Flexural performance of HPFRC plates using PPC and variation of steel fiber composition

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Abstract. High-Performance Fiber-Reinforced Concrete (HPFRC) is widely used in infrastructure applications due to its mechanical properties such as fracture toughness, ductility, control of crack width, and plate thickness reduction compared to normal concrete. However, there are still doubts about the strategy to develop the concrete technology to meet the sustainability requirements in the construction process. This study aims to investigate the improvement of flexural performance on HPFRC plates that utilize Portland Pozzolana Cement (PPC) with various compositions of steel fiber. This research uses PPC, Lumajang sand, gravel from the Malang area, water, silica fume, superplasticizer, and steel fiber. Tests were performed on 1600 mm x 900 mm x 80 mm HPFRC plates. The average HPFRC compressive strength is 59.59 MPa. The splitting tensile strength is 3.54 MPa. Steel fibers vary from 0.2% to 1.0% of the HPFRC plate volume. The test was performed with the three-point bending method. Observations were made to the load capacity, deflection and the crack pattern of the HPFRC plates. The study shows that the optimum bending strength failure of the HPFRC plate is obtained when the steel fiber composition is about 0.8% with an external load value of 31.76 kN and a deflection of 14.99 mm.

1 Introduction

High-Performance Fiber-Reinforced Concrete (HPFRC) is widely used in infrastructure applications due to its mechanical properties. Fracture toughness, ductility, durability, control of crack width, plate thickness reduction and increased permissible connection spacing compared to normal concrete are the advantages of the mechanical properties of HPFRC.

Many factors have been shown to influence the flexural tensile strength of the HPFRC element, particularly the level of stress, size, age and confinement to concrete flexure member [1]. The bond between concrete and steel reinforcement embedded in the HPFRC plate has a function to transfer of force between reinforcement and concrete. Bond affects the structures at the crack width and deflection serviceability and at a limit state of rotation capacity of the plastic hinge regions. The bond between the steel and HPFRC material consists of three mechanisms: adhesion, friction and mechanical interlocking [2]. In high strength concrete,

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the resulting failure pattern is more brittle, having a longer linear behavior range, but its post-peak region is smaller and the stresses drop faster (snap back) [3]. Post-cracking or residual tensile strength of a structural element design manufactured with HPFRC material is a very important property [4].

However, in order to meet the sustainability requirements of HPFRC material technology in the construction process, there is still the need to determine the right strategy to develop this kind of concrete technology. This study aims to investigate the improvement of flexural performance on HPFRC plates that utilize Portland Pozzolana Cement (PPC) with various compositions of steel fibers.

2 Literature review

A one-way HPFRC plate with a line load at the center of the span, as shown in Fig. 1, will bend in the perpendicular direction to its longitudinal axis. The external load acting as the lateral load will be converted as the internal moment causing the tensile force at the lower side of the plate and the compressive force on the upper side of the plate. The maximum moment in the member due to service loads M_a (N-mm) at stage deflection is calculated by the equation:

$$M_a = \frac{1}{4} P \cdot l - \frac{1}{8} q l^2 \quad (1)$$

where P is a centralized line load and a uniform load q due to its own weight of the HPFRC plate and l is the span length of the HPFRC plate.

Fig. 1. The external line load acting on the one-way HPFRC plate.

The HPFRC plate element as shown in Fig. 2 is assumed to be a rectangular cross-section of size $b \times h$, where d_s is the thickness of the concrete cover as the steel reinforcement lid. The moment of inertia of the HPFRC plate section about a centroidal axis (I_g) is calculated according to the cross-sectional condition of the HPFRC plate before cracking, using the equation:

$$I_g = \frac{1}{12} b h^3 \quad (2)$$

Fig. 2. The HPFRC plate element and variation of stress and strain across the plate depth [5].

As the tensile strength of the concrete has reached its maximum, cracks will occur on the lower side of the plate. If the concrete matrix has cracked, the fibers transmit stress across the crack and, in the process, provide some resistance to the widening of the crack. The cracking moment M_{cr} can be calculated by the equation [6, 7]:

$$M_{cr} = \frac{f_r I_g}{y_t} \quad (3)$$

where y_t is the distance from the neutral line of the cross-section to the bottom fiber of the concrete cross section. f_r is commonly known as crack stress.

The next tensile force will be restrained by the steel reinforcement through the distributed system in the form of an adhesive or bond with an HPFRC matrix. At the same time, the HPFRC plate will also be deflected due to the working load. In the design of plates that bend under the lateral loading, the deflections are small compared to the thickness [8]. As the crack widens, provided that the tensile strength of the fibers is not exceeded, the fibers will gradually pull out of the matrix. Some residual strength after cracking will be available in the HPFRC specimen. This resultant increases the work of the fracture and this is referred to as toughness or fracture energy [4]. The effective moment of inertia, I_e , was developed to provide a transition between the upper and lower bounds of I_g and I_{cr} as a function of the ratio M_{cr}/M_a . For a prismatic one-way plate, I_e shall be permitted to be taken as the value obtained at the midspan of the simple spans. The effective moment of inertia I_e is calculated by the equation [7]:

$$I_e = \left(\frac{M_{cr}}{M_a} \right)^3 I_g + \left[1 - \left(\frac{M_{cr}}{M_a} \right)^3 \right] I_{cr} \quad (4)$$

According to Fig. 2, the distance y is determined using the upper concrete strain ϵ_c and the steel reinforcement strain ϵ_s and calculated by the equation:

$$y = \frac{\epsilon_c}{\epsilon_c + \epsilon_s} d \quad (5)$$

The propagation of the crack will occur after the crack is formed at the interface due to the slip between steel and concrete. The crack propagates in an unstable manner and leads to longitudinal splitting cracks [9]. The addition of fiber is expected to reduce the brittleness of high-strength concrete, increase the fracture toughness and enhance the fracture energy of high-strength concrete, with the result that it becomes more ductile, that the impact resistance and shrinkage resistance is improved, and that the flexural strength of the plate is increased. Ductility is the ability of the structure to deliver the post-yield deformation before the collapse [3]. The crack depth that occurs on the HPFRC plate due to the external load is given a notation of letter a . The crack depth is zero when the concrete has not cracked. At the time of the fracture of the I mode edge through the thickness of the HPFRC plate element, the

working moment will be referred to as the M_F fracture moment as the concept developed by Carpinteri [5]. After the crack occurs, the form of stress on the compression concrete will change shape as in Fig. 2. The moment that occurs will be restrained by the eccentric force F_s acting on the reinforcing steel with the broadness of A_s , the concrete tensile strength expressed as T_1 and T_2 and by the compressive strength of the concrete cross-section C .

3 Materials and methods

This research uses Portland Pozzolana Cement (PPC) according to SNI 0302:2014 [10], gravel from the Malang area; Lumajang sand; water; silica fume containing extremely fine latently reactive silicic dioxide conforming to BS EN 13263-1:2005 with a total chloride ion content of < 0.3 M-% and a density of ~0.65 kg/L; steel fiber with type Dramix® 3D, l/d aspect ratio 80, length 60 mm; Bright Glued and superplasticizer Polycarboxylate Sika® ViscoCrete®-7150 according to BS EN 934-6:2001 [11]. The mix design of the HPFRC uses the absolute volume method [12]. The physical and mechanical properties of the aggregate in this research are shown in Table 1 [13].

Table 1. Physical and mechanical properties of aggregate.

Properties of Lumajang sand	Unit	Value
Fineness modulus	-`	2.67
Humidity	%	2.80
Water absorption	%	0.30
Specific gravity	-	2.70
Finer material less than a 75-µm	%	0.00
Properties of gravel from Malang area	Unit	Value
Fineness modulus	-	7.05
Humidity	%	1.19
Water absorption	%	1.95
Specific gravity	-	2.69
Los Angeles abrasion value	%	18.65

This study was conducted using 4 specimens of HPFRC plates with a span length of 1600 mm, a width of 900 mm and a thickness of 80 mm. Along with the HPFRC plate casting, 3-cylinder specimens of 15 cm x 30 cm for a concrete compressive test as shown in Fig. 3b, and 2-cylinder specimens of 15cm x 30 cm for a splitting tensile test, were also prepared. The steel fiber Dramix @ 3D 80/60 BG is used varyingly from 0.2% to 1.0% from the HPFRC plates’ volume.

Fig. 3. Material testing equipment. a) Material Testing System (MTS), b) Universal Testing Machine (UTM).

The HPFRC plates bending test is carried out using a center-point loading method [14] or three-point bending method [15] of the flexural strength test standard of concrete using a simple HPFRC plate. The distribution of load on the plate width uses the IPE-100 profile. Measurement equipment used was a 20-ton load cell to measure the external load, a strain gauge and strainmeter for measuring strain on upper side concrete and lower the steel reinforcement, and a LVDT for measuring the deflection on the HPFRC plate. The load capacity of the HPFRC plates, deflection, and the cracking pattern are the objects observed. The test set can be seen in Fig. 4.

Fig. 4. The setting of flexural HPFRC plate experiment.

4 Result and discussion

The mechanical property of the HPFRC material in this study is shown in Figs. 5 and 6 with a steel fiber content of 0.2%, 0.6%, 0.8% and 1.0%, respectively. The unit weight of the HPFRC material is 24.93 kN/m³. From the diagram, the addition of 0.8% of the fiber composition achieves the optimal value on the splitting tensile test results of about 4.09 MPa. The compressive strength of the HPFRC plate shows an increase with ranges from 54.35 MPa to 67.67 MPa, and the average of the compressive strength is 59.59 MPa.

Fig. 5. Compressive strength of HPFRC plates with variation of steel fiber content.

Fig. 6. Splitting tensile strength of HPFRC plates with variation of steel fiber content.

Fig. 7 shows that the flexural load capacity that can be resisted tends to increase according to the steel fiber composition in the HPFRC plate. The flexural load capacity that can be resisted by the HPFRC plates when the first crack happens ranges from 10.24 MPa to 17.89 MPa. While the flexural load capacity that occurs at the time of the HPFRC plate failure ranges from 27.77 MPa to 31.76 MPa. Increased crack loads are seen from the HPFRC 1 plate to the HPFRC 3 plate. However, the crack load value in the HPFRC 4 plate is the same as an HPFRC 3 plate. This is consistent with the results of the splitting tensile test that indicates that the optimal splitting tensile strength occurs in the composition of 0.8% of the steel fiber. In Fig. 8, the deflection tends to decrease as the proportion of steel fiber increases. The deflection occurs when the first crack of the HPFRC concrete matrix is between 1.37 mm to 2.35 mm. While the deflection occurs when the HPFRC concrete plate failure is between 14.99 mm to 19.75 mm. The test results show that the smallest deflection at the time of the HPFRC plate collapse occurred in the composition of 0.8% steel fiber. This is in accordance with the behavior of HPFRC material based on the results of the splitting tensile test in Fig. 6.

Fig. 7. Load capacity of HPFRC plates at the 1st crack and at the collapse crack.

Fig. 8. Deflection of HPFRC plates at the 1st crack and at the collapse crack.

The external load and the deflection correlation which occur in HPFRC plates are shown in Fig. 9. It appears that before the first crack occurs due to the internal tensile stress exceeding the tensile stress capability of the HPFRC matrix, the plate will be deflected linearly in an elastic state. After the crack, the plate will have non-linear deflection, with the addition of a much larger deflection, until the load will not increase anymore when the HPFRC plate collapses. After the load is reduced the deflection will decrease, but will not return to zero.

Fig. 9. Load-deflection correlation of HPFRC plate with a variety of steel fiber content.

The correlation between stress and strain on each plate is shown in Fig. 10. Prior to the crack, the addition of external loads caused the stress-strain relationship on each plate to behave linearly. At the first crack, there is a considerable change in the tensile strain on the reinforcing steel on the lower side of the HPFRC plate, so that the diagram shows a horizontal line. Next, the strain will behave non-linearly with a larger increment until the collapse of the HPFRC plate occurs. The collapse of the plate is marked by no increase of the external load value acting on the HPFRC plate.

Fig. 10 Tensile Stress-Strain correlation of HPFRC plate with a variety of steel fiber content.

Crack patterns that occur in the flexural test are shown in Fig. 11. The crack is uniformly distributed on the lower side of the HPFRC plate between the plates’ support. The crack distribution indicates that the HPFRC concrete matrix and the reinforcing steel have a good bond during loading after the first crack. When the flexural loads increase, it will increase the HPFRC plate tensile stress on the lower side of the HPFRC plate. When the HPFRC matrix tensile strength is surpassed, new cracks are formed on the lower side of the HPFRC plate, and then the tensile strength will be distributed to the reinforcing steel. This happens repeatedly so that the distribution of cracks occurs.

Fig. 11. HPFRC plates crack pattern.

5 Conclusion

The test results show that the composition of steel fiber is very influential to the improvement of the flexural strength at the 1st crack and when the HPFRC plate collapses. The optimum bending strength of the HPFRC plate when the collapse occurs is obtained when the steel fiber composition is about 0.8% with an external load value of 31.76 kN and a deflection of 14.99 mm. The cracking pattern occurring on the lower side of the HPFRC plate showing the uniform distribution of cracks between the plate supports proves that the use of steel fiber can provide a good bond distribution between the HPFRC matrix and the reinforcing steel.

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