Evaluation on the Mechanical Properties of Steel-Fiber Concrete at Elevated Temperatures

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Abstract. This paper presents experimental results on mechanical properties of steel-fibre concrete burned at high temperatures, which consists of tensile strength, modulus of elasticity and flexural modulus. The steel-fibre usage is limited to 0.5% of concrete volume. The reviewed parameters in the evaluation include compressive strength of normal to high-strength concrete, and temperature (normal, 300°C, 600°C, 900°C). The specimens are heated up after it reached 120 days of age. Experimental results toward mechanical behaviour indicate that tensile strength tends to decline linearly at 300°C and 600°C respectively. The value of modulus of elasticity and flexural modulus of fibre-reinforced concrete heated at 300°C, 600°C and 900°C tend to decline linearly. The results of the experimental evaluation also proposed a model for tensile strength degradation equation, modulus of elasticity and flexural modulus against temperature.

1. Introduction
Recently, there has been considerable developments in concrete technology. High-strength concrete (f’c > 50 MPa), or even ultra high strength concrete (f’c > 100 MPa) are produced at mass scale to date. Among others, Antonius [1] has done extensive research for design equation of high-strength concrete, and then developed a confinement model [2]. Another development of concrete technology is steel-fiber concrete. Due to its ductility, this material has become one of the preferred choices for construction at high-seismic intensity zone. The use of steel-fiber concrete also has the advantage of being more efficient at installing confinement bars [3].

Steel-fiber concrete is tremendously sensitive towards high temperatures. Various tests have been conducted where the thermal properties of steel-fiber concrete are tested at normal to high temperatures [4-6]. Zaidi et al. [7] investigates and proposes a model for confined post-heating fiber-reinforced concrete behavior. Antonius et.al. [8] also investigates mechanical properties of steel-fiber concrete at a normal to high temperature. The results proposed a model for degradation equation of compressive strength of steel-fiber concrete from normal to high temperature and stress-strain model, but other mechanical behavior such as tensile strength (fₜ), modulus of elasticity (Eₑ) and modulus of rupture (Eᵣ) are still yet to be further explored. This paper describes and discusses experimental evaluation of tensile strength, modulus of elasticity and modulus of rupture behavior of steel-fiber concrete at various temperatures (7).

2. Program Experiment

2.1. Design of Concrete Mixture
Design of steel-fiber concrete mixture is shown in Table 1. The utilized content of steel fiber is 0.5% of concrete volume, where the length to diameter ratio is approximately between 40 and 50. The test specimens are divided into three categories based on water-cement ratio: Mixture I, II, and III. The mixing process uses common materials such as cement, fine aggregate and coarse aggregate. Viscocrete is added to Mixture II and III to maintain concrete workability that has a low composition of water-cement ratio (w/c < 0.45).

### Table 1. Mix design of fiber-reinforced concrete

| Materials                  | Mixture I | Mixture II | Mixture III |
|----------------------------|-----------|------------|-------------|
| w/c = 0.53 (Mixture I)    | 350       | 419.98     | 485         |
| w/c = 0.38 (Mixture II)   | -         | 74.11      | 82.83       |
| w/c = 0.30 (Mixture III)  | 200       | 160        | 140         |
| Cement (kg/m³)            | 400       | 370        | 350         |
| Fly ash (kg/m³)           | 74.11     | 82.83      | 90          |
| Water (L/m³)              | 200       | 160        | 140         |
| Viscocrete 0.5% (L/m³)    | -         | 6.228      | 9.28        |
| Fine aggregate (kg/m³)    | 722.9     | 696.62     | 662.07      |
| Coarse aggregate (kg/m³)  | 886.8     | 1044.93    | 1080.22     |

2.2. Heating of Specimens and Testing Method
The specimens are heated up to 300ºC, 600ºC and 900ºC, this process is explained in detail by Antonius et. al. [7]. The method to evaluate tensile strength, modulus of elasticity and flexural modulus refers to ASTM standard [9-11].

3. Experimental Results and Discussion
The above design of concrete mix resulted in three categories of compressive strength ($f'_c$) for each specimen: 30.4 MPa, 51.1 MPa and 72.5 MPa. The specimens consist of unheated specimens or normal temperature (32ºC), and specimens heated at 300ºC, 600ºC and 900ºC. Each compressive strength with a specific thermal condition consisted of three specimens, which will be explained further below.

### 3.1. Tensile Strength of Fiber-Reinforced Concrete in Various Temperatures
The tensile strength test results of all test specimens are shown in Table 2. Furthermore, the relationship between tensile strength of normalized specimen and tensile strength of specimen at a normal temperature ($f_0/f'_c$) towards temperature, is shown in figure 1. As seen in figure 1, the 40% loss of tensile strength in concrete occurs if specimens are heated at 300ºC, this loss will keep increasing linearly until it reaches 600ºC. Furthermore, specimens at temperature 600ºC to 900ºC showed a steady decline in terms of tensile strength. Based on figure 1, a relational equation between tensile strength and temperature at normal temperatures up to 600ºC, and above 600ºC can be derived at the basis of linear regression.

### Table 2. Tensile strength at elevated temperatures

| Compressive strength | Specimen | Normal temperature | Temperature of 300°C | Temperature of 600°C | Temperature of 900°C |
|----------------------|----------|--------------------|---------------------|----------------------|----------------------|
|                      |          | $P_{max}$ (kN)     | $f_t$ (Mpa)         | $P_{max}$ (kN)       | $P_{max}$ (kN)       |
| 30.4 MPa             | 1        | 392                | 2.77                | 230                  | 1.63                 | 90                   | 0.64 | 60 | 0.42 |
|                      | 2        | 376                | 2.66                | 220                  | 1.56                 | 88                   | 0.62 | 80 | 0.57 |
|                      | 3        | 380                | 2.69                | 215                  | 1.52                 | 85                   | 0.6       | 65 | 0.46 |
| average              |          | 382.67             | 2.71                | 221.67               | 1.57                 | 87.67                | 0.62 | 68.33 | 0.48 |
| 51.1 MPa             | 1        | 580                | 4.1                 | 390                  | 2.76                 | 140                  | 0.99 | 110 | 0.78 |
|                      | 2        | 591                | 4.18                | 360                  | 2.55                 | 130                  | 0.92 | 103 | 0.73 |
4.06 340 2.41 130 0.92 108 76
average 581.67 4.11 363.33 2.57 133.33 0.94 107.00 25.84
72.5 Mpa
1 2 3
705 724 724
4.99 5.12 5.12
450 445 451.67
3.18 3.15 3.20
190 192 189.00
1.34 1.36 1.34
90 86 95.33
0.64 0.61 0.68
average 706.33 5.00 451.67 3.20 189.00 1.34 95.33 0.68

For $T \leq 600^\circ C$:

$$\frac{f_{it}}{f_i} = 1 - 0.0013T$$  \hspace{1cm} (1)

where $R^2=0.992$

and $T > 600^\circ C$:

$$\frac{f_{it}}{f_i} = 0.4 - 0.0003T$$  \hspace{1cm} (2)

where $R^2=0.992$

![Figure 1. Tensile strength vs elevated temperatures](image)

3.2. Modulus of Elasticity of Steel-Fiber Concrete in Various Temperatures

Table 3 shows the test results of modulus of elasticity of steel-fiber concrete. At a normal temperature, all specimens tend to have an inflated modulus of elasticity value that is proportional to the root of concrete compressive strength root (figure 2). The following equation is the result of linear regression:

$$E_c = 4410\sqrt{f_{c}} + 1000$$  \hspace{1cm} (3)

| Compressive strength | Specimen | Normal temperature | Temperature of 300°C | Temperature of 600°C | Temperature of 900°C |
|----------------------|----------|--------------------|----------------------|----------------------|----------------------|
| 30.4 MPa             | 1        | 23236              | 20743                | 12876                | 8650                |
|                      | 2        | 23241              | 19574                | 11683                | 8658                |
|                      | 3        | 24478              | 19750                | 12750                | 9683                |
|                      | average  | 23651.67           | 20022.33             | 12436.33             | 8997.00             |
| 51.1 MPa             | 1        | 33210              | 26960                | 16480                | 10465               |

Table 3. Modulus of Elasticity at elevated temperatures
2 32252 25876 18463 9738
3 31674 24769 16432 10468
average 32378.67 25868.33 17125.00 10223.67

72.5 Mpa
1 39489 33860 18765 14748
2 39247 35987 19276 13499
3 40478 36850 18760 13241
average 39738.00 35565.67 18933.67 13829.33

Figure 2. Modulus of Elasticity at a normal temperature

Figure 3 shows the trend of linear downturn value of modulus of elasticity against the escalation of temperature. At 300ºC, 600ºC, and 900ºC, the downturn trend of elasticity modulus stands at 20%, 50% and 65% against the value modulus of elasticity at normal temperatures. The result of linear regression is shown in equation (4).

Modulus of rupture value of steel-fiber concrete is declining consistently at a linear fashion from normal temperatures to 300ºC, 600ºC and 900ºC, where the rates of decline are 35%, 75% and 97% (figure 4). Modulus of rupture value in this test has a drastic decline compared to preceding modulus of elasticity

3.3. Modulus of Rupture of Steel-Fiber Concrete in Various Temperatures

The flexural modulus value of steel-fiber concrete at various temperatures is shown in table 4. Modulus of rupture value of steel-fiber concrete is declining consistently at a linear fashion from normal temperatures to 300ºC, 600ºC and 900ºC, where the rates of decline are 35%, 75% and 97% (figure 4). Modulus of rupture value in this test has a drastic decline compared to preceding modulus of elasticity
test, which still leaves approximately 25% of the initial strength at 900°C. The relationship that explains degradation value between flexural modulus of steel-fiber concrete and temperature is determined based on linear regression that resulting in equation (5).

### Table 4. Modulus of rupture at elevated temperatures

| Compressive strength | Specimen | Modulus of Rupture, fr (MPa) |
|----------------------|----------|-------------------------------|
|                      |          | Normal temperature | Temperature of 300°C | Temperature of 600°C | Temperature of 900°C |
| 30.4 MPa             | 1        | 5.9               | 4.1               | 1.4               | 0.15               |
|                      | 2        | 6.3               | 4.4               | 1.05              | 0.16               |
|                      | 3        | 5.4               | 3.9               | 1.3               | 0.17               |
|                      | average  | 5.87              | 4.13              | 1.25              | 0.16               |
| 51.1 MPa             | 1        | 8.1               | 5.6               | 2.2               | 0.22               |
|                      | 2        | 8.3               | 5.4               | 2.4               | 0.19               |
|                      | 3        | 7.8               | 5.25              | 2.1               | 0.2                |
|                      | average  | 8.07              | 5.42              | 2.23              | 0.20               |
| 72.5 Mpa             | 1        | 11.1              | 7.2               | 3.9               | 0.78               |
|                      | 2        | 10.1              | 7.7               | 3.7               | 0.75               |
|                      | 3        | 11.6              | 7.2               | 3.65              | 0.74               |
|                      | average  | 10.93             | 7.37              | 3.75              | 0.76               |

![Figure 4. Modulus of rupture vs elevated temperatures](image)

4. Conclusion
From normal temperatures to 600°C, tensile strength value of steel-fiber concrete tend to decline linearly. At 600°C to 900°C, it begins to decline disproportionately. The decline of modulus of elasticity of steel-fiber concrete against elevation of temperature tends to be consistent and linear up to the residual limit, which is approximately 25% at 900°C. The decline of modulus of rupture of steel-fiber concrete against elevation of temperature tend to happen drastically and linearly until it has no relative value at 900°C. Relationship between tensile strength, modulus of elasticity, and flexural modulus against temperature is modeled through equation (1), (2), (4) and (5).
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