Flexural behavior of T-beams made of high-volume fly ash self-compacting concrete, strengthened with carbon fiber reinforced polymer (CFRP)

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Abstract. This study utilized fly ash, a hazardous B3 waste from coal combustion, as a replacement for a large portion of cement in Self-Compacting Concrete (SCC) to reduce CO_2 emissions and environmental problems. The concrete used in this study was High Volume Fly Ash – Self-Compacting Concrete (HVFA-SCC) which the fly ash proportion was 50 %. The HVFA-SCC beam specimen had a T-beam cross section with the web size of 120 mm × 240 mm and the flange size of 80 mm thickness and 440 mm width. There were three types of beam specimens. The first type without CFRP strengthening, the second type was strengthened with one layer of 100 mm width of CFRP, while the third type was strengthened with 50 mm width of CFRP. The beams were tested under monotonic two-points loading. The results show that the HVFA-SCC T-beams with CFRP had smaller deflection compared to the HVFA-SCC T-beams without CFRP. These phenomenon indicated that CFRP increased the HVFA-SCC T-beam ductility and provided better deformation control.

1 Introduction

Increasing carbon dioxide emissions from the construction sector, particularly from the Portland cement industry, are a major contributor to global warming and have driven the development of more environmentally friendly, low-carbon concrete materials. One widthly studied innovation is High Volume Fly Ash Self-Compacting Concrete (HVFA-SCC), a self-compacting concrete in which a high proportion of cement is replaced with fly ash to reduce the carbon footprint while simultaneously utilizing coal combustion waste classified as B3 [1].

Fly ash is mainly composed of silica and alumina, which react with calcium hydroxide produced during cement hydration to form compounds that contribute to strength development, so at a cement replacement level of about 50 percent, concrete with adequate compressive strength can still be achieved. HVFA-SCC also offers advantages such as high flowability and self-compaction without vibration, good homogeneity, and the potential to

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increase construction efficiency and reduce noise on site. However, several studies have shown that high-volume fly ash can reduce load-carrying capacity and increase deflection compared with normal concrete, so appropriate structural strengthening strategies are required [1].

Fly ash is a residue from coal combustion. The chemical elements of fly ash are silica (SiO2), alumina (Al2O3), ferrous oxide (Fe2O3) and calcium oxide (CaO), and contains other elements, namely magnesium oxide (MgO), titanium oxide (TiO2), alkaline (Na2O and K2O), sulfur trioxide (SO3), phosphorus oxide (P2O5) and carbon (C) [2].

Self-compacting concrete (SCC) is concrete that can flow under its own weight. SCC has a very high flow rate and a homogenous mix that prevents bleeding or segregation. Self-compacting concrete (SCC) offers benefits such as reduced construction time and labor costs, vibration reduction, noise reduction, high compressive strength, and a dense structure. [3]

On the other hand, the use of Fiber Reinforced Polymer (FRP) composites, particularly Carbon Fiber Reinforced Polymer (CFRP), has been proven effective for repairing and strengthening reinforced concrete elements in terms of flexural, shear, and ductility capacity, with advantages including light weight, good corrosion resistance, and ease of application [4]. Previous studies on HVFA-SCC concrete beams strengthened with CFRP have generally been carried out on rectangular sections [5,6]. Meanwhile, studies using T-sections for HVFA-SCC concrete are still limited. On the other hand, T section beams are commonly used in various structures, such as bridges and toll roads, because they have more efficient cross-sectional dimensions, which results in higher flexural stiffness due to greater moment of inertia than rectangular beams. Additionaly, in building practice, floor beams more often behave as T-beams due to their monolithic connection with the slab. To date, studies on the flexural behavior of HVFA-SCC T-beams strengthened with CFRP remain limited, so further research is needed to specifically investigate the flexural response of such systems.

This study aims to investigate the flexural behavior of High Volume Fly Ash Self-Compacting Concrete (HVFA-SCC) T-beams strengthened with SIKA Carbodur CFRP laminates and to compare to the HVFA-SCC T-beams without CFRP. Experimental tests are conducted on T-beams with CFRP laminate widths of 50 mm and 100 mm under two-point loading to evaluate flexural capacity, deflection, concrete strain, and reinforcing-steel strain. The findings are expected to provide a reference for the flexural strengthening design of HVFA-SCC T-beams that are more environmentally friendly and safer for application in building structures.

2 Literature review

Initially, fly ash in concrete technology innovation was used as a cement substitute, limited to a range of 15-25%. Then, currently, high strength development uses concrete using high volume fly ash where the cement replacement with fly ash is at least 50%. Shear testing of beams with HVFA concrete with variations of cement replacement of 50%, 60%, and 70%, gave optimum results at 50% cement replacement with fly ash [7].

Experimental studies on HVFA concrete beams with varying fly-ash contents indicate that replacing 50% of cement or fine aggregate with fly ash provides optimum shear performance and load capacity compared with 60% and 70% replacement. Other studies on reinforced HVFA-SCC concrete beams with a strength of about 40 MPa show that, compared with normal beams, HVFA-SCC beams tend to exhibit larger deflections and lower load-carrying capacity, but higher ductility. Several works also report that increasing the proportion of fly ash as a fine-aggregate replacement can improve the capacity of certain HVFAC beams, indicating that the influence of fly ash on structural behavior depends on the mix configuration and loading system [8].

On the other hand, the use of Fiber Reinforced Polymer (FRP) as an external strengthening material for reinforced concrete has been width investigated due to its advantages of low density, high corrosion resistance, and ease of application in the field. Carbon Fiber Reinforced Polymer (CFRP) is specifically used to enhance the flexural, shear, axial capacity, and ductility of concrete elements; some test results show increases in flexural capacity of up to about 40% in reinforced concrete beams strengthened with CFRP laminates compared with control beams [9]. However, this strength enhancement is often accompanied by a reduction in ductility, which is influenced by the steel reinforcement ratio and the amount of CFRP [10]. In the design context, various standards and guidelines such as SNI 2847:2019 [11] and SNI 8971:2021 [12] provide provisions for the design of externally bonded FRP sheet systems for concrete strengthening, including environmental reduction factors and limits on the effective CFRP strain.

Previous research on HVFA-SCC concrete beams strengthened with CFRP has generally been conducted on rectangular cross-sections, so information on the flexural behavior of CFRP-strengthened HVFA-SCC T-beams is still limited. In practice, however, floor beams generally behave as T-beams because they work monolithically with the floor slab. The novelty of this thesis lies in the experimental investigation of the flexural behavior of HVFA-SCC T-beams with 50% cement replacement by fly ash and SIKA Carbodur-type CFRP strengthening, targeting a compressive strength of about 30 MPa. The results of this study are expected to enrich the literature on the combination of environmentally friendly HVFA-SCC concrete systems and CFRP strengthening in T-beam elements as a reference for flexural strengthening design in the field.

3 Experimental program

An experimental study was selected as the research method in this work, because direct testing allows the cause-and-effect relationship of a variable to be observed by comparing the influence of other variables. In this experimental program, the variable investigated is the flexural strengthening of T-beams made of high volume fly ash self-compacting concrete using carbon fiber reinforced polymer (CFRP). The tests were carried out in the Structural and Building Materials Laboratory, Civil Engineering Study Program, Faculty of Engineering, Atma Jaya Yogyakarta University.

3.1 Material

3.1.1 High volume fly ash – self compacting concrete (HVFA-SCC)

High Volume Fly Ash – Self-Compacting Concrete (HVFA-SCC) is a concrete with high flowability that can compact itself without the aid of mechanical vibration and offers advantages such as more homogeneous mixed, lower permeability, and a finer pore structure and must be comply to the EFNARC [13]. In this study, ready-mix HVFA-SCC supplied by PT Solusi Bangun Beton (SBB), a subsidiary of PT Solusi Beton Indonesia engaged in concrete production, is used. The target compressive strength is $\boldsymbol{f'_c = 30}$ MPa with 50% fly ash used as a replacement for cement in the HVFA-SCC specimens.

3.1.2 Carbon fiber reinforced polymer (CFRP)

The strengthening system using Carbon Fiber Reinforced Polymer (CFRP) is employed to increase the strength of structural elements, particularly to enhance the flexural and shear capacity of beams and columns. CFRP has very high tensile strength, making it effective as external reinforcement. In this study, the shear capacity of the beams is increased using CFRP products manufactured by PT SIKA Indonesia.

- Sika CarboDur

  Sika CarboDur is used in the form of plates with a thickness of 1.2 mm, bonded with SIKADUR-30 epoxy adhesive. The installation procedure involves roughening the concrete surface, applying the epoxy adhesive to the concrete surface and to the Sika CarboDur plate, and then bonding the plate to the concrete.

3.1.3 Strain gauge

Strain gauges were installed on the beam specimens to measure strains in both the concrete and the reinforcing steel. In this study, two types of strain gauges were used: type PL-06-11 with a gauge length of 60 mm to monitor concrete strain during loading, and type FLA-11 with a gauge length of 6 mm to measure the strain in the reinforcing steel inside the beam.

3.2 Test specimen

3.2.1 T-beam specimens

The beam specimens were cast using High Volume Fly Ash – Self-Compacting Concrete (HVFA-SCC) with 50% fly ash replacement and a target compressive strength of $f'_c = 25$ MPa. The beams were designed with a T-shaped cross-section, representing practical conditions in which beams and slabs generally act monolithically with the floor slab. One normal beam without CFRP strengthening was prepared as a control, and four beams with CFRP strengthening were prepared for shear-capacity testing. The T-beam specimens have a total flange width (b_f) of 440 mm, web width (b_w) of 120 mm, overall height (h) of 240 mm, and flange thickness of 80 mm, with a total beam length (L) of 3000 mm. Flexural reinforcement consists of 12 mm bars (P12), with 6 mm stirrups (P6) for shear reinforcement, while the slab reinforcement uses 6 mm bars at 150 mm spacing (P6-150) in double layers. The specimen details are presented in Table 1, and the configurations of the normal and strengthened beams are shown in Figures 1, 2, and 3.

Table 1. Test beam data

Test beam	Type of strengthening	Testing type
BR-NORMAL	Normal beam	Control beam
BS-HVFA-SCC-CFRP50-3000-1	SIKA CFRP wrap, 1 layer, 50 mm width, 150 mm spacing	Flexural test
BS-HVFA-SCC-CFRP50-3000-2	SIKA CFRP wrap, 1 layer, 100 mm width, 150 mm spacing	Flexural test
BS-HVFA-SCC-CFRP100-3000-1	SIKA CFRP wrap, 1 layer, 250 mm width, 300 mm spacing	Flexural test
BS-HVFA-SCC-CFRP100-3000-1 (dup.)	SIKA CFRP wrap, 1 layer, 250 mm width, 300 mm spacing	Flexural test

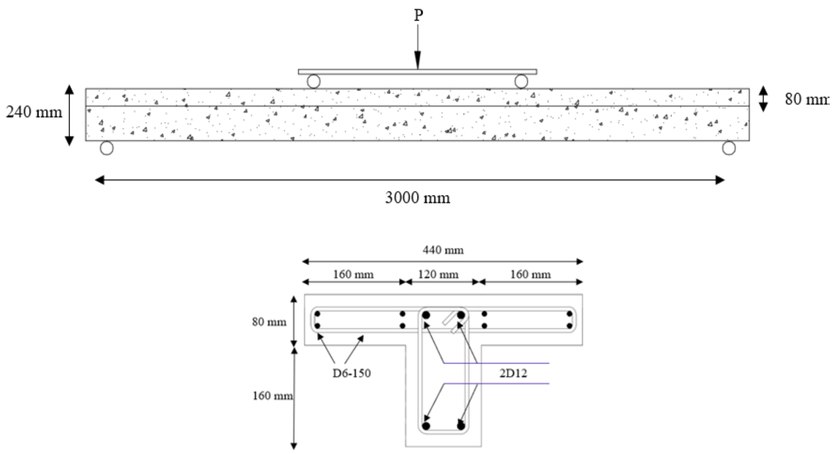


Fig. 1. BR-Normal.

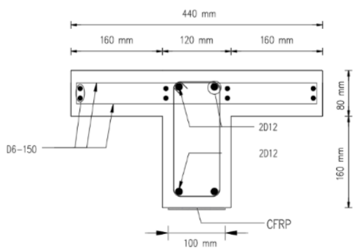


Fig. 2. BF-HVFA SCC 100-3000.

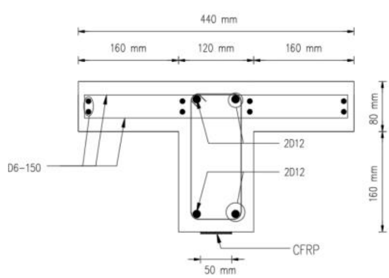


Fig. 3. BF-HVFA SCC 50-3000

3.2.2 Testing Method

One strain gauge for measuring concrete strain was installed on the bottom surface of the beam at a distance of 1.5 m from the support (midspan) (Figure 4). Meanwhile, to obtain the tensile reinforcement strain due to flexure, one strain gauge was attached to the tension reinforcement at 1.5 m from the support (midspan), and another strain gauge was installed on the tension reinforcement at a distance of 1 m from the support (directly under the P/2 load).

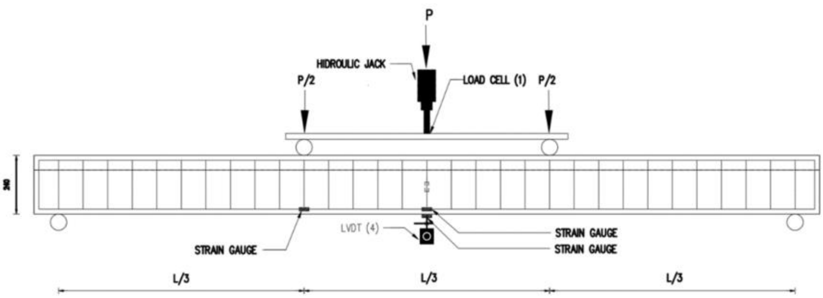


Fig. 4. Placement of strain gauges on the test beam

3.2.3 Test setup

The beam specimens were installed on a loading frame with pin–roller supports at both ends. The test was carried out by applying static loads incrementally with specified load intervals. The load was applied at two points spaced 1,000 mm apart so that a condition of pure shear and flexure could be obtained. The surface of each test beam was painted white and marked with perpendicular black lines at 50 mm spacing. Deflection was measured using an LVDT (Linear Variable Displacement Transducer) with a maximum capacity of 150 mm placed at midspan of the beam. Loading was stopped when the test beam had failed and the data logger no longer recorded any increase in load.

4 Results and discussion

4.1 Concrete material

The constituent materials of the concrete were first tested, including coarse and fine aggregates, to provide a basis for reliable results in the beam tests. The concrete mix composition using fly ash and self-compacting concrete can be seen in Table 2, while the results of the 28-day concrete compressive strength tests are presented in Table 3.

Table 2. Mix composition of High Volume Fly Ash – Self-Compacting Concrete

Code	**Water (kg/m^3)**	**Cement (kg/m^3)**	**Fly Ash (kg/m^3)**	**Gravel (kg/m^3)**	**Sand (kg/m^3)**	**Plasticizer (Normet - 6RD) (lt/m^3)**	**Plasticizer (Normet - 60R) (lt/m^3)**
HVFA-SCC 50%	140	250	250	735	946	1.5	3

Table 3. Compressive strength test results of 28-day concrete specimens

Compressive Strength	**Strengthening Type**		**Modulus of Elasticity of Test Results**	**Average**
Sample	**Load (kN)**	**f'c (MPa)**	E=4700 $\sqrt{fc}$	**f'c (MPa)**

SCC 50% (9)	600	33.95	27387	35.16
SCC 50% (10)	615	34.80	27727	
SCC 50% (11)	580	32.82	26926	
SCC 50% (12)	690	39.05	29369	

Table 3 shows that the 50% SCC concrete at 28 days had a medium compressive strength, with an average of approximately 35.16 MPa.

4.2 Experimental testing of beams with flexural strengthening

The beams subjected to loading tests produced results recorded by a data logger, which were then processed into graphs showing the relationships between load and deflection and between load and strain. Each beam was tested to its capacity, with the applied load increased incrementally until failure. The test results for each beam specimen are presented in Table 4.

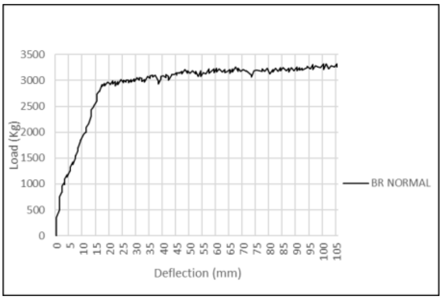
Table 4. Test results of beam capacity

Test beam	Load capacity (kg)	Beam deflection (mm)	Concrete strain (με)	Rebar strain (strain gauge at midspan) (με)	Rebar strain (strain gauge 1 m from support) (με)
BR-NORMAL	3255	105.95	714.39	1785.54	3149.98
BS-HVFA-SCC-CFRP50-3000-1	3452.5	80.05	300.95	1380.96	1683.01
BS-HVFA-SCC-CFRP50-3000-2	2812.5	66.2	1505.71	2153.6	1663.2
BS-HVFA-SCC-CFRP100-3000-1	3832.5	100.05	NA	1419.4	3159.41
BS-HVFA-SCC-CFRP100-3000-2	3827.5	56.4	904.77	863.94	3586.77

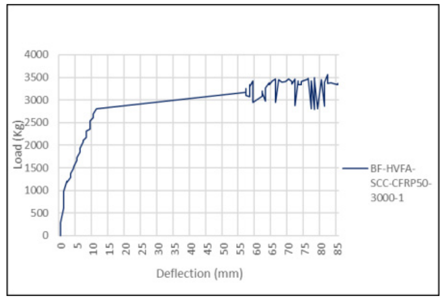
Table 4 shows that the beam strengthened with 50 mm width CFRP (BF HVFA SCC CFRP50 3000) had a maximum load of 3452.5 kg (an increase of 6%) and the beam strengthened with 100 mm width CFRP (BF HVFA SCC CFRP100 3000) had a maximum load of 3827.5 kg (an increase of 18%) compared to the normal beam (BR NORMAL). The average deflection of the beam strengthened with CFRP was smaller, while the concrete strain was greater than that of the normal beam, indicating changes in stiffness and cracking behavior due to the use of alternative materials and CFRP strengthening.

4.3 Load-Deflection Relationship

Figure 5 shows the load-deflection relationship or each beam.



(a)



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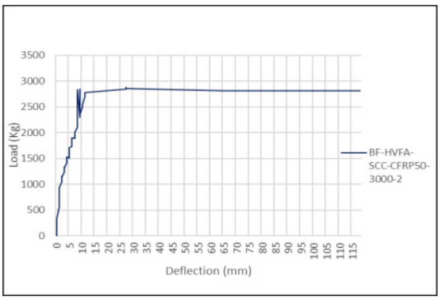

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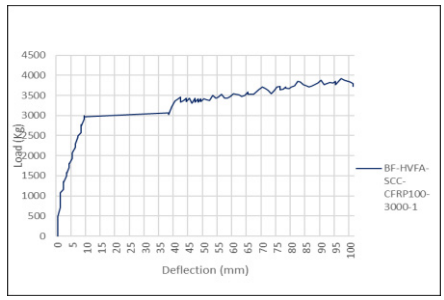

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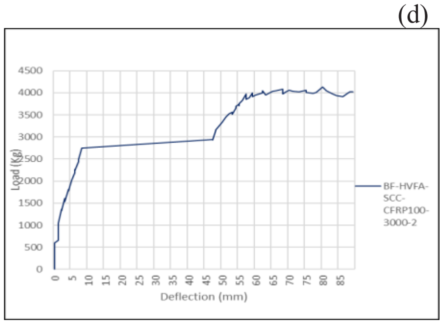

(e)

Fig. 5. (a) Load-Deflection Relationship Graph – BR NORMAL; (b) Load-Deflection Relationship Graph – BF-HVFA-SCC-CFRP50-3000-1; (c) Load-Deflection Relationship Graph – BF-HVFA-SCC-CFRP50-3000-2; (d) Load-Deflection Relationship Graph – BF-HVFA-SCC-CFRP100-3000-1; (e) Load-Deflection Relationship Graph – BF-HVFA-SCC-CFRP100-3000-2.

In general, variations of HVFA in SCC concrete tend to increase the ductility of beams (greater deformation capacity before collapse), while the addition and variation of CFRP quantity/configuration primarily enhanced initial stiffness and load capacity but tended to reduce ductility in the strengthening is too rigid. From Figure 1, which shows the load-deflection relationship graphs from this testing, it is evident that HVFA and CFRP variations alter beam behavior primarily in two aspects: initial stiffness (initial curve slope) and ductility (curve length until collapse). Overall, normal beams exhibited sufficiently high stiffness and good ductility, whereas specific combinations of HVFA-SCC with CFRP could slightly decrease or increase stiffness and modify the extent of deflection that could still occur after approaching maximum load

HVFA in SCC concrete enabled some beams to undergo substantial deflections before failure, resulting in more ductile behavior compared to highly brittle beams.

The addition of CFRP increased or maintained load capacity and initial stiffness, but in certain configurations, it tended to reduce ductility due to more sudden failure (graphs end more abruptly at smaller deflections) compared to BR-NORMAL.

4.4 Crack Pattern of T-Section Test Beams

Figures 6 through 10 show the documented crack patterns observed on each type of test beam after loading.

Fig. 6. Crack Pattern on Normal Test Beam Specimen (BR-Normal)

Figure 6 shows that the normal beam (BR-Normal) exhibited a typical flexural crack pattern with substantial deflection before collapse, indicating ductile behavior. The primary cracks developed in the mid-span tensile zone and propagated toward the load points, signifying that the failure mechanism was dominated by flexure rather than shear or sudden collapse.

Fig. 7. Crack Pattern on Test Beam Specimen with CFRP Strengthening (BF-HVFA-SCC-CFRP100-3000-1)

Figure 7 shows that the BF-HVFA-SCC-CFRP100-3000-1 beam with CFRP strengthening exhibited a flexural crack pattern in the tensile zone, but its deflection appeared more controlled compared to the normal beam. Cracks propagated with relatively close spacing but did not indicate sudden collapse, indicating that CFRP strengthening enhanced stiffness and maintains flexural capacity while still providing sufficiently ductile behavior.

Fig. 8. Crack Pattern on Test Beam Specimen with CFRP Strengthening (BF-HVFA-SCC-CFRP100-3000-2)

Figure 8 shows the BF-HVFA-SCC-CFRP100-3000-2 beam before and after loading, where post-test numerous vertical-inclined flexural cracks were observed spreading densely in the tensile zone along the mid-span. This spreading crack pattern indicated that CFRP strengthening effectively resists large localized damage at a single point, resulting in more uniform failure, and the beam still exhibits sufficiently ductile flexural behavior despite significant surface deformation and damage.

Fig. 9. Crack Pattern on Test Beam Specimen with CFRP Strengthening (BF-HVFA-SCC-CFRP50-3000-1)

Figure 9 shows that the BF-HVFA-SCC-CFRP50-3000-1 beam strengthened with CFRP exhibited a fairly uniform flexural crack pattern along the tensile zone after loading, with dense vertical-inclined cracks that were not concentrated at a single point. This indicated that the CFRP 50-3000-1 strengthening enhanced the beam's capacity and stiffness while maintaining ductile behavior, as damage spread and the beam could still undergo significant deformation before total collapse.

Fig. 10. Crack Pattern on Test Beam Specimen with CFRP Strengthening (BF-HVFA-SCC-CFRP50-3000-2)

Figure 10 shows the BF-HVFA-SCC-CFRP50-3000-2 beam with CFRP strengthening before and after loading, where post-test substantial deflection was observed, but the surface crack pattern was relatively sparse and did not spread as widthly as in other beams. This condition indicated that the CFRP50-3000-2 configuration provided good stiffness and effectively delays the onset of extensive cracking, resulting in more controlled damage and the beam exhibiting sufficiently stable flexural behavior up to near maximum load.

5 Conclusion

Based on the experimental program and the discussion above, several conclusions can be drawn as follows:

1. The test results showed that HVFA-SCC with 50% cement replacement by fly ash, achieved an average compressive strength of 35.16 MPa, which is comparable to conventional normal concrete and provides adequate compressive strength for structural applications. The calculated modulus of elasticity between 26.9-29.4 GPa indicates that the stiffness of HVFA-SCC is also within the range of normal concrete. Thus, suggest that HVFA-SCC concrete can significantly reduce cement usage while maintaining adequate mechanical performance.
2. The beam strengthened with 50 mm width CFRP increase the maximum load by 6% and beam strengthened with 100 mm width CFRP increase the maximum load by 18% compared to the normal concrete beam without strengthening. The average deflections at maximum load were smaller, while the concrete strains were greater than those of the normal concrete beam.
3. The used of HVFA-SCC generally increases beam ductility, while CFRP strengthening increased the initial stiffness and load capacity but tended to reduce ductility due to more abrupt failure.
4. All specimens exhibited flexural crack–dominated failure. HVFA-SCC with CFRP strengthening T-beams, exhibited more controlled and uniformed flexural crack patterns in tensile zones compared to normal beams. The beams with 100 mm spacing of CFRP strengthening showed cracks that propagated with

relatively dense spacing but did not indicate sudden collapse. The 50 mm CFRP spacing showed crack patterns that were relatively sparser than 100 mm spacing. This spreading crack pattern indicated that CFRP strengthening effectively resists large-localized damage at a single point and provide sufficient ductile flexural behaviour.

5. From this study, it can be concluded that HVFA-SCC with with larger width of CFRP tends to provide better strength, higher deformation, and improved stiffness.

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