Effect of steel fiber volume fraction to the tensile splitting strength of concrete cylinder

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Abstract. Concrete is strong in compression but weak in tension. To improve the concrete strength and ductility under tension, embedded micro-cement reinforcement such as steel fiber can be used. In this paper, the effect of the volume fraction ratio to the tensile strength of concrete is investigated. The steel fiber volume fraction considered are 0%, 0.5%, 1%, 1.5%, and 2.0%. From the test result, a linear increased in concrete tensile strength as function of the steel fiber volume fraction was observed. The amount of the steel fiber volume fraction also affects the concrete workability. The fiber orientation in the concrete was also observed to capture its effect on tensile strength from the splitting cylinder test.

1. Introduction

The utilization of steel fiber in concrete can improve concrete mechanical properties, such as tensile strength, compressive strength, ductility, and toughness [1-4]. When a crack occurs in steel fiber reinforced concrete (SFRC), the tensile stress between cracks is transferred and resisted by steel fibers. At this stage, the steel fibers assign the tensile load at the crack location along its embedded length inside the concrete. This tensile load is transferred from fiber to concrete through shear stress that works on the steel fiber perimeter embedded in the concrete. The steel fiber reinforced concrete (SRFC) behavior can be affected by the properties of steel fiber, fiber orientation within the matrix, aspect ratio (length \(l/diameter\)), and the fraction volume [5-8].

Concrete mix design plays an important role when preparing steel fiber reinforced concrete. The correct proportion from different materials must be well-designed. The physical and mechanical properties of composites depend on the volumetric fraction of the steel fiber, the steel fiber itself, and the concrete matrix. After steel fibers are fully bonded with the concrete, the behavior of the final composite changes, particularly during the cracking phase. With the additional steel fiber, the tensile strength and ductility of the concrete can be improved. With the well-design concrete mix proportion, a good quality of SFRC concrete can be achieved [9-12].

In this paper, one complete series of tensile splitting tests of SFRC concrete cylinder is reported. The tensile splitting test is preferred over the uniaxial direct tensile test due to the size of the steel fiber in which may not fit the formwork. The volumetric fraction of the steel fiber considered is 0%, 0.5%, 1%, 1.5%, and 2.0%. The Steel fiber trademark is Dramix with hooked ends was used in this study. In the discussions, the effect of the volumetric fiber content on the concrete slump, the fiber orientation factor, and the concrete tensile strength are presented in detail.


2. Concrete mix design

Ordinary Portland Cement (OPC) used in this study was produced by PT Semen Indonesia (Persero) Tbk. The OPC is considered as Type I cement and is comply with SNI 15-7064-2004 [13]. Coarse aggregate is with compliance to SNI 1969-2008 [14]. The coarse aggregate is from PT. WiKa Beton (Persero) Tbk. and has nominal size of 10 mm. The fine aggregate which consisted of Lumajang sand is prepared and fall into the Zone 2 category according to SNI 2834:2000. The water cement ratio is set to 0.52 to ensure the workability of the fresh concrete is sufficiently high.

The mix design is prepared using the DOE method. The steel fibers are additional material and therefore share the same portion with the coarse aggregates. The concrete strength is designed to have 30 MPa strength. The factors that influence the mechanical behavior of SRFC, such as volumetric fraction, water ratio, and aggregate quality, are considered during the mix design process. The concrete was poured into a cylinder steel formwork with 100 mm diameter and 200 mm height.

| Material                  | Specimens       |
|---------------------------|-----------------|
|                           | S1-0%           |
|                           | S1-0.5%         |
|                           | S1-1.0%         |
|                           | S1-1.5%         |
|                           | S1-2.0%         |
| OPC (kg/m$^3$)            | 619             |
| Coarse Aggregate (kg/m$^3$) | 1128           |
| Gravel Sand (kg/m$^3$)    | 923.5           |
| Water (ltr/m$^3$)         | 288             |
| Fiber Steel (gr)          | 194             |
| Slump (cm)                | 10 ± 2          |

$V_f$: Volumetric fraction; OPC: Ordinary Portland Cement

The steel fiber used in this research is Dramix steel fiber which was produced through a cold drawn process with a curve at the end that will provide optimal binding. Steel fiber with the type of Dramix 65/60 BG was used. These fibers have a length of 60 mm and a diameter of 0.9 mm, with an aspect ratio of $l/d_f = 60$. They are bonded together into a bundle of 30 fibers with water-soluble glue to perform better in fresh concrete. Thus, increasing the workability of the mixture and can reduce the initial tensile strength in concrete. The main characteristics of steel fiber are presented in Table 2.

| Geometry and Properties | Values         |
|-------------------------|----------------|
| Diameter (mm)           | 0.9            |
| Length (mm)             | 60             |
| Aspect Ratio ($l/d_f$)   | 65             |
| Young’s Modulus (N/mm$^2$) | 200000       |
| Tensile Strength (N/mm$^2$) | 1600          |

3. Experimental program

Five concrete cylinders were prepared for the test. The experimental test was performed at Laboratory of Concrete, Advanced Material and Computational Mechanics, Civil Engineering Department, Institut Teknologi Sepuluh Nopember. Slump test, fiber orientation test and splitting test were conducted to observe the workability and performance of SRFC.

3.1. Slump test

The purpose of this test is to determine the concrete workability. The slump test is carried out using Abrams Cone. The Abrams Cone had a base diameter of 200 mm, a width of 100 mm, and a height of 300 mm. A rod compacter with a diameter of 160 mm and a length of 600 mm was used to compact the concrete. The cones are placed on a flat and wet surface. To prepare the concrete for slump test, there are three stages involved. In each of these stages, the layer is compacted 25 times by rod compactor. At
the end of the third stage, leveling the concrete surface with rod and all fresh concrete that falls around the molds should be cleaned. The mold is lifted slowly and upright. Concrete then declined. The cone is then placed in an upside-down position next to the test specimen as a reference height to measure the concrete slump. The slump was measured using a ruler from the top of the slumped concrete to the height of the Abrams Cone. This test is carried out within 2.5 minutes.

3.2. Fiber orientation
Fiber orientation is often used to estimate the fiber volumetric fraction in the specimen. The method works by manually counting the number of fibers that crosses the failure plane after the tensile splitting test was performed [15]. The number of fibers is the total amount of withdrawal fibers that appear on both sides. The orientation factor is estimated using the equation below [16].

\[
\alpha = \frac{N}{N_{th}}
\]  

where \(\alpha\) is the fiber orientation, \(N\) is the ratio number of fibers counted, and \(N_{th}\) is the cross section and theoretical number. Among all methods available (image analysis, non-destructive testing) to check the fiber orientation, this method was found to be the simplest [17-20].

3.3. Splitting test
After curing for 28 days, the splitting test was conducted for each cylinder to investigate the tensile strength of SFRC. Figure 1 shows the splitting tensile test procedure based on [21]. Two parallel steel plates are used to uniformly distribute the stress at the top and bottom sides of the concrete cylinder. The load-bearing strip should not be very narrow to avoid stress concentration at the concrete surface. The tensile strength of concrete \(f_{st}\) can be determined by:

\[
f_{st} = \frac{2P}{\pi LD}
\]  

where \(P\) is the applied compressive load to split a concrete cylinder, \(L\) is the length of the specimen and \(D\) is the diameter of the specimen. Universal Testing Machine (UTM) is used to apply the compressive loads \((P)\) at rates of 0.5/mm²/sec.

![Figure 1. Splitting test (a) geometry test; (b) experimental equipment](image)

4. Results and discussion
In this part, the test result from five specimens are presented. The discussion is focused on the effect of steel fiber volumetric ratio to the concrete slump test, the fiber orientation, and the concrete tensile strength. The specimen with notation S1-0.0% is the control specimen without steel fiber.
4.1. Slump test

The value of concrete slump was designed for 100 ± 20 mm. The slump of the concrete is measured from the top of the slumped concrete to the top level of the Abrams Cone (see Figure 3). From the measurement it was found out that as the steel fiber volumetric fraction increases, the concrete slump value is decreases. This shows that the presence of the steel fiber reduces the workability of concrete. It should be noted that in this experimental program, no admixture was used in the mixture proportion.

Table 3. Slump Test.

| Specimen | $V_f$ (%) | Slump Test (cm) |
|----------|-----------|-----------------|
| S1 – 0.0 % | 0.0 | 12 |
| S1 – 0.5 % | 0.5 | 10 |
| S1 – 1.0 % | 1.0 | 10 |
| S1 – 1.5 % | 1.5 | 9 |
| S1 – 2.0 % | 2.0 | 8 |

Figure 2. Slump test of SFRC concrete as function of $V_f$

Figure 3. Slump measurement
4.2. Fiber orientation

Like conventional reinforcement, fibers are most efficient when aligned parallel to the direction of tensile stress, and least efficient when they are perpendicular to the direction of tensile stress [22]. Table 4 shows the fiber orientation value for all of the specimens performed using manual counting of the fibers that cross the failure plane. Figure 4 shows the fiber orientation as the function of the volumetric fraction of the steel fibers. Figure 5 shows the cross-section of the fiber failure plane that used to manually counted the number of steel fiber that cross the failure plane. Some researcher noted that the fiber orientation was dependent on the concrete workability [23, 24]

| Specimen | Volumetric fraction | Fiber Orientation (α) |
|----------|---------------------|-----------------------|
| S1 – 0.0 % | 0.0 %           | -                     |
| S1 – 0.5 % | 0.5 %          | 0.486                 |
| S1 – 1.0 % | 1.0 %          | 0.864                 |
| S1 – 1.5 % | 1.5 %          | 1.440                 |
| S1 – 2.0 % | 2.0 %          | 1.960                 |

Figure 4. Fiber orientation of the specimen as function $V_f$

Figure 5. Cross-section of the concrete after tensile splitting test
4.3. Concrete tensile splitting test

Table 5 show the result of the concrete tensile splitting strength. As shown in Table 5, as the fiber volumetric fraction increases, the concrete tensile splitting strength also increases. Figure 6 shows the graph of the concrete tensile splitting strength as functions of the fiber volumetric fraction. As shown in Figure 6, linear increase in the concrete tensile splitting strength was observed from the test result. Figure 6 also shows the linear regression line for forecasting purposes. Despite of significant increase of concrete tensile strength due to the steel fiber, the improvement of the concrete compressive strength was found to be less significant [25-27].

| Specimen | Volumetric Fraction ($V_f$) | Tensile strength ($f_{st}$) |
|----------|-----------------------------|-----------------------------|
| S1 – 0.0 % | 0.0 % | 2.93 |
| S1 – 0.5 % | 0.5 % | 4.13 |
| S1 – 1.0 % | 1.0 % | 5.75 |
| S1 – 1.5 % | 1.5 % | 6.34 |
| S1 – 2.0 % | 2.0 % | 7.68 |

Figure 6. Concrete tensile splitting strength as function of $V_f$

5. Conclusions

This paper presents experimental test of concrete cylinder to evaluates the workability, fiber orientation and the concrete tensile splitting strength of the SFRC. From the experimental test, it was found out that the additional steel fiber affects the workability of concrete. The slump test value of SFRC concrete was found to be lower than normal concrete without the steel fiber. As the steel fiber content increases, the slumps decreases. In this experimental program, there are no admixture used in the mix proportion. From the investigation of the fiber orientation that measured at the cross-section of the failure plane showed that the result agrees well with the fiber volumetric fraction of the tested specimen. From the tensile splitting test of concrete, it was found out that the concrete tensile splitting strength is function of the volumetric fraction of the steel fiber and it shows a linear relation ship. Hence, linear regression analysis should be sufficient for forecasting purposes.

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