

The Mechanical Properties of High and Normal-Strength of Fly Ash Concrete Strengthened by Polypropylene and Steel Fiber

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Abstract Concrete technology has developed rapidly due to the high demand for advanced infrastructure facilities in which concrete has become the most frequently used material. Due to high CO₂ emission caused by cement utilization in concrete production, partial cement substitution by pozzolanic material such as fly ash will be beneficial for the environment. Despite the concrete high demand for infrastructure facilities, the concrete needs attention on its lower tensile strength, especially in high-strength concrete. Therefore, this paper presents a study on the effect of different types of fiber on the strength properties of fly ash concrete. The method applied in this study is an experimental program by manufacturing specimens with compression strength design variations of 25 MPa for normal-strength concrete and 45 MPa for high-strength concrete. In addition, 0.66% steel fibre BWG21 (SWF) by weight of concrete and 600 g/m³ polypropylene fibre Sika Fibre-12 (PPF) were used. Moreover, 20% fly ash as a partial substitution for cement was used to address the green concrete issue. The testing programs include the workability test for fresh concrete, compression strength test and splitting tensile strength test for cylinder concrete, and flexural strength test for the concrete beam. Besides the workability test of fresh concrete, the other testing programs were conducted after the concrete curing stage at 28 days. The test result shows that cement substitution of

20% by weight of fly ash and the addition of fibre can meet the design strength of concrete both for 25 MPa and 45 MPa. Even though this research confirms that steel fibre gives higher strength properties than polypropylene fibre, polypropylene fibre is easier to work with in the manufacturing stage. Moreover, this finding support reducing greenhouse gas release into the atmosphere coming from the construction industry through cement replacement up to 20%.

Keywords Fly Ash Concrete, Steel Fibre, Polypropylene Fibre, Greenhouse Gas, Compressive Strength

1. Introduction

Indonesia is a developing country where the construction sector keeps growing. This situation leads to significant improvements in construction technology to meet construction materials and construction technology and to show the competitiveness of Indonesian construction technology. Concrete consumption increases rapidly due to customers' needs that expect more advanced infrastructure facilities such as long-span bridges, toll roads to connect

regions, and high-rise buildings that use concrete as the primary material. Aggregates, fine and coarse, are the basic components of concrete then bound by adhesive material consisting of cement and water that produce chemical reactions during the hardening process and curing stage [1].

The advantage of concrete as a construction material includes superior compression strength, ease to manufacture to meet element shape and dimension, and the material is easily found in our surroundings. However, concrete has low tensile strength that affects its mechanical properties i.e.: low tensile strength and low flexural strength. Therefore, the concrete should be strengthened by anchoring steel as concrete reinforcement. The utilization of steel not only as longitudinal reinforcement but also it can be used as an ingredient in the concrete mixture in the form of steel fibre. Using steel fibre is beneficial to increase concrete tensile strength and compression strength, according to previous research [2]

In addition, based on research conducted by Suhendro [3] and Solikin [4], it was proved that the unfavorable properties of concrete, such as its brittleness, inability to withstand tensile stress, and low resistance to impact loads, can be solved by incorporating fibres to the concrete constituent such as steel wire or nylon fiber. Besides using steel wire, polypropylene can also be used as an alternative concrete fibre that reduces the weakness of concrete [5]. By combining steel fibre (SF) and polypropylene fibres (PPF), previous research confirmed that 75% - 25% percentage proportion of SF-PPF was beneficial to produce concrete with optimum flexural strength followed by the improvement of flexural toughness and tensile strength of concrete [2].

Polypropylene fibre belongs to plastic fibre (polypropylene) which is manufactured by high technology to produce a special thin fiber with high strength. The chemical formula is C_3H_6 , describing the material as a hydrocarbon compound. The diameter of a single thin fiber is about 18 microns and the length is about 12 mm. The density of polypropylene fibre is 0.91 kg/l and the melting point is about 160⁰ C. Polypropylene fibre at the amount of 600-900 gram/m³ of concrete is usually used to strengthen concrete [6]. Moreover, previous research confirmed that the optimum amount of polypropylene fibre in the concrete constituent is beneficial to improve the concrete splitting tensile strength at a testing age of 18 days, 56 days, and 730 days compared to the plain concrete mixture [7].

In terms of its strength, there are two categories of concrete, i.e.: normal and high-strength concrete, in which generally high-strength concrete has better quality. Normal-strength concrete has compression strength of about 15-40 MPa SNI 2847-2013, (2013), whereas high-strength concrete has a compression strength value above 40 MPa. High-strength concrete requires special treatment for mix proportion design, mixing stage, and curing stage [9].

The advantage of high-strength concrete as a

construction material leads many countries, including Indonesia, to take advantage of the available natural conditions and the use of local materials to manufacture normal and high-strength concrete. Research efforts need to be made to find a new alternative in concrete technology to reduce cement utilization by substituting part of cement by pozzolanic materials such as fly ash. The substitution is expected to reach a design strength similar to normal Portland cement concrete as studied by the previous researchers [10], [11].

Fly ash was found as a by-product in a coal power plant and researchers found it can be used as partially Portland cement replacement due to its higher silica content. The utilization of fly ash not only gives solution on waste material but also gives contribution to improve the quality of concrete particularly on improvement of fresh concrete workability, increasing the compression strength, decreasing concrete permeability, and increase sulphate resistance [12]. The contribution of fly ash to improve the mechanical properties of concrete is possible as it has so fine particles and it has spherical shapes. In addition, the utilization of fly ash in concrete is widely accepted as the material no longer belongs to hazardous material as stated in Indonesia's environmental ministry decree [13]. Moreover, based on its mineral content especially the content of SiO₂, Al₂O₃, and Fe₂O₃, fly ash can be classified as fly ash class F, class C, and class N [14], [15].

Therefore, this paper reports the study on the effect of two types of fibre, i.e. steel and polypropylene fibre, on the mechanical properties of two categories strength of concrete (normal and high-strength) in which both concrete utilize 20% of class F fly ash as cement replacement. Concrete's mechanical properties are evaluated by testing the workability, compression strength capability, splitting tensile, and flexural strength.

2. Research Method

This experimental research program was carried out by using facilities of the Civil Engineering Laboratory at Universitas Muhammadiyah Surakarta by preparing some concrete specimen types for the testing program. Besides essential concrete ingredients, two different types of fibres were employed at 600 gram/m³ for polypropylene Sika Fibre-12 (PPF) and 16 kg/ m³ for steel wire fibre (SWF). Moreover, fly ash in the amount of 20% was used to reduce the use of cement, which is relatively expensive. The concrete specimens were tested on their mechanical properties after the concrete curing stage of 28 days.

Four variations of the concrete mix proportions were prepared for the testing program, including slump test, compression strength test, splitting tensile strength, and flexural strength of concrete, comprising three specimens for each testing program. Therefore, specimens of 36 concrete cylinders and concrete beams were manufactured

for all testing programs. The specimen size of the concrete cylinder is diameter of 15 cm and height of 30 cm, whereas the specimen of concrete beams is 15 x 15 x 60 cm.

It is necessary to plan the stage that will serve as guidelines for this research. These stages are described as follows,

Stage I: Preparation of Materials

Preparation of all materials and tools required for this research, including steel fiber, polypropylene, water, fly ash, coarse and fine aggregates, cement, and fly ash.

Stage II: Material Test

It is necessary to conduct a material testing program for the materials to be used. Besides ensuring that the materials meet the requirement as concrete ingredients, this stage is intended to obtain the material properties for calculating the mix proportion of concrete.

Stage III: Concrete Mix design and specimen preparation

The concrete mix design was prepared by using the SNI method [16]. After the amount of all concrete ingredients has been prepared, dry materials were mixed first before pouring water. Moreover, the fibres were gradually put into the mixer drum to ensure the homogeneity of the mix. After one day, the samples were taken out of the mold and then followed by water immersion curing process. Table 1 and Table 2 describes mix proportion and number specimen that prepare for this research.

Stage VI: Testing

The number of testing specimens and the testing programs are described clearly in Table 2 and the testing stage were carried out at the age of 28 days at the civil engineering laboratory Universitas Muhammadiyah Surakarta.

Table 1. Mix proportion per m³ (prepare according to Indonesian standard for mix proportion [16])

| Specimen | Water (l) | Cement (kg) | Fly ash (kg) | Aggregate (kg) | | PPF (g) | SWF (kg) |
|-------------|-----------|-------------|--------------|----------------|--------|---------|----------|
| | | | | Fine | Coarse | | |
| PPF 25.FA20 | 205 | 357 | 89 | 703 | 991 | 600 | - |
| SWF 25.FA20 | 205 | 357 | 89 | 703 | 991 | - | 16 |
| PPF 45.FA20 | 205 | 456 | 114 | 493 | 1077 | 600 | - |
| SWF 45.FA20 | 205 | 456 | 114 | 493 | 1077 | - | 16 |

Note: PPF: Polypropylene fibre

SWF: Steel wire fibre

Table 2. Number of Specimens

| Testing program | Compressive strength design (MPa) | Number of fly ash concrete Specimen | |
|-----------------------------|-----------------------------------|-------------------------------------|--------------------------|
| | | With steel fibre | With polypropylene fibre |
| Compression strength | 25 | 3 | 3 |
| | 45 | 3 | 3 |
| Splitting tensile strength | 25 | 3 | 3 |
| | 45 | 3 | 3 |
| Flexural strength | 25 | 3 | 3 |
| | 45 | 3 | 3 |
| Total = 36 specimens | | | |

2.1. Concrete Testing

According to ASTM C39 [17] the concrete’s compression strength is the ratio between maximum load and area of the concrete specimen. A compression machine produces the maximum load and the concrete’s compression strength was calculated in regard to the following formula:

$$f_c = \frac{P}{A} \tag{1}$$

where:

- f_c = compression strength (MPa)
- A = section area (mm²)
- P = maximum load (N)

Additionally, splitting tensile strength was tested using ASTM C496 guidelines [18], in which specimen with the dimension same as specimens for the compression strength test was placed horizontally under a Universal testing machine (UTM). The following is a description of the formula to get the splitting tensile strength value of concrete:

$$f_{ct} = \frac{2P}{\pi LD} \tag{2}$$

where:

- f_{ct} = split tensile strength (MPa)
- P = max load (N)

- π = 3,1416
- L = length (mm)
- D = diameter (mm)

Moreover, the beam flexural strength test was conducted to check the ability of a concrete beam positioned on two supports to resist a maximum load perpendicular to the axis of the beam. A rectangular beam of 15 x 15 cm with a span between support of 45 cm was used as testing specimens. In addition, a two-point load was applied at a distance of 15 cm from the left and side support, as shown in Figure 1. The test was carried out in accordance with ASTM C78 [19], in which the flexural strength is expressed in Mega Pascal (MPa). The flexural strength is the value of the maximum bending moment divided by the resisting moment of the test beam. Therefore, the formula to find flexural strength was described as:

$$R = \frac{PL}{bd^2} \tag{3}$$

where

- R = modulus of rupture/ flexural strength of beam (MPa)
- P = maximum load (N)
- L = span length between the two-support beam (mm)
- b = average beam width at collapse section (mm)
- d = average depth of specimen at the fracture (mm)

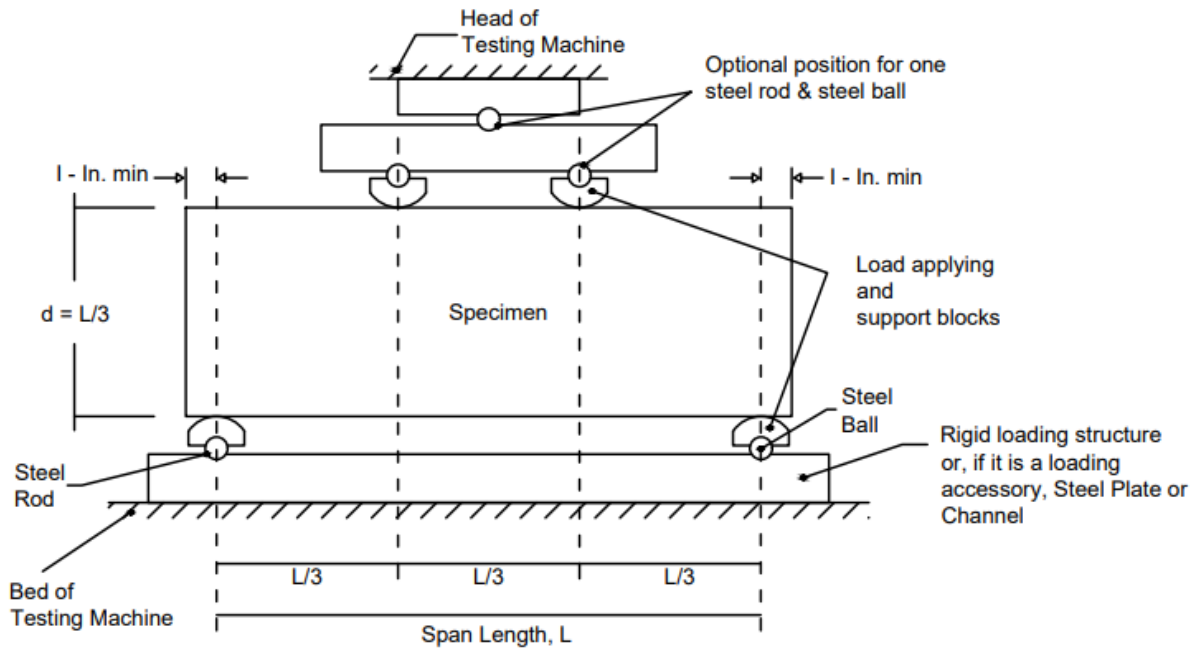


Figure 1. Flexural strength test setup (reproduction from ASTM C-78 [19])

3. Result and Discussion

3.1. Material Testing

Prior mixing stage, fine aggregate and coarse were tested to determine their properties, and the result shows that both materials meet the criteria as concrete ingredients. Moreover, according to Table 3, Chemical composition of fly ash, the fly ash that is employed in this research is categorized as type F Fly Ash because the total percentage of $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 = 77.57\%$ more than the criteria of class F Fly Ash.

Table 3. Chemical composition of Fly Ash

| Chemical composition | Percentage % | ASTM Standard |
|-------------------------|--------------|--|
| SiO_2 | 46.00 | $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ min. 70% for Class F Fly Ash |
| Fe_2O_3 | 13.87 | |
| Al_2O_3 | 17.70 | |
| CaO | 5.50 | |
| MgO | 2.30 | |
| Loss of Ignition | 0.70 | |

(Source: SBI report analysis)

3.2. Slump Test

A slump test was performed for each variation of the concrete mix using a steel slump cone with diameter of 10

cm at the top, diameter of 20 cm at the bottom, and 30 cm of height. It is necessary to perform a slump test to ascertain its workability before casting the concrete into the mold. Figure 2 describes the slump test results for each variation of the mixture.

Based on the slump test result value for concrete with a design compression strength of 25 MPa and 45 MPa, it is found that fly ash concrete with polypropylene fibres has a lower slump value than steel fibre concrete. This result is possible due to the higher friction resistance between polypropylene fibres and the other concrete ingredients in fresh state compared to steel fibres. Similar results also occurred in a study by Wang et al. [20] in which the utilization of polypropylene fibre reduces the workability of fresh concrete. Moreover, high-strength concrete use a lower water-cement ratio (0.36) than normal-strength concrete (0.46), leading to the lower slump test result of high-strength concrete. Similar results is found in research conducted by Tjaronge et al. [21] on the relationship between slump test and water demand i.e.: the higher the use of water, the higher the slump value.

3.3. Compression Strength Test

Testing of compression strength of concrete cylinder was carried out by using a Compression Testing Machine (CTM) has a cross section diameter of 15 cm and a height of 30 cm after the curing stage for 28 days. Figure 3 displays the results of the compression strength tests for concrete with normal and high strengths.

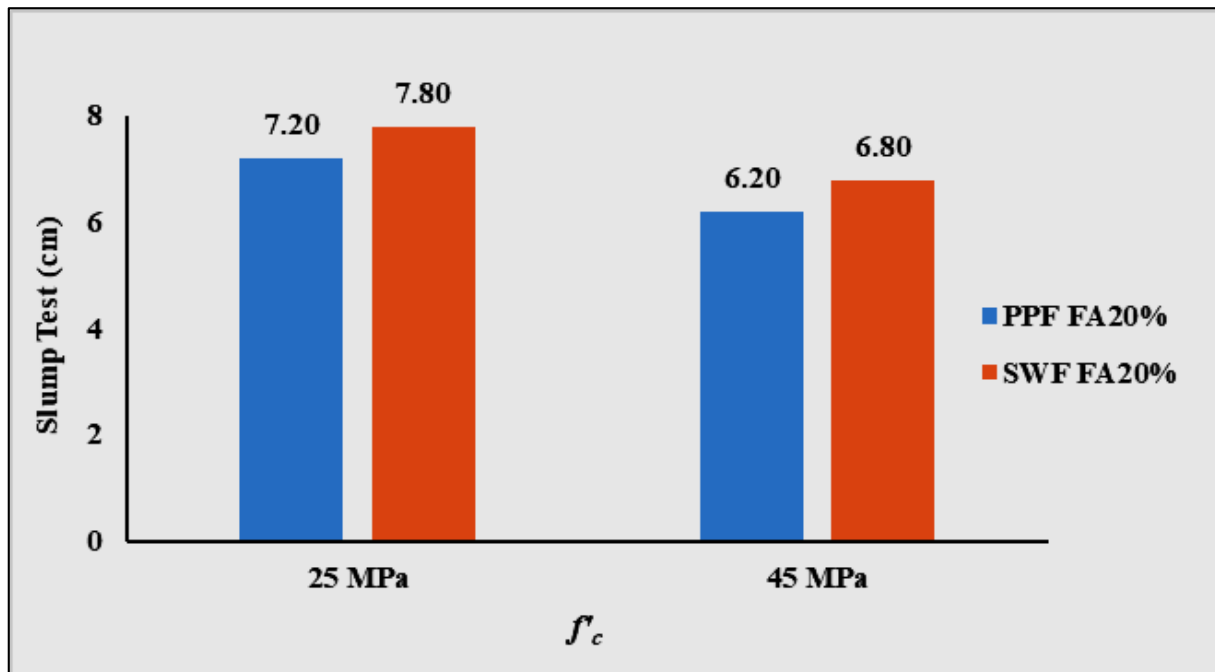


Figure 2. Slump test

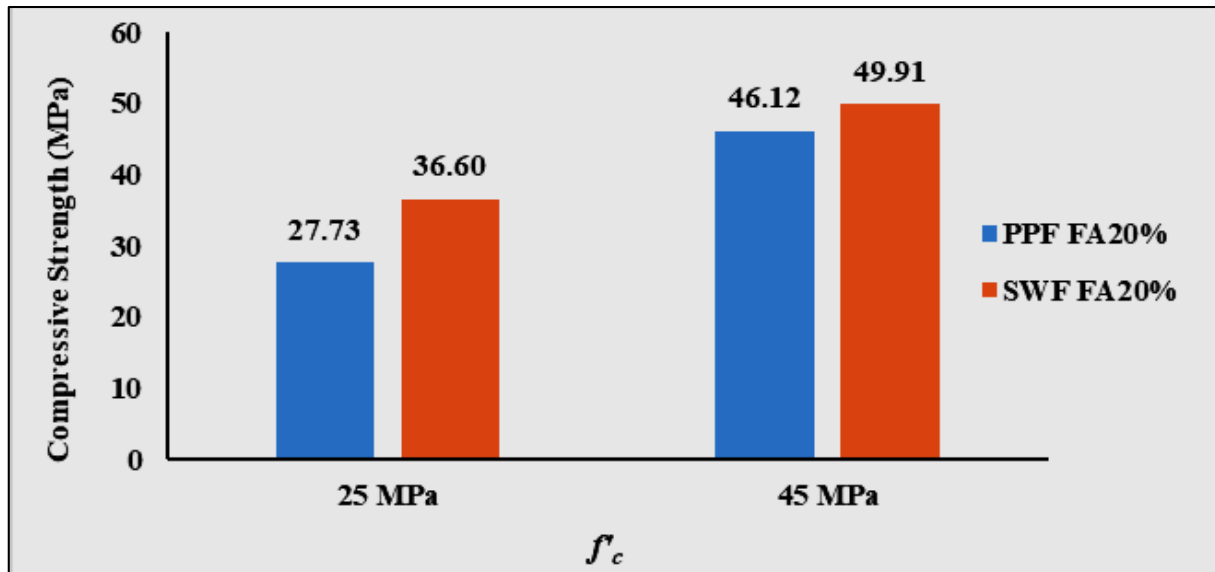


Figure 3. Compression strength test

Figure 3 shows the compression strength test result, in which fly ash concrete with two types of fibers can exceed the design strength for normal and high-strength concrete design and even higher particularly for normal design strength concrete. In addition, the use of steel wire fibre has higher compression strength than the use of polypropylene fibre in concrete cylinders. Therefore, the optimum compression strength improvement for a different type of fibre occurred for normal-strength concrete, reaching 24.23% whereas a slight improvement of 7.59% happens to high-strength concrete.

Based on these results, it is noted that steel fiber in concrete has higher compression strength than polypropylene fibre concrete especially for normal design strength concrete. This result is strongly affected by higher tensile strength of steel fibre than polypropylene fibre.

However, for high-strength concrete design, the compression strength of polypropylene fibres has a close result to steel fibres, with a difference of only 7.59%. Similar results were found in the study conducted by Hussain et al. [22] that solid wire fibres are more efficient compared to glass and polypropylene fibres in increasing compression strength (10-12%).

3.4. Splitting Tensile Strength Test

To find the splitting tensile strength of concrete, the specimens were tested using a Universal Testing Machine (UTM) on a concrete cylinder specimen which was placed horizontally under the machine after curing the stage for 28 days. Figure 4 demonstrates the value of the splitting tensile strength tests that have been carried out.

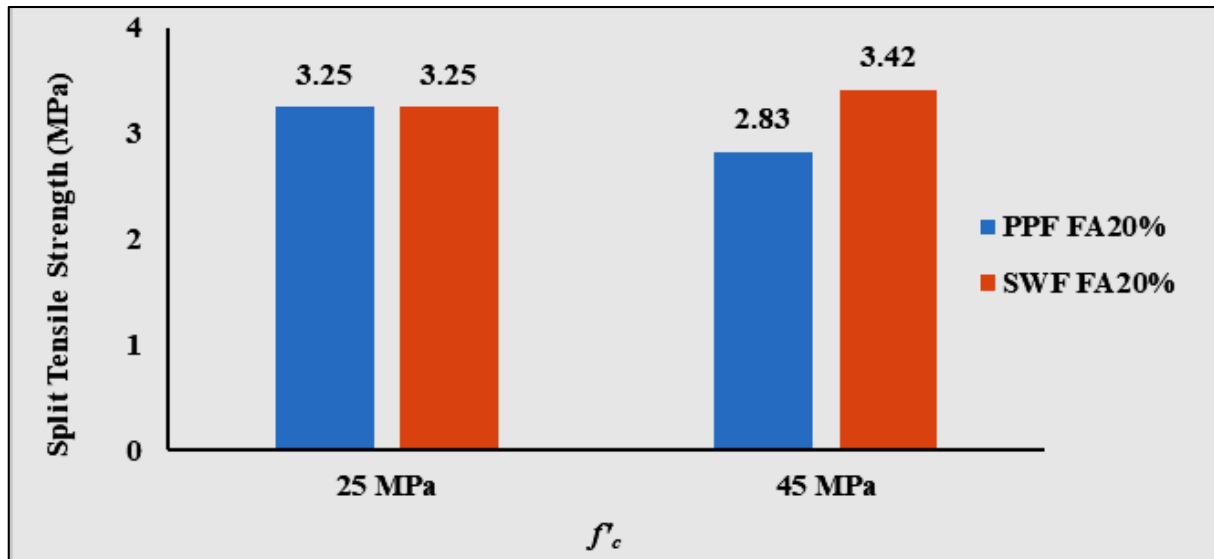


Figure 4. Split tensile strength

The value of splitting tensile strength shows for the compression design strength of 25 MPa has the same splitting tensile strength test result of 3.25 MPa for polypropylene fibre and steel wire fibre. However, for high-strength concrete (f'_c 45 MPa), the use of steel wire fibre gives a better result of splitting tensile strength compared to polypropylene fibre, in which the increase of splitting tensile strength at the value of 31.38%. This improvement is possible due to the nature of high-strength concrete that is less ductile than normal-strength concrete, so it needs fiber that has specification of higher tensile strength such as steel wire fibre to increase its ductility. Similar results occurred in a study by Tamil et al. [23] in which adding steel fibre to the concrete mix increased the split tensile strength by 29% compared to concrete without fibre at 28 days testing. Moreover, Aliem and Pradipta [24] also found that the utilization of 2% steel wire in concrete mix design with the combination of 1.5% superplasticizer can improve the splitting tensile strength by 46% compared to concrete without fibre.

3.5. Flexural Strength Test

The concrete's flexural strength was tested on a concrete beam specimen with a square dimension of 15 x 15 cm and length of 60 cm. Figure 5 displays the flexural strength value for both design strengths.

According to Figure 5, for both normal and high-strength concrete, fly ash concrete with steel fiber addition has a higher flexural strength than fly ash concrete with polypropylene fiber addition. The improvements of flexural strength in sequence for normal and high-strength concrete are 34.63% and 33.78%. This improvement is likely caused by the higher tensile properties of steel wire fibre compared to polypropylene fibre. Similar results were found in a study by Chajec and Sadowski [25] that additional steel fibre in concrete increased its strength due to improving the bond between materials in concrete. Additionally, because high-strength concrete is less ductile than normal-strength concrete, normal-strength concrete has higher flexural strength than high-strength concrete.

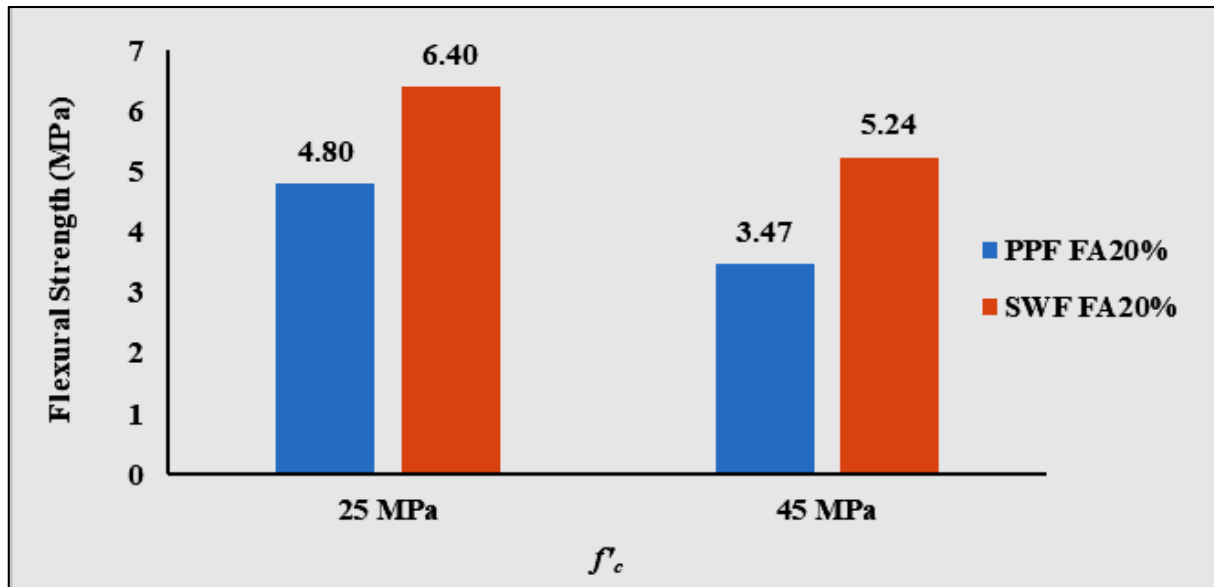


Figure 5. Flexural strength

Table 4. The ratio between compression strength and flexural strength

| Specimen | f'_c (MPa) | R (MPa) | Ratio R/f'_c (%) | f_{ct} (MPa) | $f_{ct} = 0.56 \sqrt{f'_c}$ (MPa) (ACI 318M [26]) |
|-------------|--------------|---------|--------------------|----------------|---|
| (a) | (b) | (c) | (d) = (c)/(b) | (e) | (f) = $0.56 \sqrt{(b)}$ |
| PPF 25.FA20 | 27.73 | 4.36 | 15.72 | 3.25 | 2.95 |
| SWF 25.FA20 | 36.60 | 6.67 | 18.2 | 3.25 | 3.39 |
| PPF 45.FA20 | 46.12 | 3.7 | 7.52 | 2.83 | 3.80 |
| SWF 45.FA20 | 49.91 | 5.24 | 10.50 | 3.42 | 3.96 |

3.6. The Relationship between Splitting, Flexural and Compression Strength

Based on the test data the correlation between compression strength (f'_c) to flexural strength (R) and the correlation between compression strength (f'_c) to splitting tensile strength (f_{ct}) are calculated then the results are described in Table 4.

For four different concrete mix proportions, the R/f'_c ratio ranges from 7.52 to 18.22%. The lower ratio value of high-strength concrete confirms that high strength concrete is less ductile than normal-strength concrete. Moreover, the design strength of 25 MPa has a ratio close to the result of previous research that the ratio between flexural and compression strength ranges from 12.7% to 16.9% [27]. In addition, the splitting tensile comparison value between the experiment and that suggested in ACI 318M confirms that the lower the compression strength, the higher the ductility, considering that normal design strength concrete has a relatively closer tensile splitting value to the value of ACI 318M than high design strength concrete.

4. Conclusions and Recommendation

4.1. Conclusions

According to data analysis and discussion on the topic of the utilization two different types of fibre on two different design strength of fly ash concrete, it can be concluded that:

- 1) The slump value of fly ash concrete with steel fibres has better workability than fly ash concrete with polypropylene fibres.
- 2) In terms of mixing process observation, polypropylene fibre also has the advantage of being easier to work with.
- 3) The mechanical properties show that steel wire fiber gives higher improvement on compression, splitting tensile, and flexural strength of concrete than polypropylene fibre. However, both fiber types give the same result for splitting tensile strength on normal concrete design strength.
- 4) The ratio between flexural to compression strength of normal design strength concrete has a value of 15.72%

and 18.22%, indicating that the flexural properties meet the standard.

- 5) Further research can be conducted for a combination of both fibre in one mixed proportion especially for normal design strength concrete.

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