Behaviour of macro synthetic fiber reinforced concrete columns under concentric axial compression

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Abstract

Previous studies have shown that fiber reinforced concretes can improve post-peak behaviour, ductility and energy-dissipation ability of concrete elements under flexure, shear and axial load. Ductile behaviour is one of the essential characteristics that have to be possessed by structures located in moderate to high seismic regions. This paper presents an experimental investigation of a series of nine macro synthetic fiber-reinforced concrete (MSNFRC) circular columns. The objective of the studies was to investigate the effects of the macro synthetic fibers on strength and ductility of the columns. The test parameters were the spacing of the spiral reinforcement and the volume fraction of the macro synthetic fibers. In two-thirds of the specimens, when macro synthetic fibers were added to the specimens, spiral reinforcement was reduced. The remaining specimens were detailed in accordance with the code minimum requirement for spiral reinforcement in order to examine the influence of the fibers on strength and ductility. A concentric axial compression load was applied monotonically on the column specimens. The results show that the addition of macro synthetic fibers leads to improved ductility and strength. Furthermore, based on this study, the code required spiral reinforcement can be reduced whenever MSNFRC is used.

Keywords: ductility; macro synthetic; volume fraction; spacing; spiral reinforcement

1. Introduction

Developments on fiber addition in concrete mixtures have grown significantly in recent decades as offers several advantages to the mechanical properties of concrete. Short discrete fiber addition modifies the brittle characteristic
response of the concrete leading to a significant increase in toughness and ductility compared to plain concrete. Previous studies have shown that fiber reinforced concretes (FRC) can improve post-peak behaviour, ductility and energy-dissipation ability of concrete elements under flexure [1,2,3,4,5,6], shear [7,8,9] and axial load [8]. While the main use of FRC is in nonstructural elements, its use in structural elements is permitted in some codes and is the subject of many researches.

Although several studies on steel fiber inclusion in concrete reported that the effect on the compressive strength ranges from negligible to marginal [10], other studies have demonstrated that it increases compressive strength and ductility [11,12,13]. It has also been proved that a combination of discrete steel fibers and transverse steel confinement can reduce the amount of confining reinforcement required by design codes [14,15] for HSC columns. Some other studies showed the advantage of adding discrete fibers to HSC mixtures in reinforced concrete columns for preventing premature separation of the concrete cover [16,17,18]. Also, research on mortar with steel fibers has shown that the addition of fibers leads to increases in compressive strength and strain at peak stress [10]. Investigation of the effect of fiber content on the post-peak softening branch of the compressive stress-strain curve of steel fiber reinforced concrete (SFRC) [10] found that an increase in the volumetric ratio of steel fibers leads to a relatively flatter post-peak softening branch of the curve. Nevertheless, the design considerations for steel fiber reinforced concrete (SFRC) were limited to a few structural applications [19]. Although research studies on structural applications has tended to focus on the steel and synthetic fibers, only a few attempts have been made to use the inclusion of fiber synthetic to improve concrete strength and ductility. However, a number of published studies [20,21,22] have shown a positive field experience with SNFRC, and showed some advantages over SFRC.

The influence of ductile behaviour on the mechanical properties of macro synthetic fiber reinforced concrete shown by previous research [1] is the subject of this experimental study. Ductility is one of the essential characteristics that have to be possessed by structures located in moderate to high seismic regions. While compressive strength is used for strength calculations of structural components, ductility is needed to evaluate toughness resistance, which is important for earthquake resistant structures. Typical stress strain curves of steel fiber-reinforced concrete in compression show an increase in strain at peak stress and substantially higher toughness. Toughness is a measurement of the ability to absorb energy during deformation, estimated using the area under the stress-strain curves. Design codes for concrete ensure ductile behavior of columns by setting minimum requirements for transverse steel reinforcement.

This paper presents tests on MSNFRC circular columns subjected to a concentric axial loading. The main objective of the research program was to investigate the effects of the macro synthetic fibers on the strength and ductility of the columns.

2. Experimental Program

2.1. Specimens

A number of column specimens were cast with high strength MSNFRC. Concrete was mixed with sand and coarse aggregate taken from a local quarry. The maximum coarse aggregate size was 10 mm. Ten percent by weight of portland composite cement was replaced with type F fly ash from Suralaya and silica fume (SIKA fume). High-range water reducing admixtures (1003 Sika superplastisizer) were used to improve the workability of the high strength concrete mixtures and the dispersion of the fibers. The concrete mixtures contained 0.75 and 1.25 percent by weight of macro synthetic fibers and were cast with nominally 70 MPa concrete. Cylinders of 150 mm diameter and 300 mm height were tested to obtain the control compressive strength of the columns. The concrete strength for each series was 64 MPa, 65 MPa and 63 MPa respectively for 1.25%, 0.75%, 0% volume fraction of fiber inclusion in the concrete mixtures.

The circular column specimens with a diameter of 135 mm and a cover of 10 mm contained 6 longitudinal bars of 10 mm diameter. The confining reinforcement used a spiral arrangement consisting of 6 mm diameter ties and spiral spacing of 30, 45 and 60 mm. The 30 mm spiral spacing was detailed in accordance with the code minimum requirement [14] of spiral reinforcement, while the remainings were reduced spiral spacings in order to examine the influence of volume fraction of macro synthetic fibers on strength and ductility. The yield strength of the bars was 431 MPa and 334 MPa for longitudinal and spiral bars respectively. The specimens were tested in 9 series with two columns in each series. The columns were designed as AK-XX-YY where XX is the nominal volume fraction of
macro synthetic fibers, and YY is the spiral spacing. Control specimens with the same size were prepared for plain and unconfined concrete.

2.2. Instrumentation and Testing Procedures

Details of the specimen dimensions and the reinforcement arrangements are given in Figure 1. The longitudinal axial deformations of the specimens were obtained using four linear variable differential transducers (LVDTs) with a gauge length of 25 mm attached to the four opposite sides of the specimens. One other LVDT of 50 mm gauge length was located at the machine to control the overall head movement of the machine. The relative axial displacement over the 250 mm gauge length of the specimens was measured. Two sets of strain gauges were installed at the opposite middle sides of longitudinal bars and one set of strain gauges was installed at the centre of the surface column in the longitudinal direction to determine longitudinal deformations. The transverse deformations of the columns were measured using three sets of strain gauges (gauge length of 5 mm) installed at 3 parts of the spiral ties and one set of strain gauge (gauge length of 60 mm) was installed at the centre of the surface column in the lateral direction.

Fig. 1. Specimen details and instrumentation

For the purpose of the test, the total height of each column was divided into 3 regions, comprising of two 150 mm regions at each end of the column, and a 250 mm region in the middle as the gauge length. The specimens were categorized into three configurations, representing different spiral spacings, i.e. 30 mm, 45 mm and 60 mm.

Concentric load tests were conducted on all columns using a Universal Testing Machine with a capacity of 1500 kN at the Engineering Center for Industry, Institut Teknologi Bandung. The load tests were based on displacement-controlled loading with a constant loading rate of 0.4 mm/min. All the strains, loads and deformations were measured using a data logger. Any cracking patterns, deformations etc, were recorded during testing as well.

2.3. Strength and Ductility Computation

Strength enhancement due to the confinement and macro synthetic fiber reinforced concrete is expressed as the ratio between the confined concrete strength and the unconfined concrete strength (i.e. $K = f_{cc}/f_{co}$). The history of experimentally measured confined concrete axial strain can be obtained from the average axial shortening readings from the LVDTs divided by the vertical length of the test region.
In this research, to measure ductility which is commonly evaluated in terms of a strain ductility ratio uses the ratio between the axial strain at the 0.85 $f'_{cc}$ after post peak and the axial strain at the peak stress of unconfined concrete (i.e. $\mu = \frac{\varepsilon_{0.85}}{\varepsilon_{cco}}$) [23].

3. Results and Discussion

3.1. The Experimental Results and Mode of Failure

The results of the specimen testing are provided in Table 1. Figure 3, 4 and 5 show the measured stress strain results of the tested columns. The ascending branches of the measured stress strain relationships in all test columns are almost linear. In addition, the descending branches of the columns with a closer spiral spacing and higher volume fraction of macro synthetic fibers are flatter than those with wider spacing and lower volume fraction of macro synthetic fiber.

The unconfined concrete columns (AK-0-0) failed in a sudden and explosive manner at peak load. The average measured compressive strength of the unconfined concrete was 0.86 of the compressive strength of the cylinder specimen concrete.

| Specimen     | $P_{max}$ (kN) | $f'_{cc}$ (MPa) | K   | $\mu$  |
|--------------|----------------|-----------------|-----|--------|
| AK-0-0       | 788.77         | 55.1            | 1   | -      |
| AK-0-30      | 974.61         | 68.09           | 1.24| 3.63   |
| AK-0-45      | 923.92         | 64.55           | 1.17| 2.46   |
| AK-0-60      | 851.94         | 59.52           | 1.08| 2.67   |
| AK-0.75-30   | 1094.56        | 76.47           | 1.39| 8.70   |
| AK-0.75-45   | 983.19         | 68.69           | 1.25| 4.67   |
| AK-0.75-60   | 906.16         | 63.31           | 1.15| 4.49   |
| AK-1.25-30   | 1107.39        | 77.37           | 1.40| 12.49  |
| AK-1.25-45   | 994.71         | 69.49           | 1.26| 5.92   |
| AK-1.25-60   | 924.63         | 66.09           | 1.20| 4.62   |

3.2. Effect of Spiral Spacing

Spiral spacing determines the concrete volume confined by two neighbouring ties and the confined area of the column section. The columns with closely spaced ties have an increased confined area and increased resistance of high axial loads and high lateral pressure. These behaviours are shown for the synthetic fibers reinforced concrete and for the plain one as well (Fig. 2). The three cases of the closer spiral spacing specimens show an enhancement of strength and ductility.

![Fig. 2. Confined concrete curves with different spiral spacing (a) plain concrete (0%); (b) MSFRC (0.75%); (c) MSFRC (1%)](image-url)
3.3. Effect of Volume Fraction of Macro Synthetic Fibers

Figure 3 shows the stress strain curve of the column specimens with three variations of volume fraction of macro synthetic fibers. The behaviour of the MSNFRC specimens shows greater load carrying capacity with a flatter curve compared to the plain concrete specimens. The use of MSNFRC in the column specimens with the closer spiral spacing show a significant increase in strength and ductility due to the combined confinement effect of the spiral and the inclusion of macro synthetic fibers in the concrete. The higher volume fraction of macro synthetic fibers produces a greater improvement in confinement. The MSNFRC specimens with wider spiral spacing show better behaviour in confinement compared to the plain concrete. These phenomenons are shown in Figure 3(c), with the flatter descending branches when macro synthetic fiber volume fractions of 0.75% and 1.25% were used.

![Fig. 3. Confined concrete curves with different volume fractions of macro synthetic fibers](a) S-30; (b)S-45; (c)S-60

3.4. Effect of Volume Fraction of Macro Synthetic Fibers and Reducing Spiral Spacing

![Fig. 4. Confined concrete curves with different volume fractions of macro synthetic fibers and reduced spiral spacing](a) comparison with AK-0-30; (b) comparison with AK-0-45

The AK-0-30 specimen using plain concrete with spiral spacing was detailed in accordance with the code minimum requirement [14] of spiral reinforcement. The specimens with wider spiral spacing using MSNFRC showed better behaviour on the descending curve compared to AK-0-30, as can be seen from Figure 4(a). The same trend can be seen in Figure 4(b), which indicates that specimens with a higher volume fraction of macro synthetic fibers and reduced spiral spacing were better at maintaining load in the post peak zone. These phenomenons point out that the column specimens using MSNFRC and spiral spacing less than the code requirement still had ability to confine. While previous studies [16,17,18] proved that a combination of discrete steel fibers and transverse steel confinement can reduce the amount of confinement reinforcement required according to the design codes [14,15] for HSC columns, the same is valid for macro synthetic fiber reinforced concretes.
3.5. Strength

The addition of macro synthetic fibers in reinforced concrete had a slight effect on the axial strength of the specimens in this experimental study. In most cases the effect of fibre addition on compressive strength is negligible [24]. However, a slight increase in strength ratio was achieved by addition of macro synthetic fibers volume fraction of 1.25% and 0.75% (Fig. 5(a)) and the closest spiral spacing (Fig 5b). Spiral spacing combined with MSNFRRC leads to better confinement and improved strength. The concrete under the combined confining action of MSNFRRC and reduced spiral spacing showed a good result in strength ratio. Figure 5(c) shows that combining a high volume fraction of macro synthetic fibers and reduced spiral spacing, half and twice less (AK-1.25-45 and AK-1.25-60) yielded a strength ratio of 2.06% higher and 2.93% less respectively. These results confirm that MSNFRRC has a slight effect on the strength of confined high strength concrete.

![Fig. 5. Strength ratio trend of specimens due to spiral spacing and different volume fractions of macro synthetic fibers](image)

(a) spiral spacing ; (b) volume fraction of fiber ; (c) comparison with AK-0-30

3.6. Column Ductility

Concrete strain ductility ratio is a very important factor in seismic design. It is commonly defined as the ratio between confined concrete strain at 85% of peak stress on the descending branches and unconfined concrete strain at peak stress [23]. The spiral spacing and the volume fraction of macro synthetic fibers play a significant role in ductility improvement due to their confinement of the concrete. Figure 7 shows a plot of the strain ductility versus spiral spacing (6(a)) and volume fraction of macro synthetic fibers (6(b)). According to these figures, there is a general trend wherein the ductility ratio improves with a decrease of spiral spacing and increase of the volume fraction of macro synthetic fibers. The highest improvement effect on the ductility of the confinement in this experimental study was shown by the column specimen with the highest volumetric ratio of confining reinforcement.

![Fig. 6. Ductility trend of specimens due to spiral spacing and different volume fractions of macro synthetic fibers](image)

(a) spiral spacing ; (b) volume fraction of fiber ; (c) comparison with AK-0-30
The closest spiral spacing (S-30) refers to the code minimum requirement of spiral reinforcement. The combined confinement effect of spiral spacing and macro synthetic fiber reinforced concrete resulted in a better confining ability. While the remaining specimens were detailed with reduced spiral spacing reinforcements, their behaviour exhibited better ductility when MSNFRC was used. Figure 6(c) shows that combining a high volume fraction of macro synthetic fibers and using half and twice less spiral spacing (AK-1.25-45 and AK-1.25-60) still improved ductility 62.83% and 25.03% respectively. These results confirm that MSNFRC has a significant effect on the ductility of confined high strength concrete. Hence, the code required spiral reinforcement can be reduced when MSNFRC is used.

4. Conclusions

The findings obtained from this experimental study can be summarized as follows:
1. The performance of spirally confined MSNFRC columns under concentric axial compression showed significant improvement in ductility, but only slight improvement in strength.
2. The combined confinement effect of spiral spacing and MSNFRC works well to delay brittle degradation of column strength and exhibits ductile behavior.
3. The highest improvement effect on the strength and ductility of the confinement in this experimental study was shown by the column specimen with the highest volumetric ratio of confining reinforcement.

These experimental results confirm that MSNFRC can play a significant role in confining high strength concrete and can reduce the amount of confining reinforcement required according to the design codes for HSC columns.

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