, mSf_{mp}, τ_{ymp} and η_{mp}) of matrix mortar for realizing the desirable HPFRCC fluidity are calculated primarily from Eqs.1 and 2.

Step3: The fluidity limit mSl_{ml}, mSf_{mu}, τ_{yml} and η_{ml} of mortar are calculated from Eq.3, to avoid segregation and fiber aggregation.

Step4: The indexes (mSl_m or τ_{ym} and η_m) describing the necessary matrix mortar fluidity are determined. The larger of mSl_{mp} and mSl_{ml} is selected when mSl_{mp}< 80mm, but if $mSl_{mp} \geqq$80mm, the larger of τ_{ymp}, η_{mp} and τ_{yml}, η_{ml}, is elected. When using mSf_m rather than τ_{ym} and η_m as the index, mSf_m is the smaller of mSf_{mp} and mSf_{mu}.

Step5: The relation between τ_{ym} or η_m and the mortar mix proportions is shown by Eq.4 [5]. The matrix mortar mix proportions are designed by referring to these relational expressions. When using mSl_m or mSf_m as the fluidity index, they are converted firstly into τ_{ym} by Eq.5 [6], in which the mortar density is assumed to be 1400kg/m^3 here.

$$\tau_{ym} = 30.0x_1 - 0.943x_2 + 2.12x_3 - 1.11x_4 + 116,\ \eta_m = 14.0x_1 - 0.146x_2 + 1.91x_3 - 0.525x_4 + 44.8 \quad (4)$$

where x_1: water-cement surface area ratio i.e. water membrane thickness (μm); x_2, x_3: dosage of superplasticizer and segregation control agent, respectively (mg/1g water); x_4: cement paste-sand ratio (vol.%).

$$\tau_{ym} = 4.62(150 - mSl), \quad \tau_{ym} = 2.77 \times 10^6 / mSf^2 \qquad (5)$$

Step6: According to the designed mix proportions, HPFRCC is mixed and its rheological performances are tested. If the requirements are met, the constitutive design is over; if not, the mortar mix proportions are adjusted and the mix is held till the requirements are satisfied.

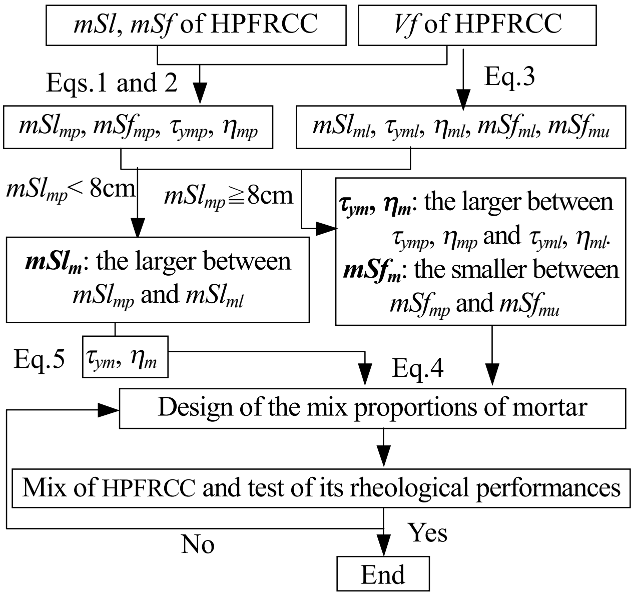

Fig.9 Flow chart of HPFRCC constitutive design

5. CONCLUSIONS

From the investigation reported in this paper, the following conclusions can be drawn.

1. The slump value can be used to estimate the fluidity of dry type HPFRCC (*mSl*<8cm), the fluidity and the segregation degree of the flowing type (*mSl*≧8cm) can be described by the slump-flow value and S_d.
2. The relative ring sinking velocity V_{rs} is related greatly to the hard fiber aggregation of HPFRCC, and decreases with increase in the hard fiber aggregation under 1.0.
3. Increase in fiber content lowers the fluidity of HPFRCC, but increases the trend of fiber aggregation for the dry matrix mortar, or the segregation and the fiber aggregation for the following mortar.
4. The quantitative relationships between *mSl*, *mSf* of HPFRCC, the rheological constants of matrix mortar and PVA fiber content are shown in Eqs.1 and 2. The limits of the matrix mortar's rheological constants for no segregation and aggregation of fibers for any fiber content can be calculated by Eq.3.
5. The constitutive rheological design of HPFRCC should be concentrated on balancing the fluidity and the segregation resistibility of matrix mortar to prevent fiber segregation and aggregation.

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REFERENCES

1. Fukuyama, H. and Kuramoto, H., "Smart Concrete - High Tenacity Concrete", Concrete Journal, ACI, Vol. 39, No. 1, 2001. 1, pp.104-109.
2. Suwada, H., Fukuyama, H. and Iso, M., "Development of Ductile Fiber Reinforced Cementitious Composite for High Performance Structures," Proceedings of the JCI, Vol.23, No.3, 2001, pp.133-138.
3. Kawasaki, T., "Practice of Viscosity Measurement Using Cylinder Viscometer," New Food Industry, Vol.22, No.4~6, pp.1-40, 1980.
4. Teranishi, K. et al., "Study on Evaluation Method of passability of High-Fluidity Concrete," J. of Structure Construction Engineering, AIJ, No.467, 1995.1, pp.19-26.
5. Miyano, K. et al., "Experiment on Mix Proportion and Rheology of High Fluidity Mortar," Proceedings of the JCI, Vol.21, No.2, 1999, pp.493-498.
6. Komura, R. et al., "Rheological Study on Slumping Behavior of Fresh Concrete," J. of Structure Construction Engineering, AIJ, No.462, 1994.8, pp.1-10.