- Technical Paper -

INFLUENCE OF FIBER ORIENTATION ON TENSILE BEHAVIOR OF HIGH PERFORMANCE FIBER FREINFORCED MORTAR

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ABSTRACT

In this study, influence of fiber orientation on tensile behavior of High Performance Fiber Reinforced Mortar (HPFRM) is examined. The parameters in this study are fiber volume and fiber orientation (0°, 45° and 90°) by the direction of flow at casting. Fiber distribution, number of fibers and fiber orientation coefficient are examined for each case of mix proportion by using high-quality electronic microscope. As a result, it is clarified that tensile strength, maximum crack width and fracture energy of HPFRM is significantly influenced by orientation coefficient.

Keywords: tensile behavior, HPFRM, fiber orientation coefficient, microscopic analysis

1. INTRODUCTION

Recently, various types of High Performance Fiber Reinforced Mortar (HPFRM) with self-compacting ability has been developed. HPFRM is expected that improve tensile characteristics (ex. tensile strength, softening) by developing of matrix and mixing of fiber. This material has some developed property, for example, high strength, high fluidly, high ductility. Those properties are enable to bring about development, for example, rationalization of cross section, power saving of working and making durable construction. According to previous study fiber orientation of material with self – compacting is influenced by flow direction [1]. As is well known, mechanical characteristics of fiber reinforced concrete strongly depend on fiber orientation. However, mechanical characteristics that consider fiber orientation have not been examined. In this study, fiber distribution, number of fibers and fiber orientation coefficient for HPFRMs with different are measured by using high-quality electronic microscope and the influence of fiber orientation on tensile strength, maximum crack width and fracture energy is examined.

2. OUTLINE OF EXPERIMENT

2.1 Mix proportion

In this study, ordinary Portland cement, fine aggregate, additive, steel fiber and water were mixed. The appropriate mixture was derived from the properties at the fresh state such as the slump flow and the funnel time following the requirement of the high-performance concrete. Target compressive strength was more than 100MPa at 28 days after casting. W/C ratio was 21.0%.The mix proportions of fibers are shown in Table 1.

Table 1 Mix proportion of fiber in mortar

Type of mortar	Fiber volume (%)	Fiber length (mm)
Plain	-	-
L-0.5	0.5	13
L-0.5	1.0	13
L-0.5	1.5	13

2.2 Casting

In this study, the influence of fiber orientation on tensile characteristic of HPFRM is examined. Therefore the fiber orientation in specimens should been decided. Concerning the fiber-reinforced mortar that possessed a character of self-compacting, the fiber orientation is strongly influenced by the flow direction of mortar [1]. The flow direction of mortar is controlled by pouring directly into the concrete mold (400mm ×1800mm ×100mm) as shown in Photo 1. After pouring, three small steel frames (200mm×180mm×100mm) are installed into the concrete mold so the specimens with three values of angle against the flow direction (0°, 45° and 90°) are obtained as shown in Photo 2.

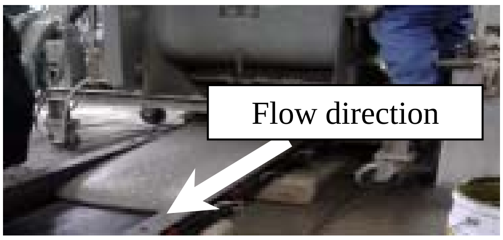

Photo 1 Casting direction

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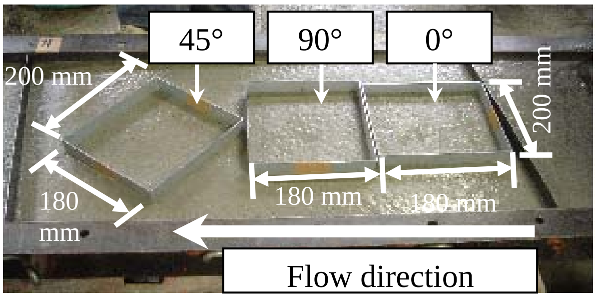

Photo 2 Arrangement of small steel frames

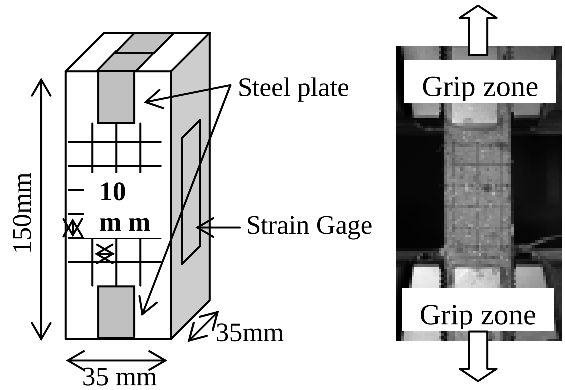

Fig. 2 Specimens for tensile test

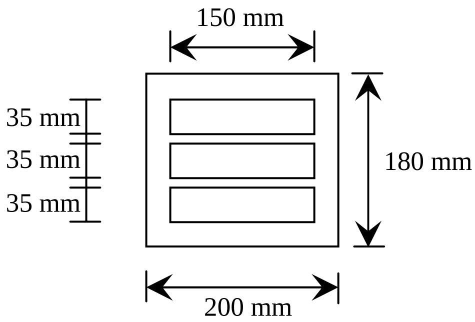

Fig. 1 Preparation of specimens for direct tension test

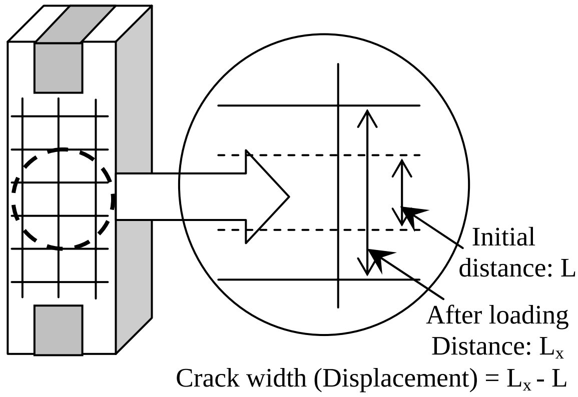

Fig.3 Measurement of crack width

2.3 Details of specimens and parameters

After demolding and curing, three test pieces (35mm×35mm×150mm) for each angle are prepared for the tensile test from the 200mm×180mm×100mm size specimens shown in Fig.1. However, test piece is broken easily with concentration of stress at the section where is attached them to machine of tensile test. As a result, load loss occurred. To prevent the failure at the upper and lower ends, two steel plates are attached as shown in Fig.2. The parameters in this study were mix proportion of fiber volume and fiber orientation according to the direction of the flow of casting (0, 45 and 90 degree). So, three type of fiber orientation are examined for each case of mix proportion. The main parameters studied in the experimental program are summarized in Table 2.

Table 2 Parameters of the experiment

Case No.	Image of flow direction	Image of fiber orientation
Case A	Flow direction	Loading direction
Case B		
Case C		

2.4 Tensile test

To obtain the tensile property of the HPFRM, the direct tensile test is conducted. Three specimens are tested for each case. The average response of the three specimens is discussed in this paper. In this test, displacement and crack widths are measured with strain gages and high-quality digital camera. By a combination of strain gages and high-quality digital camera make measuring tensile behavior continuously possible. After setting up test piece to machine for tensile test, a picture is taken before loading and every load step. And also measuring of load and strain are done at the same time. Loading speed is 0.1 mm/min up to maximum tensile stress, and after that loading speed is up arbitrarily. When test piece is separated by crack opening absolute, test is finished.

2.5 Image analysis

In this study, crack width is measured by image analysis with the picture taken in tensile test. In image analysis first, measure the displacement between two lines before loading as shown in Fig. 3. Then, measure the displacement of two lines after loading. Crack width is calculated with subtracting distance of two lines after loading from initial distance of that.

2.6 Microscopic analysis

In this study, to measure the number of fiber per unit area and the fiber orientation coefficient for each mix proportion microscopic analysis was carried out. For that advanced electronic microscopic was used.

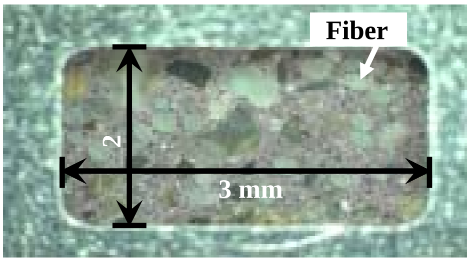

Photo 3 Fibers in microscopic analysis

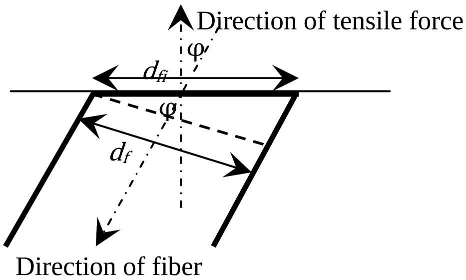

Fig.4 Diameter of fiber on slice surface

To obtain the actual number of fiber and fiber orientation coefficient of the tensile specimen, all specimen were cut in slice perpendicularly to the direction of the applied tensile force at the sections without crack after the tensile test was done. The slice specimens were neutralized by phenolphthalein solution to turn the color of the matrix into pink to show fiber location up. Then the matrix was set under microscope with special device to take photo. By using the photo taken by the microscope, the area of the fibers could be easily distinguished from the matrix by the difference in the color as shown in Photo 3. The size of a section is 2 mm × 3 mm.

From the microscopic analysis by counting the fibers and measured the dimension of fibers fiber orientation coefficient was achieved. To obtained fiber orientation coefficient, 54 sections (18 sections per one cut plane times three cut planes in a specimen) for each specimen are analyzed for 0, 45, 90 degree, respectively.

The shape of the fibers on the taken photo will only be a full circle when it is oriented at an angle of 90 degree to the slice surface [2]. At any other angle, the fiber will be seen as an ellipse. The value of the fiber diameter divided by the length of the longer major axis of an ellipse indicates the angle of each fiber orientation in the slice surface. A total orientation coefficient (η_φ) that gives a general impression about the overall orientation of all fibers in the specimens was determined by Eq. (1).

$$\eta_\varphi = \frac{1}{N}\sum_i^N \cos\varphi = \frac{1}{N}\sum_i^N \frac{d_f}{d_{fi}} \qquad (1)$$

where,
N= the no. of fiber in the slice section,
φ = the angle between the direction of the applied tensile force and the steel fiber as shown in Fig. 4.

3. RESULTS AND DISCUSSIONS

3.1 Tensile behaviors and crack pattern

The observed tensile behavior of all specimens by a digital camera and strain gages are shown in Fig. 5. Because of the variation in the compressive strength of the each batch of mortar, measured tensile stresses were normalized by the tensile strength of the plain mortar. For all volume fraction of fiber it is observed that, specimen in which fibers are parallel to the direction of the tensile force shows higher tensile strength and improves post-peak behavior. For all volume fractions of fibers, 0 degree orientation of fiber shows more ductile tension softening. Stress reduction for 0 degree orientation is gradual but stress reduction for 45 degree and 90 degree orientation is rather significant.

For 1% volume fraction of fiber 0 degree orientation shows better post –peak behavior than 1.5% volume fraction of fiber. This is due to the dispersion effect of fibers [1]. Because of the excess volume of fiber, dispersion of fiber can be occurred in matrix.

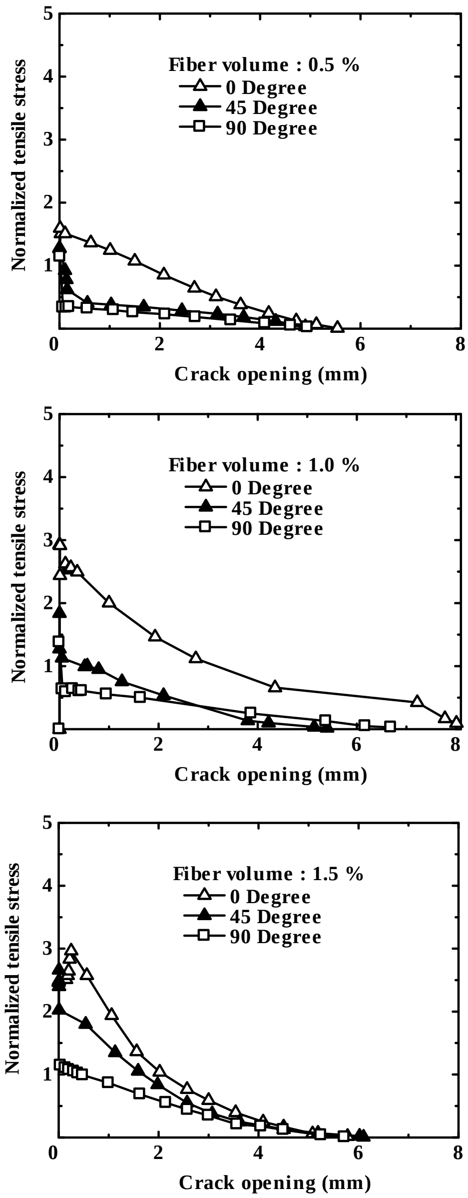

Fig.5 Tension softening curves

This results less number of firer per unit area. This will be also confirmed later, in section 3.2, by the result of number of fiber for different volume fractions.

In case of crack pattern, specimens with 0 degree fiber orientation show multiple crack patterns. After first crack also shows some hardening and then finally failed by single crack about in the middle of the specimens. Specimens with 45 and 90 degree fiber orientation also shows multiple cracking but comparatively less than 0 degree cases and finally failed by single crack.

3.2 Number of fibers and fibers distribution

From microscopic analysis the numbers of fibers per unit area for all volume fractions of fibers were measured and shown in Fig 6. From microscopic analysis it is observed that higher volume fraction of fiber cannot ensure higher number of fiber per unit area. As for 0 degree orientation 1% volume shows higher number of fiber than 1.5% volume fraction of fiber. The reason was due to dispersion of fibers as described in the previous section. So for that the post-peak behavior of tension softening curve is better for 1% volume fraction of fiber than 1.5% volume fraction of fiber in case of 0 degree fiber orientation specimen.

By microscopic analysis number of fiber for each sample is measured for all cases of HPFRM. Total 54 slices were examined for three different volume fractions of fibers. To check the real distribution of fibers in the matrix, actual number of fibers in 18 slices for each case was investigated. HPFRM that contains 1.0% volume of fiber shows a little variation in distribution but 0.5% and 1.5% volume of fiber shows rather less variation in distribution. The probability of normal distribution is calculated by Eq. (2) and the comparison of normal distribution and actual distribution of fibers for different volume fractions are shown in Fig. 7, 8 and Fig. 9.

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}}\, e^{-(x-\mu)^2/(2\sigma^2)} \qquad (2)$$

where,

$P(x)$ = The probability of normal distribution of fibers,

σ = Standard deviation,

μ = mean value of fibers

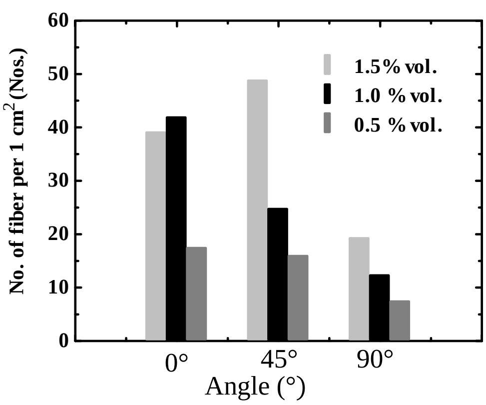

Fig.6 No. of fibers in one slice specimen for different volume fractions of fibers

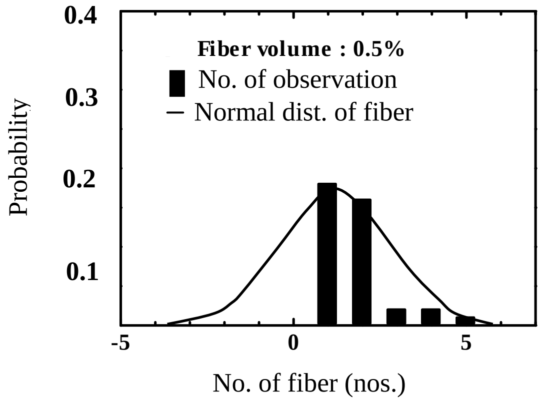

Fig.7 Comparison between normal distribution of fibers and actual distribution of fibers

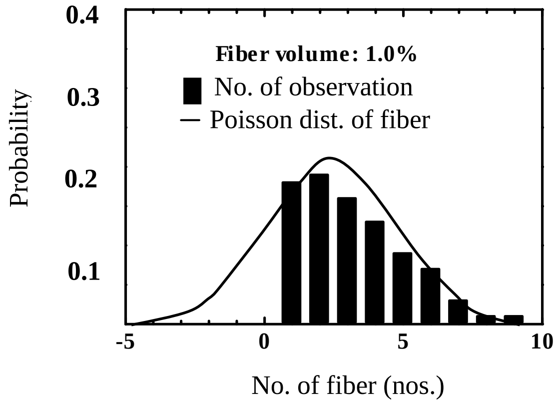

Fig.8 Comparison between normal distribution of fibers and actual distribution of fibers

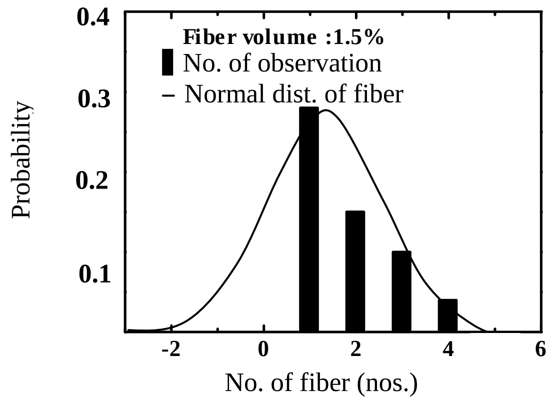

Fig.9 Comparison between normal distribution of fibers and actual distribution of fibers

The distribution of fiber in matrix is depending on flow direction, volume of fiber and physical properties of fibers (length, diameter, aspects ratio). Further examination on the distribution should be done to achieve an unique probability distribution function.

3.3 Tensile strength of HPFRM

Tensile strength of all specimens with different orientation angle is compared with different volume fraction of fiber as shown in Fig. 10. For all case of HPFRM specimens with 0 degree fiber orientation shows higher tensile strength than those of 45 degree and 90 degree. It is observed that higher volume content of fiber cannot ensure higher tensile strength. The specimens of 1% volume fraction of fiber for 0 degree fiber orientation show higher tensile strength than that of 1.5%. So for that volume fraction is appeared to be not appropriate index to understand the tensile behavior of HPFRM.

Tensile strength for all volume fractions of fibers is also compared with number of fibers as shown in Fig. 11. The tensile strength of HPFRM increases with the increase of number of fiber per unit area.

Figure 12 shows the relationships between tensile strength and orientation coefficient. The strong association between them can be found rather that number of fiber. That is, the tensile strength increases proportionally with the increase of orientation coefficient regardless to the volume fractions of fibers.

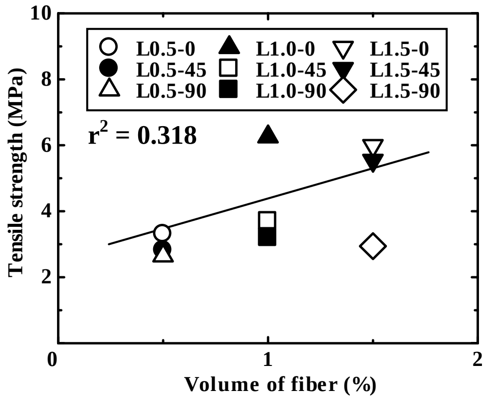

Fig.10 Relationship between tensile strength and volume fractions of fibers

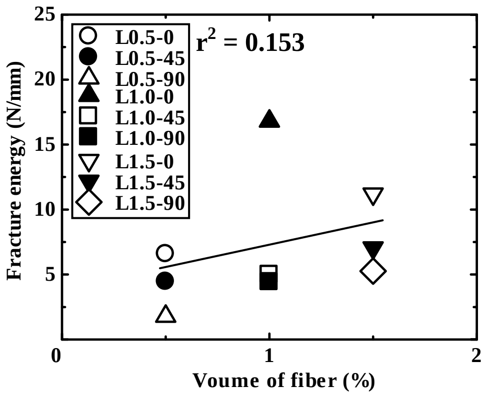

Fig.13 Relationship between fracture energy and volume fractions of fiber

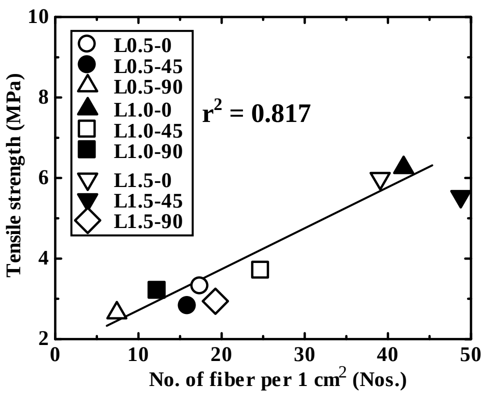

Fig.11 Relationship between tensile strength and no. of fibers

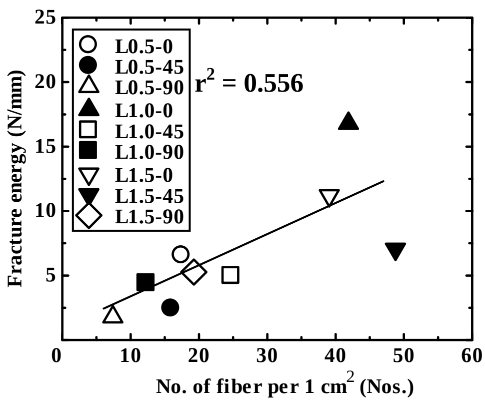

Fig.14 Relationship between fracture energy and no. of fiber

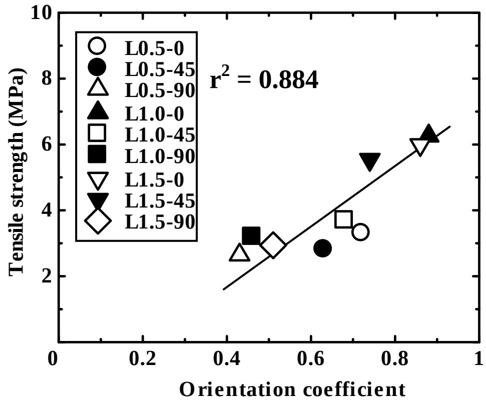

Fig.12 Relationship between tensile strength and orientation coefficient

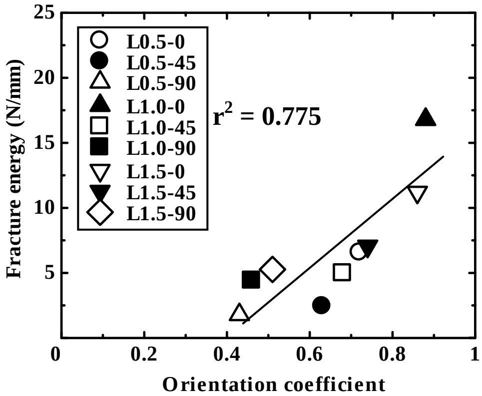

Fig.15 Relationship between fracture energy and orientation coefficient

3.4 Fracture energy of HPFRM

Fracture energy of HPFRM was measured by integrating the area of tension softening curve. The comparison of fracture energy with different volume fractions of fiber, number of fibers and orientation coefficient are shown in Figs. 13, 14 and 15, respectively. It can be said that neither volume fractions of fiber nor number of fibers are not appropriate index to represent fracture energy of HPFRM. The orientation coefficient is the most appropriate index among them.

3.5 Maximum crack width of HPFRM

The relationships between maximum crack width and fiber volume is shown in Fig.16. No clear tendency is observed. The relationships between maximum crack width and number of fibers are shown in Fig.17. The maximum crack width tends to increase as the number of fibers increase. However the value of coefficient of correlation is small. On the other hand, from Fig.18 which shows the relationships between maximum crack width and orientation coefficient, it can be said that maximum crack width might be represented by orientation coefficient.

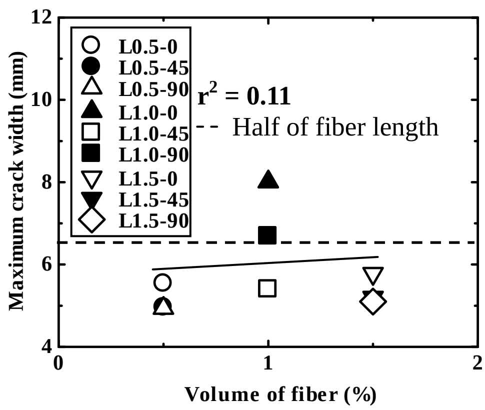

Fig.16 Relationship between maximum crack width and volume fractions of fiber

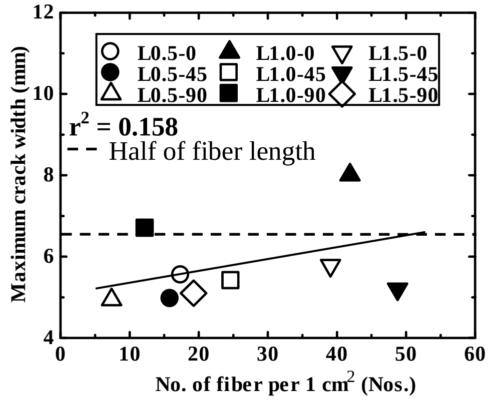

Fig.17 Relationship between maximum crack width and no. of fibers

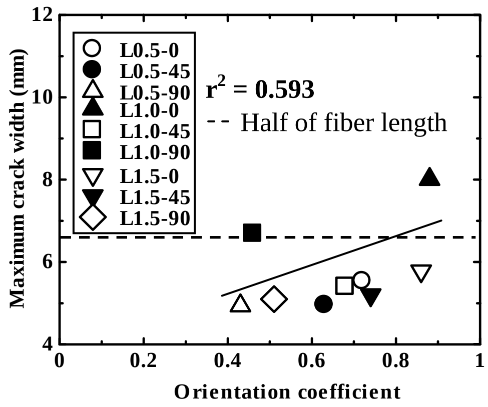

Fig.18 Relationship between maximum crack width and orientation coefficient

4 CONCLUSIONS

The following conclusions are drawn based on the findings of this study:

(1) The actual fiber orientation has strong influence on the tensile characteristics of HPFRM. So for that, in the prediction of structural performance of HPFRM members, the fiber orientation has to be considered.

(2) The fiber orientation coefficient seems to be the appropriate index to understand the tensile behavior of HPFRM. Other index like volume of fiber, number of fiber per unit area cannot predict the tensile behavior well.

(3) Excess volume of fiber cannot ensure higher tensile strength or better post-peak behavior of tension softening curve because of dispersion effect of excess volume of fiber. So for that, during production of HPFRM optimum volume of fiber has to be considered

(4) Although the distribution of fibers were assumed to be normal but the distributions are found to be flatter due to lack of data. Investigation of more specimen are needed to find a normal distribution.

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