STUDY ON EFFECTS OF FLOWABILITY ON STEEL FIBER DISTRIBUTION PATTERNS AND MECHANICAL PROPERTIES OF SFRC

A thesis submitted in fulfilment of the requirements for the degree of Master of Engineering

MINGLEI ZHAO
Master of Engineering

School of Civil Environmental and Chemical Engineering
College of Science Engineering and Health
RMIT University

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

MINGLEI ZHAO
12/08/2016
ABSTRACT

Steel fiber reinforced concrete (SFRC) is a multiple-composite material developed during the early 1970s. In SFRC, short steel fibers are randomly distributed in concrete. Steel fibers can prevent the development of micro-cracks inside the concrete and reduce the expansion and development of the macro-cracks, thus enhance mechanical performance of SFRC. However, there is lack of studies on the influence of flowability of fresh SFRC on the steel fiber distribution patterns and mechanical properties of hardened SFRC.

In this research, steel fibers made by the thin-plate shearing method are used. Standard specimens are cast in which steel fibers are added to the concrete mix. The slumps ranging from 80 mm to 200 mm are employed as the parameter to reflect the flowability of SFRC. The main research work is as follows:

(1) By cutting the specimens in three directions (transverse, horizontal and vertical sections) and quantizing the steel fibers in each section, effects of flowability on steel fiber distribution patterns are assessed. Distribution rate, distribution coefficient and orientation coefficient are the three factors used for describing steel fiber distribution patterns in this research. Calculated results of these factors of different flowability SFRC are summarized and compared.

(2) Basic mechanical properties tests including compressive strength, splitting tensile strength and flexural strength tests are conducted for different flowability SFRC. The splitting tensile tests along three directions of specimens of SFRC are carried out in view of the different orientation of steel
fibers in these directions. Load-deflection curve of flexural toughness test is plotted and analyzed.

(3) Two commonly used methods, i.e., ASTM C1018 (Standard Test Methods for Flexural Toughness and First Crack Strength of Fiber Reinforced Concrete) method and the Chinese Standard JG/T472-2015 (Steel Fiber Reinforced Concrete), are used to access flexural toughness of SFRC. Fracture energy is also calculated.

(4) Formulas for calculating moment of inertia and flexural stress of flowable SFRC are proposed.

The results show that an increase of flowability has no influence on the orientation of steel fibers and leads to a decrease of sectional uniformity. Steel fibers orientated in a longitudinal direction of higher flowability SFRC tend to precipitate towards the bottom layer of the specimens. This resulted in much better flexural performance including flexural toughness and fracture energy. This would indicate that, instead of studying the entire cross section, the distribution rate and distribution coefficient of steel fibers in tensile zone of specimen should be considered as the main factor determining flexural performance of SFRC. Calculations for bending stiffness and flexural stress based on the distribution rate of high flowability SFRC are recommended.

Moreover, due to the layering effect of steel fibers, traditional test methods are not suitable for determining basic mechanical properties such as compressive strength, splitting tensile strength and flexural strength of SFRC, which require further investigations.
**Key words:** steel fiber reinforced concrete (SFRC); orientation of steel fiber; flowability of fresh SFRC; compressive strength; splitting tensile strength; flexural strength; flexural toughness; fracture energy.
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\( m_{sf0} \) the mass of steel fibers used per cubic meter (kg/m\(^3\)),
\( m_{c0} \) the mass of cement used per cubic meter (kg/m\(^3\)),
\( m_{f0} \) the mass of fly ash used per cubic meter (kg/m\(^3\)),
\( m_{w0} \) the mass of water used per cubic meter (kg/m\(^3\)),
\( m_{s0} \) the mass of sand used per cubic meter (kg/m\(^3\)),
\( m_{g0} \) the mass of coarse aggregate used per cubic meter (kg/m\(^3\)),
\( \rho_c \) the density of cement (kg/m\(^3\)),
\( \rho_f \) the density of fly ash (kg/m\(^3\)),
\( \rho_w \) the density of water (kg/m\(^3\)),
\( \rho_s \) the density of sand (kg/m\(^3\)),
\( \rho_g \) the density of coarse aggregate (kg/m\(^3\)),
\( \beta_{s0} \) the sand ratio,
\( \rho_{sf} \) the volume fraction of the steel fiber,
\( \alpha \) the percentage of air within the concrete,
\( \rho_f \) the volume fraction of steel fiber
\( n_i \) the number of steel fibers in \( i \)th region of the section
\( A_i \) the area of \( i \)th region
\( A_{f1} \) the sectional area of single steel fiber across the section
\( m \) the number of regions of the section
\( \mu \) the average of number of steel fibers in \( m \) regions
\( \rho_x \) the distribution rate of steel fibers across section \( x \)
\( \rho_y \) the distribution rate of steel fibers across section \( y \)
\( f_{e,p} \) the equivalent initial flexural strength (MPa)
\( b \) the cross section width of the beam (mm)
\[ h \] the cross section height of the beam (mm)
\[ L \] the span of the beam (mm)
\[ \delta_p \] the mid-span deflection of the beam under peak-load (mm)
\[ \Omega_p \] the area under the load-deflection curve up to \( \delta_p \) (Nmm)
\[ f_{\text{ftm}} \] the flexural strength of SFRC (MPa)
\[ P \] the maximum flexural load (kN)
\[ \Omega_p \] the area under the load-deflection curve from \( \delta_p \) up to \( \delta_k \) (Nmm)
\[ \delta_{p,k} \] the increased mid-span deflection from \( \delta_p \) to \( \delta_k \) (mm)
\[ \delta_k \] the calculated mid-span deflection \( L/k \) (mm) when \( k \) equals to 500, 300, 250, 200, 150
\[ E \] the modulus of elasticity
\[ I \] the moment of inertia
\[ E_i \] refer the modulus of elasticity of the mixture constituents
\[ V_i \] the volume fraction of the mixture constituents
\[ E_j \] the modulus of elasticity of layer \( j \)
\[ E_C \] the modulus of elasticity of concrete
\[ E_S \] the modulus of elasticity of steel fiber
\[ \rho_j \] the distribution rate of layer \( j \)'s steel fibers
\[ \alpha_j \] the ratio of the modulus of elasticity of layer \( j \) to the modulus of elasticity of concrete
\[ A_j \] the additional sectional area of layer \( j \)
\[ b \] the width of section
\[ h \] the height of the section
\[ A_0 \] the aspect sectional area
\[ A_1 \] the additional sectional area by modulus of elasticity of layer 1
\[ A_2 \] the additional sectional area by modulus of elasticity of layer 2
\[ A_3 \] the additional sectional area by modulus of elasticity of layer 3
The additional sectional area by modulus of elasticity of layer 4

The aspect neutral axis

The altered moment of inertia before crack-elongation

The moment of elastic resistance of aspect section area $A_0$ to the edge of tensile section

The bending moment

The ratio of the modulus of elasticity of steel fiber to the modulus of elasticity of concrete.
1.1 General

Concrete is a composite of crushed stone or gravel, sand, or other coarse and fine aggregates, bound together by means of the hydration of cement or other cementitious materials. It is an important and major construction material used for building structures, hydraulic structures, harbor engineering, bridges, roads and any other infrastructures, and is the major building material used in modern civil engineering. Generally, concrete has many good properties in compressive strength, volume steady, durability, and fire resistance, accompanied with better forming ability, easily made of local resources and cheaper construction. However, it has some disadvantages such as high self-weight, long curing period to get the strength required, and easily cracked. During the development progress over the past years, concrete has experienced several great leaps.

Steel fiber reinforced concrete (SFRC) is a multiple-composite material developed during the early 1970s, in which short steel fibers are randomly oriented in concrete [1, 2]. The original purpose of SFRC was to improve the lower tensile strength and poor compressive ductility by using the restraining effect of steel fibers to stop the development of micro-cracks inside the concrete and reduce the expansion and development of the macro-cracks. With the increase of tensile strength, the properties controlled by the main tensile stress such as shear strength, flexural strength, and cracking resistance could be increased. Therefore, the performances of SFRC structures could be improved under shear, flexural, punching and impact loads, as well as under fatigue and recycled or other complex actions.
Now it is known that steel fibers in concrete have many benefits to improve the mechanical properties and durability of concrete. With proper mix proportion and production methods, SFRC has not only improved conventional properties such as compressive strength, modulus of elasticity, fracture resistance, shear resistance, tensile strength and flexural strength [2-9], but also remarkably enhanced some other properties. For example, the energy absorption, toughness, peak-strain, and residual tensile strain post peak-stress under compression could be increased with the amount of steel fibers, especially for high-strength concrete [4-7]; the multiple cracking and strain hardening of SFRC could be achieved before complete failure under uniaxial tension or multi-axial loads, where the nonlinear fracture of the concrete matrix, the bond-slip behavior between fibers and concrete matrix and the elastic response of both materials are taking place [8, 9]; the flexural toughness and residual tensile strain post peak-stress [5, 10-12], and the fracture energy and post-cracking resistance [12] could be increased, as the steel fibers bridged the cracks and restrained crack developments; the moisture diffusion could be reduced inner concrete and the drying shrinkage of SFRC in composition with steel fibers could be reduced [13]; assisted with polypropylene fibers, the residual mechanical properties and the resistance to high temperature of SFRC could be improved [14].

As mini-reinforcement distributed randomly in concrete, steel fiber is the key material of SFRC. In accordance with the specification of ACI A820 [16], four general types of steel fibers are identified based upon the products used as a source of the steel fiber material. They are cold drawn wire (type I), cut sheet (type II), melt-extracted (type III) and other fibers (type IV). Fibers may be straight or deformed. The tensile strength of steel fibers is higher than 345 MPa. The dimension and permissible variation of steel fibers presented by equivalent diameter and length, and the mechanical properties of steel fibers are also specified. Standard test method for tensile strength and Young’s modulus of fibers is specified in ASTM C 1517-03 (Standard Test Method for Tensile Strength and Young’s Modulus of Fibers) [17]. The most basic type of steel fibers is straight fibers cut out of smooth wire. Such fibers do
not ensure a full utilization of the strength of source steel, as they are lack of appropriate anchorage in concrete matrix. With the development of research and engineering application, advances of steel fibers have been achieved in production technology and composition steel. Over 90% of currently produced fibers are deformed shapes adjusted to maximize the anchorage of fibers in concrete. Flattened, spaded, coned, twisted, crimped, hooked, surface-textured steel fibers have been produced. These steel fibers have circular, square, rectangular or irregular cross-section. Each of the types can additionally vary in diameters and length. The steel fibers usually used in engineering are as shown in Figs. 1-1 to 1-3. They are cold-drawn wire with hooked ends, cut sheet with enlarged ends or indentations and milling type with deformed shape. The section of cold drawn wire is circular, others are rectangular or irregular. The hooked ends, enlarged ends and deformed shape are made to enhance the bound effects of steel fibers to concrete, however different shape has different enhancement effect. With the application of steel fiber in high-strength concrete, it is found that the tensile strength of steel fiber should be matched with the strength of concrete, hence the steel fibers should be produced with different strength grade [9, 10].

Fig. 1-1 Steel Fiber: Cold-Drawn Wire with Hooked Ends
Based on the literature review [19], the orientation of steel fibers in concrete matrix is affected by many factors. These factors include matrix of concrete, characteristics of steel fiber, volume fraction of steel fiber, workability of fresh concrete, casting approach, boundary conditions, etc. In which the matrix of concrete, workability of fresh concrete, and characteristics of steel fiber are the most critical factors [18]. Many previous studies have focused on the distribution patterns of steel fibers [20-23] and their effects on mechanical properties of SFRC [1, 22-26], while few studies have dealt with the flowability of the concrete mix [27, 28]. As the flowability of plastic concrete is low, the distribution of steel fibers is controlled by the mixing procedure. With a proper mixing procedure, steel fibers will be distributed with a random orientation in fresh concrete [27, 29].

With the introduction of superplasticizer into concrete, the long distance transportation of premixed concrete is now commonly used and one of the major ways of achieving sustainable construction. As fresh premixed concrete has the
characteristic of flowing/self-compaction, the distribution of steel fibers inside premixed concrete will be different to that of plastic concrete [30]. With the increase of flowability of fresh concrete, the distribution ratio of steel fibers tends to gradually increase from the top layer to the bottom layer of SFRC. Uniformity of steel fibers in the cross section of SFRC with higher flowability is recognized less than that of SFRC with lower flowability [31-33]. As such the flowability of SFRC could potentially have some effects on the performances of hardened concrete. It is necessary to determine the influence of flowability on properties of SFRC.

In this study, mixes and specimens of SFRC with different flowability were tested. The thesis reports the effects of flowability on the distribution rate, distribution coefficient and orientation coefficient of steel fibers, together with the compressive strength, splitting tensile strength, flexural strength, flexural toughness, and fracture energy of SFRC. Test mechanisms for determining strengths of high flowability SFRC and recommended equations for calculating bending stiffness and flexural stress based on the distribution rate of steel fibers are also presented.

1.2 Research Objectives

The main objectives of this research are to study the influences of flowability of fresh SFRC on steel fiber distribution patterns and mechanical properties of SFRC and to summarize the relationships of these distribution patterns and mechanical properties, making the flexural performances of flowable/self-compacting SFRC predictable. The study will provide technical support for design and construction of flowable/self-compacting SFRC.
The specific objectives of this research are:

(1) To compare differences of steel fiber distribution patterns of SFRC with different flowability;

(2) To test basic mechanical properties such as compressive strength, splitting tensile strength and flexural strength of SFRC with different flowability;

(3) To assess influence of flowability on the basic mechanical properties of SFRC;

(4) To discuss relationships between steel fiber distribution patterns and mechanical properties of SFRC;

(5) To analyse mechanism causing the differences of mechanical properties of different flowability SFRC;

(6) To propose formulas for calculating the modulus of elasticity, moment of inertia, bending stiffness, moment of elastic resistance and flexural stress of flowable SFRC.

1.3 Thesis Arrangement

The thesis is organized into six chapters. A brief description of each chapter is given below.
Chapter 1 Introduction

This chapter provides a brief introduction on previous studies on SFRC and the necessity of conducting this research study. The objectives of this study are outlined. Thesis structure is also presented in this chapter.

Chapter 2 Literature Review

This chapter provides a detailed literature review on previous studies conducted by other scholars on steel fibers’ distribution patterns and mechanical properties of SFRC. The remaining issues of SFRC regarding the influences of flowability on performances of SFRC are identified. Research questions and assumptions are also listed.

Chapter 3 Experimental Design

This chapter deals with detailed experiment design and mechanical property tests covering the entire experiment procedure, including the selection and tests on raw materials, the concrete mix design, the preparation and curing of specimens, the cutting method of specimens for steel fiber distribution patterns analysis, the compressive strength test of SFRC, the splitting tensile test along three directions of specimens of SFRC, and the flexural toughness test of SFRC.

Chapter 4 Evaluation of Steel Fiber Distribution Patterns

In this chapter, three factors, distribution rate, distribution coefficient and orientation coefficient are calculated for each flowability SFRC. Results are plotted, compared, and analysed to evaluate the influence of flowability on steel fiber distribution patterns.
Chapter 5 Mechanical Properties of SFRC Correlating with Steel Fiber Distribution Patterns

In this chapter, mechanical properties test results are summarized. The load-deflection curve of flexural strength was plotted and analysed. Two methods, the commonly used ASTM C1018 (Standard Test Methods for Flexural Toughness and First Crack Strength of Fiber Reinforced Concrete) method and the Chinese Standard JG/T472-2015 (Steel Fiber Reinforced Concrete), are used to access flexural toughness of SFRC. Fracture energy is also calculated. Formulas for calculating moment of inertia and flexural stress of flowable SFRC are proposed.

Chapter 6 Conclusion And Recommendation

This chapter provides conclusions of this research project and recommendations for future research.
CHAPTER 2 LITERATURE REVIEW

2.1 General

As SFRC has advantages such as better crack control, high shearing and flexural performance and greater earthquake resistance, this new kind of composite material has drawn attention of scholars all over the world.

Previous studies have studied several factors influencing steel fiber distribution. As the steel fiber distribution governs the mechanical performance of SFRC, alteration of the way steel fiber is distributed among concrete matrix could have a significant impact on the mechanical properties. To control the impact, it is necessary to know how to change the distribution of steel fiber, making it possible to control the performance of SFRC during a design of engineering application.

As premixed and flowable concrete is now commonly used in construction, the effects of flowability on the distribution patterns of steel fibers and the mechanical properties of SFRC should be studied.

This chapter provides a detailed review on previous studies conducted by other scholars on steel fiber distribution patterns and mechanical properties of SFRC. The remaining issues of SFRC regarding with the influences of flowability on performances of SFRC are pointed out. Research questions and assumptions are also listed.
2.2 Factors Influencing Steel Fiber Distribution Patterns

2.2.1 Matrix of Concrete

Cement paste is required to coat the steel fibers to form a reliable interface between the steel fibers and the concrete matrix. In a normal concrete mix the coarse aggregate will significantly affect the distribution patterns of steel fiber. As the material forming the internal frame of concrete, coarse aggregate undertakes the function of uniformly distributing the steel fibers to form the global bridging structure, which enhances the concrete matrix [21, 25]. As steel fibers are randomly distributed in gaps among coarse aggregate, the uniformity of steel fibers distribution will be affected by the particle grading of coarse aggregate [25]. When the particle size of coarse aggregate is too large, steel fibers will not be able to distribute and rotate freely in the fresh concrete mix. Therefore, maximum size of coarse aggregate should be matched to the length of steel fiber [25, 26].

2.2.2 Characteristics of Steel Fiber

Length, sectional dimension, shape, and surface configuration are the important characteristics of steel fiber. As the cross sections of steel fiber are not all circular, the equivalent diameter is used to represent the rectangular or irregular cross section [16]. The length of steel fiber controls its bridging capacity among coarse aggregate particles and affects the cohesiveness of fresh concrete mix; the sectional dimension of steel fiber determines its stiffness preventing bending and clumping, therefore, these two geometrical factors control the flowing ability of steel fibers in fresh concrete [23-25, 27]. In order to ensure that steel fibers have a relatively high degree of freedom of orientation without bending in the concrete, a length of steel fiber of 20-60 mm with an aspect ratio (i.e. length to diameter ratio) of 30-100 is suggested in SFRC designs. For the plastic fresh concrete, to ensure the effective length of steel
fiber across post-cracking section, the length of steel fiber should not shorter than $4/3$ times maximum size of coarse aggregate [26].

As stated in Chapter 1, steel fibers are made into many shapes such as hooked ends, enlarged ends and crimped, etc. for the aim of enhancing the anchorage between steel fibers and concrete. For the same purpose, the surface of steel fiber is also produced with different configurations such as impression, roughing and warping. While these changes of shape and surface configuration increase the cohesiveness to cement paste, they also influence the orientation of steel fiber in concrete [23, 26, 28]. Moreover, when the density of steel fibers is higher than fine aggregate and cement paste, steel fibers will tend to sediment towards lower layer of the section.

2.2.3 Volume Fraction of Steel Fiber

When the volume fraction of steel fibers is lower, they have less strengthening effect on the mechanical properties of SFRC since there are not enough steel fibers distributed throughout the concrete mix. When the volume fraction of steel fiber is higher than a certain extent, steel fibers tend to cluster. Therefore, there is an optimal range of volume fraction of steel fiber, in which the distribution patterns of steel fiber tends to form freely random orientation. The optimal range will be different dependent upon the concrete matrix and types of steel fibers. The optimum range is usually taken as 0.75~1.5%, with an extension from 0.5% to 2.0% [24, 27].

2.2.4 Workability of Fresh Concrete

Workability of fresh concrete is composed of three parameters, i.e. flowability, cohesiveness and water-retaining. When the latter two parameters are ensured, the flowability has inherent influence on the distribution patterns of steel fibers. For plastic fresh concrete, as the flowability is lower, the distribution of steel fiber is
controlled by the mixing procedure. With proper mix procedure, steel fibers can distribute in random orientations in fresh concrete [21, 24]. With the increase of flowability of fresh concrete, steel fibers tends to orientate along the flow direction in a horizontal plane, and the distribution ratio of steel fiber tends to gradually increase from the top layer to the bottom layer of SFRC [27, 29, 30]. Uniformity across the section of SFRC with higher flowability is lower than that in lower flowability SFRC. Also, the sedimentation of coarse aggregate will tend to force steel fibers to sediment towards lower layer of the section.

2.2.5 Casting Approach

Compaction methods such as table vibration, hand tamping and internal vibration have considerable influences on the distribution of the fibers in common concrete [28]. It is easy to understand that table vibration increases the tendency of the fibers to orientate horizontally, hand tamping causes the least non-uniformity of the fiber distribution, while internal vibration is harmful to the uniform orientation as the steel fibers tends to orientate along the axis of vibrator. During the vibration of the concrete, coarse aggregate sediments towards the bottom layer while sand and cement paste rises towards the top layer. Sedimentation of steel fibers on the top layer will be influenced by the coarse aggregate while steel fibers in the mid-section sediments with coarse aggregate. Therefore, to ensure the uniformity of SFRC, an appropriate vibration time is needed. With the increase of the flowability of SFRC, vibration time should be reduced to prevent aggregate and steel fiber layering [21, 31].

The steel fibers in self-compacting SFRC tend to orientate in a horizontal plane, the casting and compaction processes can significantly affect the distribution and orientation of steel fibers [32].
2.2.6 Boundary Condition

When cast in a formwork, SFRC mix is restrained by the boundary during formation. For plastic fresh concrete, in a relatively small element, the movement and orientating of steel fiber may be restrained by the coarse aggregate and the interface of formwork, which leads the steel fiber to have a tendency to be distributed near the interface with the formwork [22, 28]. Therefore, the boundary condition influence basic mechanical properties and the quality evaluation of SFRC.

For self-compaction fresh SFRC, the orientation and dispersion of steel fibers near rough surfaces of formwork will tend to be disturbed due to the reduction of flow rate, and thus exhibit a greater randomness near such a surface. This phenomenon usually appears in zones with a thickness of half the fiber length. However, this phenomenon will not seriously influence the global fiber distribution characteristics of a relatively large element. Also, the rigid surfaces of formwork will cause disturbances in steel fiber dispersion without random characteristics, and affect the performance of relatively large element SFRC [33-36].

2.3 Description of Steel Fiber Distribution in SFRC

Three concepts are commonly used to describe the distribution of steel fibers in the aim section [28, 29, 37].

2.3.1 Distribution Rate/concentration of Steel Fiber

This factor reflects the number of steel fibers per unit sectional area, and is defined as

\[ \rho = \frac{\sum n_i A_{fi}}{\sum A_i} \]  

(1)
where,

\[ n_i = \text{the number of steel fibers in } i\text{th region of aim section}, \]
\[ A_i = \text{the area of } i\text{th region}, \]
\[ A_{f1} = \text{the sectional area of single steel fiber across the aim section}. \]

### 2.3.2 Distribution Coefficient/uniformly Distributed Variable of Steel Fiber

This factor reflects the uniformity of steel fiber distributed in the aim section, which is expressed as

\[ \beta = e^{-\phi(x)} \]  

(2)

\[ -\phi(x) = \sqrt{\frac{\sum (n_i - \mu)^2}{m}} / \mu \]  

(3)

where

\[ m = \text{the number of regions of aim section}, \]
\[ \mu = \text{the average of number of steel fibers in } m \text{ regions}. \]

The value of \( \beta \) ranges from 0 to 1, the larger the distribution coefficient, the better the uniformity is.

### 2.3.3 Orientation Coefficient of Steel Fiber

This factor reflects the ratio of steel fiber in different aim sections, which is expressed as
\[ \theta = \frac{\rho_x}{\rho_y} \]  

(4)

where,

\[ \rho_x \] = the distribution rate of steel fibers across aim section \( x \),

\[ \rho_y \] = the distribution rate of steel fibers across aim section \( y \).

Only when steel fibers are distributed along the direction of tensile stress in the concrete matrix, can they provide crack-bridging effects in hardened concrete.

### 2.4 Relationship between Steel Fiber Distribution Patterns and Mechanical Properties of SFRC

Fiber distribution patterns in the concrete matrix are important for ensuring the required mechanical properties of SFRC. Ideal steel fiber distribution patterns should be able to match up with the stress characteristics of specific structure members (such as beams, floor slabs, columns and shear wall, etc.), so that steel fibers within the concrete should sufficient provide resistance against loadings.

In a design of a SFRC beam, when considering the flexural resistance of the beam, steel fibers should be distributed into the lower section of the beam with an orientation parallel with the direction of flexural stress. However, when considering the shear resistance of the beam, steel fibers should distribute uniformly in the beam with an orientation perpendicular with the direction of shear stress.

In the design of a SFRC floor slab, as it is only necessary to consider the flexural resistance of the slab, steel fibers should distribute in the lower section of the slab with an orientation parallel with the direction of flexural stress.
In the design of a SFRC column, as flexural resistance is not considered, steel fibers will not be needed. However, when earthquake resistance is needed, steel fibers with vertical orientation could provide shear resistance.

In the design of a SFRC shear wall, steel fibers with horizontal orientation could provide resistance of crack expansion.

It can be seen that it is necessary to study distribution patterns of steel fibers within the concrete to provide guides for designing SFRC structure members. This brings the questions: what are the factors that influence SFRC mechanical properties? what is the relationship between steel fiber distribution patterns and SFRC mechanical properties?

2.4.1 Distribution Rate/Concentration of Steel Fiber

Stroeven et al. [24] conducted experiments on concrete specimens with a water/cement ratio of 0.5, cement content of 375 kg/m³, fiber volume fractions of 0~3.0%. The specimens were vibrated externally and tested after 28 days of curing. The results showed that there was a positive linear relationship between the concentration of steel fiber and SFRC mechanical properties (bending strength and splitting tensile strength). Normally, the amounts of steel fiber plane parallel to the direction of vibration were higher than those in plane perpendicular to the direction of vibration. However, with the increase of SFRC flowability, the concentration of steel fiber plane perpendicular to the direction of vibration tends to increase. When the volume fraction of steel fiber is fixed, concentration of steel fiber plane perpendicular to the direction of vibration of SFRC with higher flowability will be greater than that of SFRC with lower workability. Since fibers plane parallel to the direction of flexural performance contribute most in the bending and splitting tensile strength of SFRC,
flowability should be a factor considered in the calculation of SFRC mechanical properties.

2.4.2 Distribution Coefficient /Uniformly Distributed Variable of Steel Fiber

S. T. Kang et al. [23] carried out a series of experiments on concrete specimens with a water/cement ratio of 0.25 and fiber volume fractions of 2.0%. Specimens were prepared by placing material parallel to the longitudinal direction of the specimens (PL) and placing material transversely to the longitudinal direction of the specimens (TL). Specimens were cut along transversely (TC), horizontally (HC) and vertical (VC) directions. The number of steel fibers in each cutting section were counted and distribution coefficients were calculated. In the case of concrete placed parallel to the longitudinal direction of the specimen, the fibers are more uniformly dispersed in the cross section cut transversely compared to the others. Furthermore, most of the fibers in the cross section cut transversely specimens are aligned more parallel to the normal direction of the cutting plane, relative to the other specimens. On the other hand, in the case of placing concrete transversely to the longitudinal direction of the specimen, the fiber dispersion coefficient is approximately 10% higher in the vertical cutting direction than in the transversal and horizontal cutting directions.

The larger value of distribution coefficients of PL-TC relative to those of TL-TC imply that the mechanical properties, represented by the flexural strength, of the PL beam specimen will be superior to those of TL beam specimens. This is because the relatively large amount of fibers in the PL specimen contributes to bridging transverse cracks, the normal direction of which is located in the same direction as the beam longitudinal axis.

There was a noticeable difference in the flexural strength between the measured and the predicted values when a uniform fiber distribution was assumed. This implies
that the simple assumption of uniformity can lead to considerable error in predicting flexural strength, and thus the placing direction of fiber reinforced concrete should be taken into account.

2.4.3 Orientation Coefficient of Steel Fiber

The variability of the mechanical properties of SFRC has been shown to be considerable. Steel fiber orientation has always been recognized to have a great influence on the mechanical properties of SFRC. Laranjeira et al [25] carried out some analysis on the characterizing of orientation pattern of steel fiber and the relationship between orientation coefficient of steel fiber and mechanical properties of SFRC. The results show that the larger the orientation coefficient, the smaller is the dispersion of fiber orientation round that value and vice versa. The mechanical properties of flowable concrete, which tend to present large orientation coefficients in certain directions, may be superior to SFRC with conventional concretes in those directions.

2.5 Issues Remaining of Flowable SFRC

Many previous studies have focused on the distribution patterns of steel fibers [20-23] and their effects on mechanical properties of SFRC [1, 22-26], while few studies dealt with the flowability of concrete mix [27, 28]. As the flowability of plastic concrete is low, the distribution of steel fibers is controlled by the mixing procedure. With a proper mixing procedure, steel fibers will be distributed with a random orientation in fresh concrete [10, 12].

With the introduction of superplasticizer into concrete, the long distance transportation of premixed concrete is now commonly used and one of the major
ways of achieving sustainable construction. As fresh premixed concrete has the characteristic of flowing/self-compaction, the distribution of steel fibers inside premixed concrete will be different to that of plastic concrete [30]. With the increase of flowability of fresh concrete, the distribution ratio of steel fibers tends to gradually increase from the top layer to the bottom layer of SFRC. Uniformity of steel fibers in the cross section of SFRC with higher flowability is lower than that of SFRC with lower flowability [31-33]. Clearly the flowability of SFRC will have some effects on the performances of hardened concrete. As such, it is necessary to determine the influence of flowability on properties of SFRC.

2.6 Research Questions and Assumptions

2.6.1 Research Questions

The following research questions are pointed out regarding the unsolved issues of flowable SFRC:

(1) How does the flowability influence steel fiber distribution patterns?

(2) What are the effects of steel fiber distribution patterns on the SFRC mechanical properties?

(3) What is the relationship between steel fiber distribution patterns and SFRC mechanical properties?
2.6.2 Assumptions

With the increases of the flowability of SFRC, there are two possible scenarios of steel fiber distributions.

The first scenario will be that steel fibers sink towards the lower section of the specimens, as shown in Fig. 2-1. As the density of steel fiber is higher than that of fresh concrete mixture, steel fibers have the potential to sink in fresh concrete. The cohesion force of cement paste and the obstruction of coarse aggregates of the fresh concrete mixture restrained the sediment of steel fibers. However, when the flowability increases, fresh SFRC is recognised to become less sticky. The mixture will have less resistance against the sediment of steel fibers meaning steel fibers could be distributed more in the lower section of high flowability SFRC.

The second scenario will be that steel fibers orientate more along the flow direction of the fresh concrete mixture, as shown in Fig. 2-2. When the flowability is high enough for the fresh concrete mixture to flow in the formwork, the stream of fresh concrete could force steel fibers to rotate along the flow direction.
In the two scenarios discussed above, steel fibers will either distribute more in the lower section (i.e. tensile section) of the specimens or orientate more along the flow direction (i.e. tensile direction) of fresh concrete mixture. These should be able to enhance flexural performances of high flowability SFRC. Thus, the following assumptions are carried out which will be verified by conducting tests on properties of SFRC.

When the flowability of SFRC Increases:

(1) Steel fibers will:
   - Distribute more in the lower section of the specimens,
   - Orientate more along the longer direction of the specimens.

(2) Mechanical properties of SFRC
   - Splitting tensile strength perpendicular to the orientation direction of steel fibers will increase
   - Flexural performance of beam will be improved
   - Load keeping capability in special conditions will increase
- Fracture energy of beam will increase

2.7 Conclusion

In this chapter, previous studies on distribution patterns of steel fiber are reviewed and summarized, the relationship between distribution patterns of steel fiber and mechanical properties of SFRC are also discussed. It is found that few studies have been carried out for a quantified relationship between workability of fresh SFRC and the distribution patterns of steel fiber, and with little consideration taken of the effects on premixed concrete.

As a new technology and one of the major ways of achieving sustainable construction, there are a number of issues that need to address for the engineering application of premixed SFRC. These include the influence of flowability on the steel fiber distribution in fresh concrete and the effect on the mechanical properties of hardened SFRC. Further studies on the relationships between steel fiber distribution patterns and mechanical properties of high workability SFRC are needed.

To solve the remaining issues of high flowability SFRC, research questions and regarding assumptions are given in this chapter. These research questions and assumptions will be used as a guide for designing the experiment of this research project.
CHAPTER 3 EXPERIMENTAL DESIGN

3.1 General

This chapter provides detailed design of experiment which covered the entire experiment procedure, including raw materials selection and tests, the concrete mix design, specimens preparation and curing, cutting method of specimens for steel fiber distribution patterns analysis, and the mechanical property tests of SFRC.

3.2 Raw Material Tests

Physical and mechanical properties of raw materials are given in Tables 3-1 to 3-3. Raw materials used for this research are listed below:

**Cement:** Grade 42.5 Portland cement [35], equivalent to Type GP cement in Australia

**Admixture:** Class-F fly ash

**Coarse aggregate:** continuous grading limestone coarse aggregate (size of 5~20 mm)

**Fine aggregate:** natural river sand (fineness modulus 2.77)
**Steel fiber:** cut sheet type with indentations. Diameter was 0.8 mm and length was 30 mm, with an aspect ratio of 37.5

**Water-reducer:** high range water-reducing admixture (HRWRA) with a water-reducing rate of 19%

**Water:** tap water

| Table 3-1 Physical and Mechanical Properties of Cement |
| --- | --- | --- | --- | --- | --- |
| Grade | Fineness (%) | Water content of standard density (%) | Setting time (min) | Compressive strength (MPa) | Flexural strength (MPa) |
| --- | --- | --- | Initial | Final | 3 d | 28 d | 3 d | 28 d |
| 42.5 | 2.0 | 27.50 | 3:20 | 5:55 | 33.72 | 50.2 | 6.6 | 9.2 |

<p>| Table 3-2 Physical Properties of Sand |
| --- | --- | --- | --- | --- | --- |</p>
<table>
<thead>
<tr>
<th>Series (mm)</th>
<th>Fineness modulus</th>
<th>Apparent density (kg/m³)</th>
<th>Bulk density (kg/m³)</th>
<th>Closed volume density (kg/m³)</th>
<th>Mud content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.16–0.5</td>
<td>2.77</td>
<td>2600</td>
<td>1503</td>
<td>1609</td>
<td>2.65</td>
</tr>
</tbody>
</table>

<p>| Table 3-3 Physical Properties of Coarse Aggregate |
| --- | --- | --- | --- | --- | --- |</p>
<table>
<thead>
<tr>
<th>Series (mm)</th>
<th>Apparent density (kg/m³)</th>
<th>Bulk density (kg/m³)</th>
<th>Crush index (%)</th>
<th>Mud content (%)</th>
<th>Closed volume density (%)</th>
<th>Content of needle-slice particle (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5–20</td>
<td>2750</td>
<td>1500</td>
<td>11</td>
<td>0.26</td>
<td>1650</td>
<td>8.4</td>
</tr>
</tbody>
</table>

![Fig. 3-1 Sample of Fiber Used](image-url)
The combination of test parameters is summarised in Table 3-4, in which the volume fraction is used to represent the content of steel fibers.

Table 3-4 Combination of Test Parameters

<table>
<thead>
<tr>
<th>Slump (mm)</th>
<th>$m_{so}$ (kg.m$^{-3}$)</th>
<th>W/C</th>
<th>$\beta_{so}$ (%)</th>
<th>HRWRA (%)</th>
<th>$\rho_{f}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80, 120, 160, 200</td>
<td>430</td>
<td>0.4</td>
<td>35, 37, 39, 41</td>
<td>0.6, 0.8, 1.0, 1.2</td>
<td>1</td>
</tr>
</tbody>
</table>

3.3 Mix Design

A direct mix design method of steel fibers was used, in which steel fiber replaced an equal volume of coarse aggregates, and the mass of steel fiber was considered in the calculation of sand ratio [34]. The water to binder ratio (w/c) was 0.4.

\[
m_{f0} + m_{c0} + m_{w0} + m_{s0} + m_{g0} = (1 - \rho_{f})m_{cp} \tag{5}\]

\[
\beta_{s} = \frac{m_{so}}{m_{so} + m_{g0} + m_{f0}} \times 100\% \tag{6}\]

\[
m_{f0} = 7800\rho_{sf} \tag{7}\]

where,

- $m_{sf0}$ = the mass of steel fibers used per cubic meter (kg/m$^3$),
- $m_{c0}$ = the mass of cement used per cubic meter (kg/m$^3$),
- $m_{f0}$ = the mass of fly ash used per cubic meter (kg/m$^3$),
- $m_{w0}$ = the mass of water used per cubic meter (kg/m$^3$),
- $m_{s0}$ = the mass of sand used per cubic meter (kg/m$^3$),
- $m_{g0}$ = the mass of coarse aggregate used per cubic meter (kg/m$^3$),
- $\rho_{c}$ = the density of cement (kg/m$^3$),
- $\rho_{f}$ = the density of fly ash (kg/m$^3$),
- $\rho_{w}$ = the density of water (kg/m$^3$),
\(
\rho_s = \text{the density of sand (kg/m}^3\text{)}, \\
\rho_g = \text{the density of coarse aggregate (kg.m}^3\text{)}, \\
\beta_{s0} = \text{the sand ratio}, \\
\rho_{sf} = \text{the volume fraction of the steel fiber}, \\
\alpha = \text{the percentage of air within the concrete.}
\)

Detailed mix proportions are shown in the table below. The binder/water ratio used in this experiment is 0.4. Class F fly ash is used to replace 20% of cement in weight. The amount of water used is 215 kg/m\(^3\). Steel fiber volume fraction is 1%. Sand ratio is 35%, 37%, 39% and 41% for 80 mm, 120 mm, 160 mm and 200 mm, respectively. The increase in sand ratio is meant to increase the flowability and ensure there will be enough mortar for concrete to flow.

<table>
<thead>
<tr>
<th>Slump (mm)</th>
<th>Cement (kg/m(^3))</th>
<th>Water (kg/m(^3))</th>
<th>Fly ash (kg/m(^3))</th>
<th>Coarse aggregate (kg/m(^3))</th>
<th>Sand (kg/m(^3))</th>
<th>Steel fiber (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>430</td>
<td>215</td>
<td>107.5</td>
<td>980</td>
<td>570</td>
<td>1</td>
</tr>
<tr>
<td>120</td>
<td>430</td>
<td>215</td>
<td>107.5</td>
<td>950</td>
<td>600</td>
<td>1</td>
</tr>
<tr>
<td>160</td>
<td>430</td>
<td>215</td>
<td>107.5</td>
<td>915</td>
<td>635</td>
<td>1</td>
</tr>
<tr>
<td>200</td>
<td>430</td>
<td>215</td>
<td>107.5</td>
<td>880</td>
<td>665</td>
<td>1</td>
</tr>
</tbody>
</table>

### 3.4 Specimens Preparation

During mixing, cement and fly ash were blended first in a dry condition for 30 second. Then aggregates were added and blended for another 30 second. Subsequently half of the HRWRA and water were mixed in a bucket and added to the dry mix. The remaining half of the HRWRA and water were added to the mixture gradually to ensure homogeneity in the mixture. The mixture was blended for 1 minute. Then steel fibers were added to and blended for 1 minute to achieve a uniform distribution of the steel fibers in the concrete.
The slump flow test was used to measure the flowability.

After the slump test, the mixture was then placed in the moulds and vibrated. To avoid over-vibration, vibration time was controlled for each trial. 80 mm, 120 mm, 160 mm and 200 mm slump specimens were vibrated for 1 minute, 40 second, 20 second and 10 second, respectively.
Details of the tests and dimensions of the specimens are given in Table 3-6.

<table>
<thead>
<tr>
<th>Test</th>
<th>Dimension of specimens (mm)</th>
<th>Number of trials per flowability</th>
<th>Number of specimens per trial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cubic compressive strength</td>
<td>$150 \times 150 \times 150$</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Splitting tensile strength</td>
<td>$150 \times 150 \times 150$</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Flexural strength</td>
<td>$150 \times 150 \times 550$</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Fiber distribution analysis</td>
<td>$150 \times 150 \times 550$</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

3.5 Curing of Specimens

The cast surface of specimens was covered by a plastic sheet for 12 hours before being demoulded. After that, the specimens were cured in a standard curing room maintained at a temperature of $20 \pm 2 \degree C$ and 95% relative humidity for 28 days before testing.
3.6 Cutting Specimens for Steel Fiber Distribution Patterns Analysis

By cutting the specimens in three directions (transverse, horizontal and vertical sections) and counting amounts of steel fibers in each section, effects of flowability on steel fiber distribution patterns can be assessed. As shown in Fig. 3-6, specimens were cut into four equal sized cubes along the transverse direction, the steel fibers orientated along longitudinal direction were observed on these three cross-sections. Two cubes were then cut into six equal sized slices horizontally, the steel fibers orientated along vertical direction were observed on these four horizontal sections. The other two cubes were cut into six equal sized slices vertically, the steel fibers orientated along transverse direction were observed on these four vertical sections.

Images of the cross sections were acquired and inputted into AutoCAD for gridding as shown in Fig. 3-7. Each section was divided into a 4 × 4 grid for counting steel fibers.
Fig. 3-6 Simulation of Cutting Orientation of The Specimens

Fig. 3-7 Gridding of Section Using AutoCAD

Fig. 3-8 Photos of Cut Specimens
3.7 Mechanical Properties Tests

Standard tests, according to the Chinese Standard JG/T472-2015 (Steel Fiber Reinforced Concrete), were conducted on specimens to study effects of flowability on the mechanical properties of the concrete, including compressive strength, splitting tensile strength and flexural strength and toughness.

3.7.1 Compressive Strength Test

Three 150 mm cubic specimen was used per trial. Loading rate was controlled within 0.5 – 0.8 MPa/s. After the failure of the specimen, maximum load was recorded.

3.7.2 Splitting Tensile Strength Test

To simulate the influence of different orientations of steel fibers on SFRC tensile strength, splitting tensile tests were conducted in three directions (see Fig. 3-10). Nine
150 mm cubic specimens are used per trial. Loading rate was controlled within 0.5 – 0.8 MPa/s. After the failure of the specimen, maximum load was recorded.

3.7.3 Flexural Strength Test

Electro-hydraulic servo universal testing machine with computer controlled automatic classification was used for flexural strength test, where load control before the ultimate load and deflection control after the ultimate load. Considering the influence of fiber layering effect of high flowability SFRC, flexural tests were loaded on the cast surface of specimens, rather than their side as specified in ASTM C1018 designation [36].
CHAPTER 4 EVALUATION OF STEEL FIBER DISTRIBUTION PATTERNS

4.1 General

In this chapter, three factors, i.e., distribution rate, distribution coefficient, and orientation coefficient are calculated for each flowability SFRC. Results are plotted and compared to evaluate the influence of flowability on steel fiber distribution patterns.

4.2 Distribution and Orientation of Steel Fibers

The distribution rate of each orientation steel fibers is calculated and plotted in Fig. 4-1. There is a slight difference in the distribution rate of the steel fibers orientated along longitudinal direction in each layer of the transverse section of 80 mm and 120 mm slump SFRC, where the steel fibers in 120 mm slump SFRC distributed more homogenously. Steel fibers of higher flowability SFRC tended to precipitate towards bottom layers of specimens. This tendency of steel fibers layering increased with the flowability.

Flow of steel fibers in the transversal direction was restricted by the boundary of the mould, especially when the flowability was low. Sedimentation of steel fibers was not as obvious as that in the longitudinal direction, which resulted in heterogeneous fiber distribution among each layer in 80 mm and 120 mm slump SFRC. As the width of the specimen was only 150 mm, steel fibers of 30 mm length were not able to flow
in this short distance, especially with due to the obstruction of coarse aggregate. During the vibration of the concrete, coarse aggregates precipitated towards the bottom layer and the sand and cement paste rose towards the top layer. Steel fibers on the top layer were influenced by coarse aggregates while steel fibers in the middle part precipitate with coarse aggregates. When the flowability of the concrete was higher (160 mm and 200 mm slump), obstruction of both cement paste and coarse aggregate was reduced, which allowed fibers to precipitate, the distribution ratio tended to increase from the top layer to the bottom layer [29].

Fibers in vertical direction were not influenced by the flowability, fibers in every layer of each flowability SFRC have a similar distribution rate.

Fig. 4-1 Distribution Rate of Steel Fibers versus Layers of Specimens of Different Flowability SFRC
Images of transverse section of different flowability SFRC are shown below.

(a) Transverse Section of 80 mm Slump SFRC

(a) Transverse Section of 120 mm Slump SFRC
(c) Transverse Section of 160 mm Slump SFRC

(b) Transverse Section of 200 mm Slump SFRC

Fig. 4-2 Transverse Section of Different Flowability SFRC
Images of vertical section of different flowability SFRC are shown below.

(a) Vertical Section of 80 mm Slump SFRC

(b) Vertical Section of 120 mm Slump SFRC
(c) Vertical Section of 160 mm Slump SFRC

(d) Vertical Section of 200 mm Slump SFRC

Fig. 4-3 Vertical Section of Different Flowability SFRC
Images of horizontal section of different flowability SFRC are shown below.

(a) Horizontal Section of 80 mm Slump SFRC

(b) Horizontal Section of 120 mm Slump SFRC
(c) Horizontal Section of 160 mm Slump SFRC

(d) Horizontal Section of 200 mm Slump SFRC

Fig. 4-4 Horizontal Section of Different Flowability SFRC
The distribution coefficient of each flowability SFRC is summarized in Table 4-1. It can be seen that SFRC with 120 mm slump had the highest sectional distribution coefficient for all three orientations and an average coefficient above 0.7 for each layer, which showed better uniformity. The 200 mm slump SFRC had the worst sectional distribution coefficient due to the layering of steel fibers precipitating towards bottom of specimens, resulted in an uneven distribution rate of each layer. However, it should be noticed that the coefficient of the bottom layer of the transverse section of 200 mm slump SFRC was 0.76, which indicated good uniformity in the tensile zone.

<table>
<thead>
<tr>
<th>Table 4-1 Distribution Coefficient of SFRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Transverse</td>
</tr>
<tr>
<td>Vertical</td>
</tr>
<tr>
<td>Horizontal</td>
</tr>
</tbody>
</table>

The orientation coefficient of each flowability SFRC is shown in Table 4-2. Steel fibers distributed in transverse section was slightly higher than that of vertical and horizontal section, i.e. more steel fibers distributed along the longitudinal direction, which showed a tendency of steel fibers to distribute along longer direction of specimens. However, there was little difference among each group’s results, which indicated that flowability had no effect on steel fibers orientation.

<table>
<thead>
<tr>
<th>Table 4-2 Orientation Coefficient of SFRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slump of SFRC</td>
</tr>
<tr>
<td>Longitudinal to transverse direction</td>
</tr>
<tr>
<td>Longitudinal to vertical direction</td>
</tr>
</tbody>
</table>
4.3 Conclusion

Flowability has an influence on layering effect of the steel fibers orientated along longitudinal and transverse direction. The steel fibers orientated along longitudinal and transverse direction of 80 mm and 120 mm slump SFRC did not precipitate as those of 160 mm and 200 mm slump SFRC. The steel fibers in 120 mm slump SFRC showed better homogenous distribution and steel fibers in 200 mm slump SFRC layered along the height of specimens. The distribution coefficient of steel fibers in each section of 120 mm slump SFRC was the highest in all trials where that of 200 mm slump SFRC was the lowest. However, the coefficient of the bottom layer of the transverse section of 200 mm slump SFRC was 0.76, which indicated good uniformity in the tensile zone.
CHAPTER 5 MECHANICAL PROPERTIES OF SFRC AND THEIR CORRELATION WITH STEEL FIBER DISTRIBUTION PATTERNS

5.1 General

In this chapter, mechanical properties test results are summarized. Load-deflection curve of flexural strength is plotted and analysed. Two methods, the commonly used ASTM C1018 (Standard Test Methods for Flexural Toughness and First Crack Strength of Fiber Reinforced Concrete) method [36] and the Chinese Standard JG/T472-2015 (Steel Fiber Reinforced Concrete) [39], are used to access flexural toughness of SFRC. Fracture energy is also calculated. Formulas for calculating moment of inertia and flexural stress of flowable SFRC are proposed.

5.2 Strength of SFRC

Compressive strength, splitting tensile strength, and flexural strength at 28-days, are presented in Table 5-1. It can be seen that there is little difference in flexural strength of SFRC among each trial, which indicates that flowability had little influence on the ultimate flexural strength of SFRC.

The compressive strength tests were conducted on the side surface of the specimens, which was perpendicular to the cast surface. The steel fibers of higher flowability SFRC distributed more on the bottom of the specimens, resulting in eccentric material distribution on compression surface. After a certain amount of deformation, compressive stress distributed eccentrically, causing the reduction of
ultimate compressive load. On the other hand, as the ultimate deformation of SFRC increased with the increase of the amount of steel fibers, eccentric compression would cause the cast surface of higher flowability SFRC (which had less steel fibers) to damage first. Both will result in the reduction of compressive strength in higher flowability SFRC.

Splitting tensile tests were meant to simulate the effect of fiber orientation on tensile performances of SFRC. However, as the dimension of test specimens was not large enough for steel fibers to freely flow and rotate, there was no difference in splitting tensile test results among each flowability SFRC.

Table 5-1 Mechanical Properties of SFRC

<table>
<thead>
<tr>
<th>Slump (mm)</th>
<th>Compressive strength (MPa)</th>
<th>Splitting tensile strength (MPa)</th>
<th>Flexural strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(a)</td>
<td>(b)</td>
</tr>
<tr>
<td>80*</td>
<td>52.31</td>
<td>2.30</td>
<td>-</td>
</tr>
<tr>
<td>80</td>
<td>53.97</td>
<td>2.50</td>
<td>2.54</td>
</tr>
<tr>
<td>120</td>
<td>52.25</td>
<td>2.65</td>
<td>2.98</td>
</tr>
<tr>
<td>160</td>
<td>48.24</td>
<td>2.60</td>
<td>2.43</td>
</tr>
<tr>
<td>200</td>
<td>46.76</td>
<td>2.92</td>
<td>2.65</td>
</tr>
</tbody>
</table>

Note: *represents different loading as shown in Fig. 3-10.
* represents the trial of concrete without adding steel fibers.

The results raise the questions on whether current test mechanisms are suitable for determining strengths of SFRC. Test mechanisms of traditional tests for splitting tensile and compressive strengths are conducted on small cubic specimen to reflect the homogenous strength performance of the specimen, which do not consider the phenomenon of steel fibers flowing and layering of high flowability SFRC. These results cannot reflect the real life situation of splitting tensile and compressive strength of high flowability SFRC.

Similarly, as the traditional flexural strength test is conducted on small beam specimens whose boundaries limit steel fiber flow along the transverse direction, it is not suitable for flexural strength designs of slab-like members (in which each side is long enough for fibers to flow).
Moreover, to meet the steel fiber layering effect of high flowability SFRC, all tests should be loaded on the cast surface of the specimens. For example, as shown in Fig. 5-1 (a), when the slump of SFRC is above 160 mm, steel fibers tend to distribute more at the bottom of specimen. However, as shown in Fig. 5-1 (b), instead of conducting on the cast surface, the traditional splitting tensile strength test is conducted on a side face of the specimen. During the test, as the rigidity of the test machine is quite large, both sides of specimens are forced to deform with the same deformation. However, as the side with more steel fibers has a higher tensile strength, loading on the side surface of specimens will be larger than loading on the cast surface. Test results of typical splitting tensile test will be less reliable. As such the suitable test methods should be developed in order to accurately measure mechanical properties of SFRC.

![Real situation considering fiber layering effect](image)

(a) Real Situation Considering Fiber Layering Effect
5.3 Evaluation of Flexural Performance of SFRC

5.3.1 Accessing Flexural Toughness through ASTM C1018 Standard

Flexural toughness reflects the capability of concrete to absorb energy. SFRC with higher flexural toughness will be able to absorb more energy before its failure. As one of the most widely accepted methods for accessing flexural toughness, ASTM C1018 standard (Standard Test Methods for Flexural Toughness and First Crack Strength of Fiber Reinforced Concrete) test method [36] was used. The indices $I_5$, $I_{10}$, $I_{20}$, $I_{30}$ can be calculated as ratios of the areas under the load-deflection curve up to deflections of 3.0, 5.5, 10.5 and 15.5 times of first-crack deflection to the area under the load-deflection curve up to first-crack deflection respectively. According to the definition, all indices are equal to 1 for an elastic brittle material, and equal to 5, 10, 20 and 30, respectively, for an ideal elastic-plastic material. Table 5-2 shows the toughness indices calculated based on the results by using ASTM C1018 method. Fig. 5-2 is the schematic illustration for determining flexural toughness index by ASTM C1018. Formulas for calculating $I_5$, $I_{10}$, $I_{20}$ and $I_{30}$ are listed below,
\[ I_5 = \frac{S_{OACD}}{S_{OAB}} \quad (8) \]

\[ I_{10} = \frac{S_{OAEF}}{S_{OAB}} \quad (9) \]

\[ I_{20} = \frac{S_{OAGH}}{S_{OAB}} \quad (10) \]

\[ I_{30} = \frac{S_{OAEF}}{S_{OAB}} \quad (11) \]

Where,
\[
\delta = \text{the first crack deflection},
\]
\[
S_{OAB} = \text{the areas under load-deflection of } \delta,
\]
\[
S_{OACD} = \text{the areas under load-deflection of } 3 \times \delta,
\]
\[
S_{OAEF} = \text{the areas under load-deflection of } 5.5 \times \delta,
\]
\[
S_{OAGH} = \text{the areas under load-deflection of } 10.5 \times \delta,
\]
\[
S_{OAIJ} = \text{the areas under load-deflection of } 15.5 \times \delta,
\]

A higher toughness index indicates better ductility and more energy absorption capability of the concrete.
However, there are two issues regarding the use of ASTM C 1018 method for determining flexural toughness in this research. Firstly, the first-crack deflection cannot be accurately determined as the addition of steel fiber effectively prevented the expansion of cracks, leading to the change in the load-deflection curve not being clear. Election of first-crack deflection point could lead to a significant difference in the subsequent calculations. Secondly, as the first-crack deflection is rather small, even 15.5 times of first-crack deflection is still below 1 mm for each flowability specimens. The selected area under the load-deflection curve is not able to cover the situation after 1 mm deflection, which is not suitable for reflecting the actual flexural performance of SFRC.

<table>
<thead>
<tr>
<th>Slump (mm)</th>
<th>$I_5$</th>
<th>$I_{10}$</th>
<th>$I_{20}$</th>
<th>$I_{30}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>4.31</td>
<td>8.21</td>
<td>15.38</td>
<td>20.53</td>
</tr>
<tr>
<td>120</td>
<td>3.68</td>
<td>7.16</td>
<td>13.61</td>
<td>19.45</td>
</tr>
<tr>
<td>160</td>
<td>3.53</td>
<td>6.65</td>
<td>12.66</td>
<td>18.34</td>
</tr>
<tr>
<td>200</td>
<td>4.49</td>
<td>9.10</td>
<td>17.99</td>
<td>26.52</td>
</tr>
</tbody>
</table>

Fig. 5-2 Definition of Toughness Indexes According To ASTM C 1018 Method
5.3.2 Accessing Flexural Toughness by using JG/T 472-2015 Standard

A more suitable method for calculating flexural toughness of SFRC, as suggested by Chinese Standard JG/T472-2015 (Steel Fiber Reinforced Concrete) [39], is used in this research. This method avoids the difficulty of determining the first-crack deflection and the influence of the slope of the pre-crack load-deflection curve. The calculation process is more flexible in different deflection scenarios and makes the results more appropriate for structural evaluation in the practical engineering of SFRC. The ultimate flexural strength point is used to separate the flexural performance of SFRC into the pre-peak-load deflection scenario and post-peak-load deflection scenario. Fig. 5-3 shows the definition of toughness indexes according to JG/T 472-2015 method.

The initial flexural toughness ratio \( R_{e,p} \) is used to represent the pre-peak-load deflection toughness scenario, which can be calculated by the following equations,

\[
R_{e,p} = \frac{f_{e,p}}{f_{ftm}} (0 < R_{e,p} \leq 1)
\]  
(12)

\[
f_{e,p} = \frac{\alpha_{pL}}{bh^2\delta_p}
\]  
(13)

\[
f_{ftm} = \frac{PL}{bh^2}
\]  
(14)

where,
\[f_{e,p}\] = the equivalent initial flexural strength (MPa),
\[b\] = the cross section width of the beam (mm),
\[h\] = the cross section height of the beam (mm),
\[L\] = the span of the beam (mm),
\[\delta_p\] = the mid-span deflection of the beam under peak-load (mm),
\( \Omega_p \) = the area under the load-deflection curve up to \( \delta_p \) (N.mm),

\( f_{\text{ftm}} \) = the flexural strength of SFRC (MPa),

\( P \) = the maximum flexural load (kN).

The remaining flexural toughness ratio \( R_{e,k} \) is used to represent the post-peak-load deflection toughness scenario, which can be calculated by the following equations,

\[
R_{e,k} = \frac{f_{e,k}}{f_{\text{ftm}}} \quad (0 < R_{e,k} \leq 1) 
\]

(15)

\[
f_{e,k} = \frac{\Omega_{p,k} L}{bh^2 \delta_{p,k}}
\]

(16)

\[
\delta_{p,k} = \delta_k - \delta_p
\]

(17)

where,

\( f_{e,k} \) = the equivalent flexural strength (MPa) corresponding to the deflection of \( \delta_k \),

\( \Omega_p \) = the area under the load-deflection curve from \( \delta_p \) up to \( \delta_k \) (N.mm),

\( \delta_{p,k} \) = the increased mid-span deflection from \( \delta_p \) to \( \delta_k \) (mm),

\( \delta_k \) = the calculated mid-span deflection \( L/k \) (mm) when \( k \) equals to 500, 300, 250, 200, 150.

From the perspective of physical significance, \( R_{e,p} \) reflects the pre-peak-load flexural toughness of SFRC, a larger value indicates that steel fibers provide a better enhancement of flexural performance of SFRC before it reaches the ultimate flexural strength. On the other hand, \( R_{e,k} \) reflects the remaining flexural toughness of SFRC, a larger value indicates that steel fibers have greater contribution on the remaining flexural strength and energy absorption capability of SFRC. For both \( R_{e,p} \) and \( R_{e,k} \)
values, 1 represents the ideal elastic-plastic material, i.e., the closer those values get to 1, the better elastic-plastic properties the material has.

![Load vs. Deflection Curve](image)

Fig. 5-3 Definition of Toughness Indexes According to JG/T472-2015 Method

Table 5-3 summarizes the results calculated by the use of JG/T 472-2015 method [39]. It can be seen that initial flexural toughness ratios, $R_{e,p}$ of the four groups are quite similar, while the remaining flexural toughness ratio $R_{e,k}$ increases with the flowability of SFRC. When the slump increases from 80 mm to 200 mm, $R_{e,500}$, $R_{e,300}$, $R_{e,250}$, $R_{e,200}$ and $R_{e,150}$ increase up to 3%, 21%, 27%, 36% and 48% respectively. In addition, with the increase of the calculated mid-span deflection $\delta_k$, $R_{e,k}$ varies differently. $R_{e,k}$ value decreases rapidly for 80 mm slump specimen in which $R_{e,500}$ is 77% higher than $R_{e,150}$, while $R_{e,500}$ of 200 mm slump specimen is only 24% higher than $R_{e,150}$. This indicates that higher flowability SFRC has better load-keeping capability.

<table>
<thead>
<tr>
<th>Slump (mm)</th>
<th>$f_{e,p}$ (MPa)</th>
<th>$R_{e,p}$</th>
<th>$f_{e,500}$ (MPa)</th>
<th>$R_{e,500}$</th>
<th>$f_{e,300}$ (MPa)</th>
<th>$R_{e,300}$</th>
<th>$f_{e,250}$ (MPa)</th>
<th>$R_{e,250}$</th>
<th>$f_{e,200}$ (MPa)</th>
<th>$R_{e,200}$</th>
<th>$f_{e,150}$ (MPa)</th>
<th>$R_{e,150}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>2.67</td>
<td>0.82</td>
<td>2.75</td>
<td>0.85</td>
<td>2.17</td>
<td>0.68</td>
<td>2.01</td>
<td>0.62</td>
<td>1.80</td>
<td>0.56</td>
<td>1.54</td>
<td>0.48</td>
</tr>
<tr>
<td>120</td>
<td>2.67</td>
<td>0.88</td>
<td>2.66</td>
<td>0.88</td>
<td>2.35</td>
<td>0.77</td>
<td>2.19</td>
<td>0.72</td>
<td>1.98</td>
<td>0.65</td>
<td>1.73</td>
<td>0.57</td>
</tr>
<tr>
<td>160</td>
<td>2.69</td>
<td>0.86</td>
<td>2.79</td>
<td>0.89</td>
<td>2.58</td>
<td>0.82</td>
<td>2.48</td>
<td>0.79</td>
<td>2.34</td>
<td>0.75</td>
<td>2.11</td>
<td>0.67</td>
</tr>
<tr>
<td>200</td>
<td>2.64</td>
<td>0.85</td>
<td>2.73</td>
<td>0.88</td>
<td>2.54</td>
<td>0.82</td>
<td>2.46</td>
<td>0.79</td>
<td>2.36</td>
<td>0.76</td>
<td>2.20</td>
<td>0.71</td>
</tr>
</tbody>
</table>
The way toughness ratios vary in each flowability SFRC specimen corresponds with the shape of the load-deflection curves shown in Fig. 5-4. Although the ultimate flexural strength of the different flowability SFRC was almost identical, the flexural performance of each SFRC was quite different. The flexural performance of higher flowability SFRC was much better than that of lower flowability SFRC, especially after the peak load. The 80 mm slump SFRC displayed a sudden drop in load when the deflection reached about 1.0 mm, and load decreased rapidly afterwards. In higher flowability SFRC, load decreased gently and the shape of the load-deflection curve tended to be flatter.

![Load-deflection Curve of Different Flowability SFRC](image.png)

Both the pre-peak-load and the post-peak-load flexural performance are related to steel fiber distribution patterns of SFRC. Before the specimen reaches its maximum flexural load, flexural resistance is provided by the bottom layer fibers. For every flowability SFRC, there were some steel fibers lying on the bottom of specimens. After first crack appeared, bottom-layer steel fibers start to participate in the flexural resistance. The tensile strength of SFRC kept increasing until most of the bottom-layer steel fibers reached their yield stress or were pulled out from concrete. As there was no difference in the amount of bottom-layer steel fibers in each trial, the ultimate flexural strength of SFRC was similar.
5.3.3 Fracture Energy ($G_{e,p}$)

The fracture energy $G$ can be calculated by the area under the load-deflection curve. As shown in Table 5-4, higher flowability SFRC had an advantage over lower flowability SFRC. At the same deflection, the fracture energy of higher flowability SFRC tended to be greater than that of lower flowability SFRC, for higher flowability SFRC had better load keeping capability. Especially after the deflection reached 2.25 mm and 3 mm ($\delta_{200}$ and $\delta_{150}$ respectively), the fracture energy of 200 mm slump SFRC is 30% and 41% higher than that of 80 mm slump SFRC.

Table 5-4 Fracture Energy

<table>
<thead>
<tr>
<th>Slump (mm)</th>
<th>$G_{e,p}$ (N.mm)</th>
<th>$G_{e,500}$ (N.mm)</th>
<th>$G_{e,300}$ (N.mm)</th>
<th>$G_{e,250}$ (N.mm)</th>
<th>$G_{e,200}$ (N.mm)</th>
<th>$G_{e,150}$ (N.mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>1403</td>
<td>18510</td>
<td>24828</td>
<td>27427</td>
<td>30845</td>
<td>35321</td>
</tr>
<tr>
<td>120</td>
<td>3932</td>
<td>17954</td>
<td>26866</td>
<td>30302</td>
<td>34402</td>
<td>40226</td>
</tr>
<tr>
<td>160</td>
<td>1346</td>
<td>18806</td>
<td>29083</td>
<td>33645</td>
<td>39691</td>
<td>47657</td>
</tr>
<tr>
<td>200</td>
<td>2134</td>
<td>18373</td>
<td>28693</td>
<td>33412</td>
<td>40030</td>
<td>49828</td>
</tr>
</tbody>
</table>

5.4 Analysis on Pre-peak-load Performance of SFRC

5.4.1 Change in Bending Stiffness (B)

The factors influencing flexural toughness of SFRC are the bending stiffness of the section and the flexural stress of SFRC. Bending stiffness primarily governs the deformation of SFRC before first-crack appears and a small region till crack elongation and expansion, where flexural stress reflect the capability of preventing crack development. The equation of bending stiffness $B$ can be expressed as:

$$ B = EI $$

(18)
where,
\[ E = \text{the modulus of elasticity}, \]
\[ I = \text{the moment of inertia}. \]

From the formula it can be seen that the bending stiffness \( B \) is governed by the modulus of elasticity \( E \) of the material and the moment of inertia \( I \) of the cross section. Since adding steel fiber will have impact on the properties of mixture,

### 5.4.2 Change in Modulus of Elasticity (E) of SFRC

Before crack elongation, the effective section depth and \( I \) remained unchanged. However, as the steel fibers distribution rate of each layer in the transverse section was different for each flowability SFRC, the modulus of elasticity was different.

Using the law of mixtures approach, modulus of elasticity can be expressed as follows [40, 41]:

\[
E = E_1V_1 + E_2V_2 + \ldots + E_iV_i \tag{19}
\]

where,
\[
E_i = \text{the modulus of elasticity of the mixture constituents respectively},
\]
\[
V_i = \text{the volume fraction of the mixture constituents respectively}. \]

With the addition of steel fibers in concrete, the modulus of elasticity is influenced by the amount of steel fibers in the section. As the distribution rate of each layer of specimens transverse section was different, the modulus of elasticity will be altered along the height of the section. Using equation (19), modulus of elasticity of each layer can be calculated as:
\[ E_j = E_C (1 - \rho_j) + E_S \rho_j \]  

(20)

where,

\( E_j \) = the modulus of elasticity of layer \( j \),

\( E_C \) = the modulus of elasticity of concrete,

\( E_S \) = the modulus of elasticity of steel fiber,

\( \rho_j \) = the distribution rate of layer \( j \)’s steel fibers.

Changes of each layers modulus of elasticity result in the change of moment of inertia of the section. The altered moment of inertia is simulated in Fig. 5-5, which can be calculated by the following equations:

\[ \alpha_j = \frac{E_j}{E_C} \]  

(1)

\[ A_j = (\alpha_j - 1)bh/4 \]  

(22)

\[ A_0 = bh + A_1 + A_2 + A_3 + A_4 \]  

(23)

\[ y_0 = \frac{\left(\frac{bh^2}{2} + \frac{A_2h}{8} + \frac{3A_3h}{8} + \frac{5A_4h}{8} + \frac{7A_5h}{8}\right)}{A_0} \]  

(24)

\[ I_0 = \frac{by_0^3}{3} + \frac{b(h-y_0)^3}{3} + A_1\left(\frac{h}{8} - y_0\right)^2 + A_2\left(\frac{3h}{8} - y_0\right)^2 + A_3\left(\frac{5h}{8} - y_0\right)^2 + A_4\left(\frac{7h}{8} - y_0\right)^2 \]  

(2)

where,

\( \alpha_j \) = the ratio of the modulus of elasticity of layer \( j \) to the modulus of elasticity of concrete,

\( A_j \) = the additional sectional area of layer \( j \),

\( b \) = the width of section,

\( h \) = the height of the section,
\( A_0 \) = the aspect sectional area,
\( A_1 \) = the additional sectional area by modulus of elasticity of layer 1,
\( A_2 \) = the additional sectional area by modulus of elasticity of layer 1,
\( A_3 \) = the additional sectional area by modulus of elasticity of layer 1,
\( A_4 \) = the additional sectional area by modulus of elasticity of layer 4,
\( y_0 \) = the aspect neutral axis,
\( I_0 \) = the altered moment of inertia before crack-elongation.

Fig. 5-5 Simulation of SFRC Stiffness

With the calculated moment of inertia \( I_0 \) and the modulus of elasticity of concrete \( E_C \), bending stiffness of SFRC \( B \) before its ultimate flexural strength is calculable using equation (18).

In addition, moment of elastic resistance \( W_0 \) is usually used to represent the capability of flexural resistance of the section, which can be expressed as:

\[
W_0 = I_0/(h - y_0)
\]  

where, \( W_0 \) is the moment of elastic resistance of aspect section area \( A_0 \) to the edge of tensile section. The ultimate flexural stress \( \sigma \) of SFRC can be calculated accordingly:

\[
\sigma = M_{cr}/W_0
\]
\[ M_{cr} = \frac{PL}{6} \]  

(28)

where, \( M_{cr} \) is the bending moment.

The calculated results are shown in Table 5-5. As the modulus of elasticity of steel fiber is higher than concrete, from equation (20), a layer with higher steel fiber distribution rate will have a higher modulus of elasticity. With the increase of flowability, steel fibers tended to distribute in lower layers of specimens, resulting in the modulus of elasticity of lower layers being higher than those of upper layers. Theoretically, SFRC with higher flowability should have better bending stiffness. However, as the flowability of 80mm and 120 mm slump SFRC in this experiment was not able to allow steel fibers to freely flow and precipitate in fresh concrete, the layering effect of steel fibers was not obvious. Comparing the bending stiffness, there is little difference among each group, which is the reason why the slope of the load-deflection curve before maximum flexural load appears similar. On the other hand, the neutral axis tends to move towards tensile section with an increase of flowability, leading to an increase in the moment of elastic resistance. From equation (27) and (28), when subjected to the same load, higher flowability SFRC will have a higher moment of elastic resistance and a less flexural stress. Both the tensile stress of the steel fibers and the bond stress among the steel fibers and cement will be less than those of lower flowability SFRC. Elongation and expansion of cracks could be well controlled, which will result in better ductility and post-crack flexural performance. In addition, there are differences in the calculated results of flexural properties whether considering the effects of steel fibers distribution patterns or not. The influence of steel fibers on the flexural properties of higher flowability SFRC should not be ignored and require further research.
Table 5-5 Data of Flexural Resistance of SFRC

<table>
<thead>
<tr>
<th>Slump (mm)</th>
<th>$I_0$ (mm$^4$)</th>
<th>$B$ (N.mm$^2$)</th>
<th>$W_0$ (mm$^3$)</th>
<th>$\sigma$ (MPa)</th>
<th>$f_{hm}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>4.374E+07</td>
<td>1.422E+12</td>
<td>5.824E+05</td>
<td>3.128</td>
<td>3.239</td>
</tr>
<tr>
<td>120</td>
<td>4.368E+07</td>
<td>1.420E+12</td>
<td>5.827E+05</td>
<td>2.927</td>
<td>3.032</td>
</tr>
<tr>
<td>160</td>
<td>4.356E+07</td>
<td>1.416E+12</td>
<td>5.832E+05</td>
<td>3.028</td>
<td>3.140</td>
</tr>
<tr>
<td>200</td>
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<td>1.420E+12</td>
<td>5.872E+05</td>
<td>2.986</td>
<td>3.117</td>
</tr>
<tr>
<td>Reference*</td>
<td>4.219E+07</td>
<td>1.371E+12</td>
<td>5.625E+05</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Note: * represent the calculated results without considering effects of steel fiber on SFRC properties.

### 5.4.3 Change in Moment of Inertia ($I_0$)

This is another way to determine the altered moment of inertial. Only in this way, the modulus of elasticity is considered unchanged.

\[
\alpha_e = \frac{E_s}{E_c} \quad (29)
\]

\[
A_0 = bh + (\alpha_e - 1)(A_1 + A_2 + A_3 + A_4) \quad (30)
\]

\[
y_0 = \left(\frac{bh^2}{2} + \frac{(\alpha_e-1)A_1h}{8} + \frac{3(\alpha_e-1)A_2h}{8} + \frac{5(\alpha_e-1)A_3h}{8} + \frac{7(\alpha_e-1)A_4h}{8}\right)/A_0 \quad (31)
\]

\[
I_0 = \frac{by_0^3}{3} + \frac{b(h-y_0)^3}{3} + (\alpha_e - 1)A_1\left(\frac{h}{8} - y_0\right)^2 + (\alpha_e - 1)A_2\left(\frac{3h}{8} - y_0\right)^2 \\
+ (\alpha_e - 1)A_3\left(\frac{5h}{8} - y_0\right)^2 + (\alpha_e - 1)A_4\left(\frac{7h}{8} - y_0\right)^2 \quad (32)
\]

where,

\[\alpha_e \quad \text{the ratio of the modulus of elasticity of steel fiber to the modulus of elasticity of concrete.}\]
5.5 Post-peak-load Performance

When the bottom layer steel fibers could no longer provide enough flexural resistance, specimens reached their ultimate flexural strength. Cracks elongated and expanded deeper and wider in the beam, and steel fibers in subsequent layers successively jointed in flexural resistance. Flexural strength of SFRC decreased with the decrease of effective depth of crack section. As shown in Fig. 5-6, steel fibers are dispersed more uniformly and closely in the lower layers of higher flowability specimens. When one layer of steel fibers was not able to provide enough resistance to the load the next layer of steel fibers could participate immediately, which prevented the rapid development of cracks and produced a much smoother and flatter load-deflection curve. In lower flowability specimens, steel fibers were scattered throughout the whole section with larger spaces between each layer, which led to discontinuous fiber-flexural-resistance and a sudden drop of load after the deflection reached 1 mm. $R_{e,k}$ values of 80 mm slump SFRC decrease much more rapidly than that of higher flowability SFRC.

(a) Simulation of crack elongation and expansion
5.6 Conclusion

The mechanisms of traditional splitting tensile, compressive and flexural strength tests does not consider steel fibers flowing and layering phenomenon of high flowability SFRC. These methods are deemed not suitable for measuring strength of high flowability SFRC. Moreover, to meet the steel fiber layering effect of high flowability SFRC, all tests should be loaded on the cast surface of specimens. Suitable test methods should be investigated in order to properly measure mechanical properties of SFRC.

Both ASTM C1018 and JG/T472-2015 methods were used in this study to assess flexural toughness of SFRC. Due to the difficulty of determining first crack deflection, ASTM C1018 indices are considered less suitable for reflecting flexural performance of SFRC. While analysing with the JG/T472-2015 method, even though the ultimate splitting and flexural strengths of each flowability SFRC was about the same, SFRC with higher flowability showed much better flexural performance and load-keeping capability. These advantages are attributed to the layering effect of transverse section steel fibers as it enhances the crack-bridging capability of the tensile section when
loading is in displacement control. Steel fibers in lower layers efficiently controlled the elongation and expansion process of cracks and prevented a sudden drop of load.

As the steel fibers in higher flowability SFRC tended to sink towards the lower layer of specimen, the moment of initial and modulus of elasticity of high flowability SFRC were different with that of lower flowability SFRC. Calculations of moment of inertia and flexural stress of flowable SFRC should consider the influence of steel fiber layering. The tendency of bending stiffness and moment of elastic resistance increasing with flowability should be more obvious in higher flowability SFRC.
CHAPTER 6 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The following conclusion can be drawn from the research study:

(1) Flowability has an influence on the layering effect of the steel fibers orientated along longitudinal and transverse direction. Steel fibers orientated along longitudinal and transverse direction of 80 mm and 120 mm slump SFRC do not precipitate as those of 160 mm and 200 mm slump SFRC. The steel fibers in 120 mm slump SFRC show better homogenous distribution and steel fibers in 200 mm slump SFRC sink towards the bottom of the specimens. The distribution coefficient of steel fibers in each section of 120 mm slump SFRC is the highest in all trials where that of 200 mm slump SFRC was the lowest. However, the coefficient of the bottom layer of the transverse section of 200 mm slump SFRC is 0.76, which indicated good uniformity in the tensile zone.

(2) Flowability does not affect the orientation of steel fibers. Aggregate size is hypothesized as the main factor influencing the orientation of steel fibers, as large coarse aggregate restricts orientation and dispersion of fibers.

(3) The traditional splitting tensile and compressive strength tests are conducted on small cubic specimen, whose mechanisms does not consider steel fibers flowing and layering phenomenon of high flowability SFRC. As distribution patterns of steel fibers clearly had influence on strength of SFRC, results of traditional tests methods do not reflect real situation of strength of high flowability SFRC. Similarly, as traditional flexural strength test is conducted on small beam, whose boundaries limit
steel fibers to flow along transverse direction. It is deemed not suitable for measuring flexural strength of slab-like members. Moreover, to meet the steel fiber layering effect of high flowability SFRC, all tests should be loaded on the cast surface of specimens. Suitable test methods should be investigated in order to properly measure mechanical properties of SFRC.

(4) Both ASTM C1018 and JG/T472-2015 methods were used in this study to assess flexural toughness of SFRC. Due to the difficulty of determining first crack deflection, ASTM C1018 indices are considered less suitable for reflecting flexural performance of SFRC. While analysing with the JG/T472-2015 method, even though the ultimate splitting and flexural strengths of each flowability SFRC was about the same, SFRC with higher flowability showed much better flexural performance and load-keeping capability, especially after the peak-load. When the slump increased from 80 mm to 200 mm, flexural toughness increased up 48%. With the increase of deflection, flexural toughness of 80 mm slump specimen decreased up to 77%, where flexural toughness of 200 mm slump specimen decreased only 24%. Moreover, when the deflection of specimens reached 3 mm, the fracture energy of 200 mm slump SFRC was 41% higher than 80 mm slump SFRC. These advantages are attributed to the layering effect of transverse section steel fibers as it enhances the crack-bridging capability of the tensile section when loading is in displacement control. Steel fibers in lower layers efficiently controlled the elongation and expansion process of cracks and prevented a sudden drop of load. When the volume fraction of steel fibers remains unchanged, increasing the flowability can be a way to improve flexural performance of SFRC.

(5) As the steel fibers in higher flowability SFRC tended to sink towards the lower layer of specimen, the moment of initial and modulus of elasticity of high flowability SFRC were different with that of lower flowability SFRC. Calculations of moment of inertia and flexural stress of flowable SFRC should consider the influence of steel fiber layering. The tendency of bending stiffness and moment of elastic
resistance increasing with flowability should be more obvious in higher flowability SFRC.

6.2 Recommendations for Future Studies

From the conclusion of the research, it can be seen that it is necessary to future study the influence of flowability on the performance of flowable SFRC.

(1) Current test methods for determining mechanical properties of SFRC are recognized as partially unsuitable. The development of new test method is required to accurately determine the performance of SFRC.

(2) Vibration time can have a large impact on the distribution of the steel fibers, especially when the slump of SFRC is above 160 mm. Over-vibration will lead the steel fibers to sink towards the bottom of specimens. Control of the vibration time could be a key to control the distribution of the steel fibers.

(3) Although formulas for calculating mechanical performance of SFRC are proposed in this research, there is not sufficient data to justify whether these formulas can be used for all situation. Experiment should be carried out to provide data for verifying the formulas.

(4) It is quite clear that the change in flowability will influence significantly on the mechanical properties of SFRC. However, with the data gathered from this research, it is not possible to propose a formula which is able to calculate mechanical properties directly using flowability. Further research is required to determine if such a relationship can be determined.
REFERENCE


