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# High Strength Polypropylene Fibre Reinforcement Concrete at High Temperature

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***Abstract.*** Concrete is an inherently brittle material with a relatively low tensile strength compared to compressive strength. Reinforcement with randomly distributed short fibres presents an effective approach to the stabilization of the crack and improving the ductility and tensile strength of concrete. A variety of fibre types, including steel, synthetics, and natural fibres, have been applied to concrete. Polypropylene (PP) fibre reinforcement is considered to be an effective method for improving the shrinkage cracking characteristics, toughness, and impact resistance of concrete materials. Also, the use of PP fibre has been recommended by all of the researchers to reduce and eliminate the risk of the explosive spalling in high strength concrete at elevated temperatures. In this study, constitutive relationships are developed for normal and high-strength PP fibre reinforcement concrete (PPFRC) subjected to high temperatures to provide efficient modelling and specify the fire-performance criteria for concrete structures. They are developed for unconfined PPFRC specimens that include compressive and tensile strengths, elastic modulus, modulus of rupture, strain at peak stress as well as compressive stress–strain relationships at elevated temperatures. The proposed relationships at elevated temperature are compared with experimental results. These results are used to establish more accurate and general compressive stress–strain relationships prediction. Further experimental results for tension and the other main parameters at elevated temperature are needed in order to establish well-founded models and to improve the proposed constitutive relationships, which are general, rational, and fit well with the experimental results.

**Keywords:** Constitutive relationships, Polypropylene fibre reinforcement concrete, Fire, Mechanical properties, Elevated temperature

## 1. Introduction

Fiber reinforced concrete (FRC) has been studied over the past three decades in terms of the improved crack control. This is of further importance when fibers are incorporated in an inherently brittle material such as high strength concrete (HSC), the use of which has increased progressively not only due to the higher load carrying capacity but also due to the improvement in durability and service

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life. The higher load carrying capacity of HSC is normally accompanied by more brittle behavior, which can be compensated in a rational manner through the incorporation of fibers. Many studies on the degradation of concrete when it is exposed to high temperatures have been reported. Concrete structures may be exposed to high temperatures, by accidental causes or by the characteristics of the structural application. As a consequence, concrete undergoes changes that may result, in many cases, in extensive cracking. In this sense, it is interesting to study the contribution of fibers to control crack formation and propagation [10].

The mechanical properties of fiber reinforced concrete (FRC) after high temperatures have received considerable attention in recent years [8, 11, 17, 19]. When PP fibers are utilized to control fresh and hardened properties of cement-based materials at ambient temperature, it has been found that PP fibers can decrease the plastic shrinkage [1], and they also have a minor effect on the compressive and flexural strengths. The effect on strength, in fact, has been reported to be contradictory [1, 2]. Therefore, the beneficial effect of avoiding or reducing explosive spalling raises the question of how much PP fibers will affect the residual mechanical behavior of high performance concrete (HPC) exposed to elevated temperatures. The investigation on cement paste by Komonen and Penttala [12] have indicated that inclusion of PP fibers produces a finer residual capillary pore structure, decreases residual compressive strength and improves residual flexural strength when temperature ranged from 150°C to 440°C, whereas the residual flexural strength decreases considerably when temperature rises beyond 440°C to 520°C. Furthermore, Poon et al. [17] have concluded that inclusion of PP fibers results in a quicker loss of the compressive strength and toughness of concrete (besides Portland cement, cement both with and without metakaolin or silica fume were included in their research) after exposure to elevated temperature (up to 800°C). However, they also have found that the residual compressive strength of HPC with ordinary Portland cement containing PP fibers (0.22% by volume) increases 4.6% after exposure to 600°C, while it decreases 3.2% after exposure to 800°C, compared with that for HPC without PP fibers. From their investigation, it may be deduced that the effects of PP fibers on the residual mechanical strength of HPCs after exposure to elevated temperatures still need to be further studied [21].

Structural fire safety is one of the primary considerations in the design of high-rise buildings and infrastructures, where concrete is often the material of choice for structural members. At present, the fire-resistance of reinforced concrete (RC) members is generally established using prescriptive approaches that are based on either the standard fire-resistance tests or empirical methods of calculation. Although these approaches have drawbacks, there have been no significant failures of concrete structures or members made of either high-strength PPFRC exposed to high temperatures when designed in accordance with current codes, there is an increased focus on the use of numerical methods for evaluating the fire performance of structural members. Because this depends on the properties of the constituent materials, knowledge of the elevated-temperature properties of concrete is critical for fire-resistance assessment under performance-based codes [3].

The properties that are known to control PPFRC behavior at elevated temperatures are compressive strength, tensile strength, peak strain (i.e. strain at peak stress), modulus of elasticity, flexural tensile strength (modulus of rupture), and others that are non-linear functions of temperature. Many compressive and tensile constitutive models for concrete at normal temperature are available. The constitutive laws of concrete materials under fire conditions are complicated and current knowledge of thermal properties is based on the outcome of limited experimental tests of material properties. There are only limited test data for some high-temperature properties of PPFRC and there are considerable variations and discrepancies in the high-temperature test data for other properties of PPFRC. This paper proposes reliable constitutive relationships for high strength PPFRC for fire-resistance predictions of RC members.

## 2. Research Significance

Although computational methods and techniques for evaluating the fire performance of structural members of buildings have been developed in recent years, research related to supplying input information (material properties) into these computational methods has not developed enough. There is an urgent need to establish constitutive relationships for modeling the fire response of PPFRC members because the use of PPFRC has considerably developed during the last years. The objectives of this study are: a) proposing new mechanical properties relationships for PPFRC mixtures at elevated temperature (i.e. compressive and tensile strengths, modulus of elasticity, modulus of rupture, and peak strain at maximum compressive strength), b) proposing new compressive and tensile stress–strain relationships for PPFRC at elevated temperatures.

## 3. Database of Experimental Results

An experimental results database from various published investigations is an effective tool for studying the applicability of the various high temperature behaviors for PPFRC. To apply the models to a particular concrete mixture accurately, it is necessary to use only investigations that are sufficiently consistent with the applied testing methodology. The PPFRC experimental results included in the database were gathered mainly from papers presented at various published articles. The database includes information regarding the composition of the mixtures, fresh properties of PPFRC, testing methodology, and conditions. Mechanical properties at high temperatures have not been investigated as much as the other aspects of PPFRC.

Tables 1 and 2 include general information about the experimental tests, such as fiber content ($V_f$), type of fiber, aggregate and cement type, temperatures, rate of heating, and specimens type. Table 1 shows that general type of cement that is used in the most of researches is Ordinary Portland Cement (OPC). Also, PP fiber content ($V_f$) is varied between 0.11% and 0.6%. Moreover, most of fine aggregate that are used in the database is natural river sand and type of coarse aggregate is varied. Table 2 indicates different type of PPFRC specimens are used for thermal behavior analysis. Also, heating rate range in the experimental results database is between 0.5°C/min to 10°C/min. The temperature that is used for different research is varied between 20°C to 900°C.

## 4. Compressive Strength of PPFRC at Elevated Temperatures

The residual compressive behavior of concrete has been under investigation since the early 1960s (see the contributions by Zoldners, Dougill, Harmathy, Crook, Kasami et al., Schneider and Diederiches, all quoted in [18]. Attention has been focused mostly on the compressive strength (the strength at room temperature after a specimen has been heated to a test temperature and subsequently cooled) as such, on the residual strain and on strength recovery with time [9]. In this contribution the efforts are focused on producing compressive strength relationships for PPFRC of different strength classes which incorporate different PP fiber content, in order to investigate their performance after exposure at gradually up scaled temperature.

In this study, the relationships proposed for the compressive strength of PPFRC by considering PP fiber various volume fractions at elevated temperature are based on regression analyses on existing experimental data with the results expressed as Equations (1) to (2). The main aim of regression analyses is considering the variation experimental compressive strength of PPFRC behaviors at different elevated temperatures and developing the rational and simple relationships that can fit well with experimental data.

The nonlinear regression understating and interpreting are described as follow. Similar to linear regression, the goal of nonlinear regression is to determine the best-fit parameters for a model by minimizing a chosen merit function. Where nonlinear regression differs is that the model has a nonlinear dependence on the unknown parameters, and the process of merit function minimization is an iterative approach. The process is to start with some initial estimates and incorporates algorithms to improve the estimates iteratively. The new estimates then become a starting point for the next iteration. These iterations continue until the merit function effectively stops decreasing.

The compressive strength versus fiber volume fraction prediction is proposed as Eq. (1). Also, the PPFRC compressive strength at elevated temperatures based on the experimental results are captured as shown in Equation (2). The Equation (1) should use in the Equation (2) to appropriate prediction of PPFRC compressive strength at different high temperatures and fiber content. These proposed relationships are compared separately with test results, as shown in Figures 1 to 2.

$$f'_{cf} = f'_c - 46.36\ V_f \tag{1}$$

**Table 1**
**Experimental Results Database Properties**

| Reference | Fiber content ($V_f$) | Type of fiber | Aggregate and cement type |
|---|---|---|---|
| Chen and Liu [8] | 0.6% | Straight, round PP fibers (length 15 mm × diameter 0.01 mm) | Crushed limestone aggregate, river sand, and OPC |
| Poon et al. [17] | 0.11% and 0.22% | PP fibers (length 19 mm × diameter 0.052 mm) | Crushed granite aggregate, natural river sand, and OPC |
| Noumowe [14] | 0.2% | PP fibers (length 13 mm) | OPC, French CPA CEM I 52.5 |
| Peng et al. [15] | 0.11% | PP fibers (length 20 mm × diameter 0.02 mm) | Crushed limestone aggregate and OPC |
| Suhaendi and Horiguchi [20] | 0.25% and 0.5% | PP fibers (length 6, 30 mm × diameter 0.06 mm) | Sandstone coarse aggregate, river sand, and OPC |
| Xiao and Falkner [21] | 0.22% | PP fibers (length 15 mm × diameter 0.045 mm) | Calcareous and crushed stone, river sand, and OPC |
| Behnood and Ghandehari [7] | 0.11%, 0.22% and 0.33% | PP fibrillated fibers (length 12 mm) | Limestone coarse aggregate, river sand, and OPC |
| Pliya et al. [16] | 0.11% and 0.22% | PP fibers (length 6 mm × diameter 0.018 mm) | Alluvial siliceous–calcareous aggregate and cement was I 52.5 N CE CP2 NF |

$$f'_{cT} = f'_{cf} \left\{ \begin{array}{ll} 1.0 & 20^{\circ}\mathrm{C} \\ 1.0237 - 0.00105\ T + 1 \times 10^{-7}\, T^2 & 100^{\circ}\mathrm{C} \leq T \leq 800^{\circ}\mathrm{C} \end{array} \right\} \tag{2}$$

where $f'_c$ is the compressive strength without fiber, $f'_c$ is the compressive strength of fiber reinforced concrete. Figure 1 makes an evaluation between proposed relationship for compressive strength against PP fiber volume fraction. Experimental results show that compressive strength will be decreased by increasing PP fiber content. Comparison of compressive strength of concrete with different fiber content shows that compressive strength will decreases 10.03%, 20%, 30.1%, and 40.1% by adding 0.2%, 0.4%, 0.6%, and 0.8% fiber to the concrete, respectively. Figure 2 creates comparison between proposed relationship for compressive strength of PPFRC at different temperatures against published unstressed experimental test results (unstressed tests: the specimen is heated, without preload, at a constant rate to the target temperature, which is maintained until a thermal steady state is achieved) [7, 8, 11, 14, 16, 20, 21]. The experimental results indicate that compressive strength decreases up to 38.30% at 400°C temperature and it reduces to 75.23% at 800°C temperature. The proposed relationships fit the experimental results well in comparison with others.

**Table 2**
**Continued Experimental Results Database Properties**

| Reference | Temperatures | Rate of heating | Specimens type |
|---|---|---|---|
| Chen and Liu [8] | 20°C, 200°C, 400°C, 600°C, and 800°C | 10°C/min | (100 mm) cubes |
| Poon et al. [17] | 20°C, 600°C, and 800°C | 2.5°C/min | (100 mm) cubes and (100 × 200 mm) cylinders |
| Noumowe [14] | 20°C and 200°C | 0.5°C/min | (160 × 320 mm) cylinders and (110 × 220 mm) cylinders |
| Peng et al. [15] | 20°C, 400°C, 600°C and 800°C | 10°C/min | (100 mm) cubes and (300 × 100 × 100 mm) flexural beams |
| Suhaendi and Horiguchi [20] | 20°C, 200°C, and 400°C | 10°C/min | (100 × 200 mm) cylinders |
| Xiao and Falkner [21] | 20°C, 100°C, 200°C, 300°C, 400°C, 500°C, 600°C, 700°C, 800°C, and 900°C | 3°C/min | (100 mm) cubes and (515 × 100 × 100 mm) flexural beams |
| Behnood and Ghandehari [7] | 20°C, 100°C, 200°C, 300°C, and 600°C | 3°C/min | (102 × 204 mm) cylinders |
| Pliya et al. [16] | 20°C, 150°C, 300°C, 450°C, and 600°C | 1°C/min | (160 × 320 mm) cylinders and (400 × 100 × 100 mm) flexural beams |

## 5. Tensile Strength of PPFRC at Elevated Temperatures

Very little attention has been paid to concrete behaviour in tension, either direct or indirect (in bending or splitting) at high temperatures. Before the mid-1980s [18], the studies in this area are limited and a few of them are still unpublished. Furthermore, another reason to investigate concrete properties in tension is spalling of the material [9]. In this study, the relationships proposed for the tensile strength of PPFRC by including fiber content at elevated temperature are based on regression analyses on existing experimental data with the results expressed as Equations (3) to (4). The main aim of regression analyses is considering the changeable experimental tensile strength of PPFRC behaviors at different elevated temperatures and developing the rational and simple relationships that are in good correlation with test results. The tensile strength versus fiber volume fraction prediction is proposed as Equation (3). The Equation (3) should use in the Equation (4) to suitable prediction of PPFRC tensile strength at different high temperatures and fiber content.

$$f_{ctf} = f_{ct} + 0.626\ V_f \tag{3}$$

$$f_{ctT} = f_{ctf} \left\{ \begin{array}{ll} 1.0 & 20^{\circ}\mathrm{C} \\ 1.0237 - 0.00107\ T + 1 \times 10^{-7}\ T^2 & 100^{\circ}\mathrm{C} \le T \le 800^{\circ}\mathrm{C} \end{array} \right\} \tag{4}$$

where $f_{ct}$ is the tensile strength without fiber, $f_{ctf}$ is the tensile strength of fiber reinforced concrete. Figure 3 creates an evaluation between proposed relationship for tensile strength against steel fiber volume fraction. Experimental results show that tensile strength will be increase by increasing steel fiber content. Comparison of tensile strength of concrete with different fiber content shows that tensile strength will increases 2.18%, 4.26%, 6.26%, and 8.18% by adding 0.2%, 0.4%, 0.6%, and 0.8% fiber to the concrete, respectively. Figure 4 makes comparison between PPFRC tensile strength proposed relationship at different temperatures against published unstressed experimental test results [7, 8, 15, 20]. The experimental results indicate that tensile strength decreases up to 38.83% at 400°C temperature and it reduces to 76.83% at 800°C temperature. The proposed relationships for tensile strength of PPFRC against the unstressed experimental results are shown that the results provide a reasonable fit to the available experimental data.

## 6. Modulus of Elasticity of PPFRC at Elevated Temperatures

The elastic modulus of concrete could be affected primarily by the same factors that influence its compressive strength [13]. The modulus of elasticity versus fiber volume fraction prediction is proposed as Equation (5). Moreover, a relationship is proposed to evaluate the elasticity modulus of PPFRC at elevated temperatures using regression analyses conducted on experimental data and is expressed as Equation (6). The regression analyses is considering the changeable experimental elastic modulus of PPFRC behaviors at different elevated temperatures and developing the rational and simple relationships that can fits well with experimental data. The Equation (5) should use in the Equation (6) to proper prediction of PPFRC modulus of elasticity at different high temperatures and fiber content.

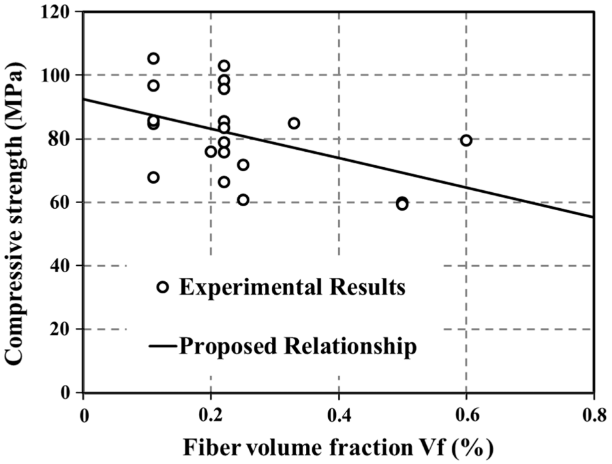

**Figure 1. Effect of fiber volume on compressive strength.**

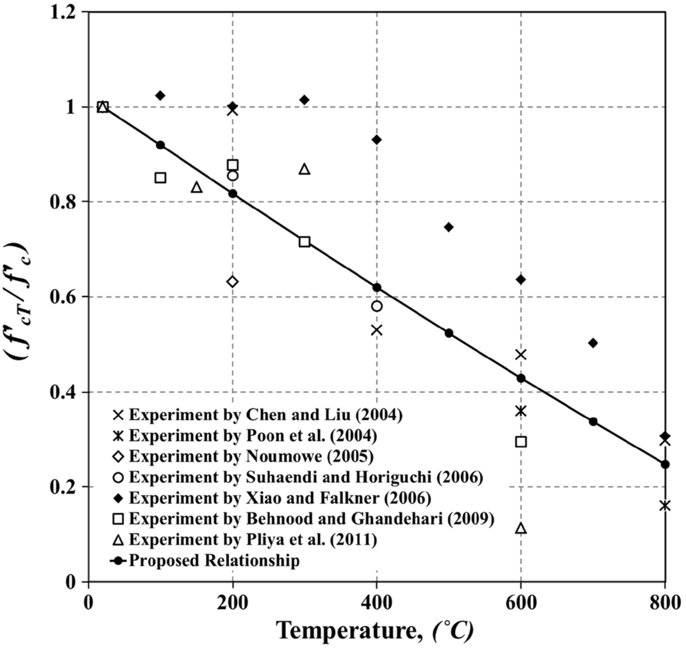

**Figure 2. Comparison between compressive strength proposed relationship of PPFRC with experimental test results.**

$$E_{cf} = E_c - 31.177\ V_f \tag{5}$$

$$E_{cT} = E_{cf} \begin{Bmatrix} 1.0 & 20°\text{C} \\ 1.01 - 0.0013\ T + 10^{-7}\ T^2 & 100°\text{C} \le T \le 800°\text{C} \end{Bmatrix} \tag{6}$$

where $E_c$ is the modulus of elasticity without fiber, $E_{cf}$ is the modulus of elasticity of fiber reinforced concrete. Figure 5 makes comparison between proposed relationship for modulus of elasticity against PP fiber volume fraction. Experimental results show that modulus of elasticity will be slightly increase by increasing PP fiber content. Comparison of modulus of elasticity of concrete with different fiber content shows that modulus of elasticity will increases 13.67%, 27.35%, and 41.03% by adding 0.2%, 0.4%, and 0.6% fiber to the concrete, respectively. Figure 6 makes comparison between PPFRC modulus of elasticity proposed relationship at different temperatures against published unstressed experimental test results [14, 16, 20]. The experimental results indicate that modulus of elasticity decreases up to 49.4% at 400°C temperature and it reduces to 96.6% at 800°C temperature. The proposed relationship is in agreement with the experimental test results.

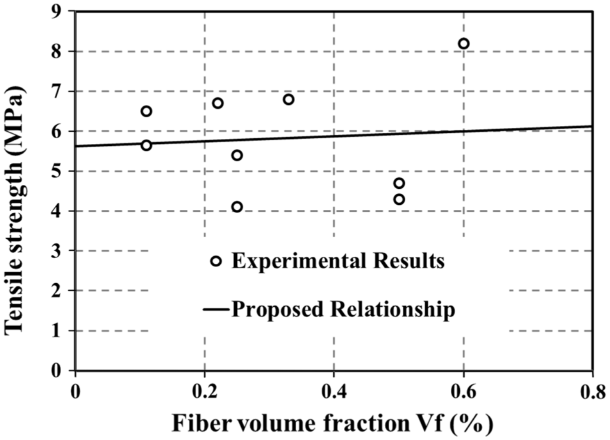

**Figure 3. Effect of fiber volume on tensile strength.**

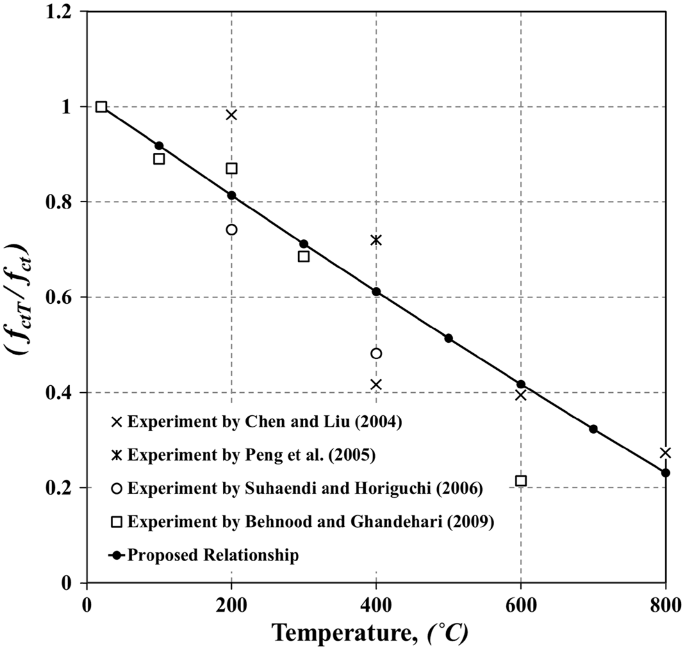

**Figure 4. Comparison between tensile strength proposed relationship of PPFRC with experimental test results.**

## 7. Modulus of Rupture of PPFRC at Elevated Temperatures

There are studies on flexural tensile strength (modulus of rupture). For example, Lau and Anson (2006) carried out both compression and flexural tests on both

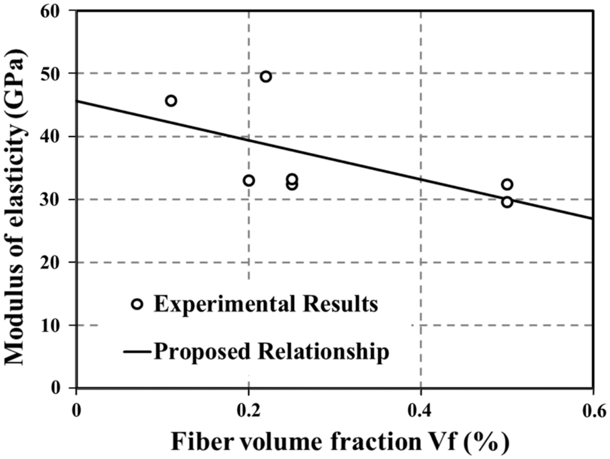

**Figure 5. Effect of fiber volume on modulus of elasticity.**

plain concrete and 1% PPFRC under high temperatures ranging between 105°C and 1,200°C. Their results indicated a decrease in both compressive and flexural strength for both the plain and PPFRC. However, PPFRC was able to resist high temperatures much better than plain concrete—as seen by a much higher residual strength at all temperature levels. Poon et al. [17] experimented with compression to determine strength and toughness of PPFRC and polypropylene FRC, at temperatures between 200°C and 800°C. At temperatures lower than 200°C, the compressive strength of both plain and FRC remained unchanged. The strength was found to decrease linearly as the temperature increased above 200°C. As for compression toughness, PPFRC was found to maintain its energy absorption better than plain concrete even at the highest temperatures. The modulus of rupture versus fiber volume fraction prediction is proposed as Equation (7). Also, a relationship is suggested to calculate the modulus of rupture of PPFRC at elevated temperatures using regression investigates conducted on experimental data and is expressed as Equation (8). The regression analyses is considering the variable experimental modulus of rupture of PPFRC behaviors at different elevated temperatures and developing the rational and simple relationships that can fits well with experimental data. The Equation (7) should use in the Equation (8) to proper calculation of PPFRC modulus of rupture at different high temperatures and fiber content.

$$f_{crf} = f_{cr} - 1.726\ V_f \tag{7}$$

$$f_{crT} = f_{crf} \left\{ \begin{array}{ll} 1.0 & 20^\circ\mathrm{C} \\ 1.1 - 0.0019\ T + 8 \times 10^{-7}\ T^2 & 100^\circ\mathrm{C} \leq T \leq 900^\circ\mathrm{C} \end{array} \right\} \tag{8}$$

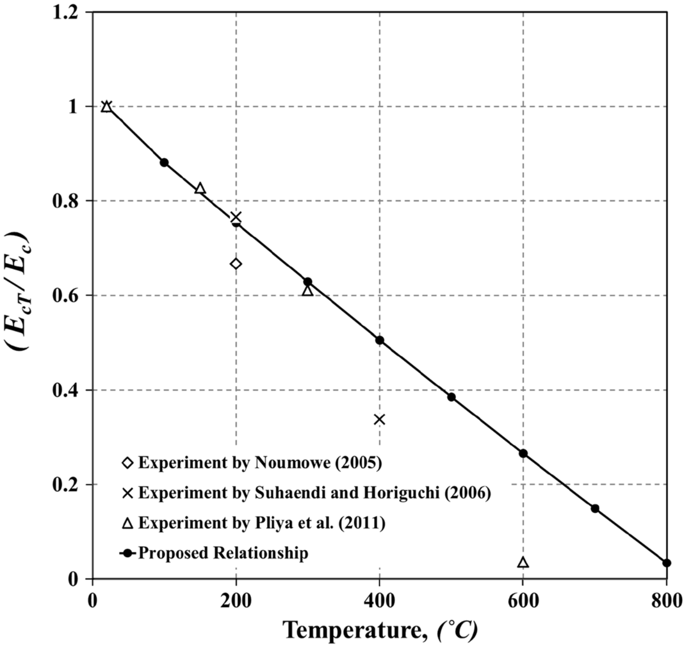

**Figure 6. Comparison between modulus of elasticity proposed relationship of PPFRC with experimental test results.**

where $f_{cr}$ is the modulus of rupture without fiber, $f_{crf}$ is the modulus of rupture of fiber reinforced concrete. Figure 7 makes comparison between proposed relationship for modulus of rupture against PP fiber volume fraction. Experimental results show that modulus of rupture will be decreased by increasing PP fiber content. Comparison of modulus of rupture of concrete with different fiber content shows that modulus of rupture will increases 5.22% and 10.45% by adding 0.2% and 0.4% fiber to the concrete, respectively. Figure 8 makes comparison between PPFRC modulus of rupture proposed relationship at different temperatures against published unstressed experimental test results [16, 21]. The experimental results indicate that modulus of rupture decreases up to 53.2% at 400°C and 96.2% at 900°C temperature. The proposed relationship is in agreement with the experimental test results.

## 8. Strain at Peak Stress (Peak Strain) at Elevated Temperatures

In this study, the relationships proposed for the peak strain of PPFRC at elevated temperature are based on regression analyses on existing experimental data with the results expressed as Equations 9 and 10. The Equation (9) should use in the Equation (10) to suitable calculation of PPFRC peak strain at different high temperatures and fiber content.

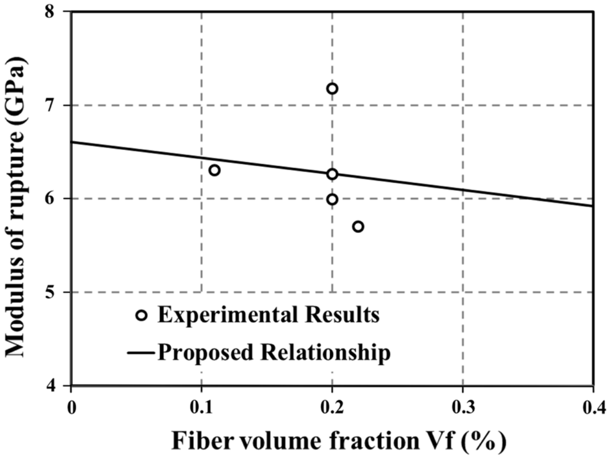

**Figure 7. Effect of fiber volume on modulus of rupture.**

$$\varepsilon_{cf} = 0.0088 - 0.0075\ V_f \tag{9}$$

$$\varepsilon_{cT} = \varepsilon_{cf} \left\{ \begin{array}{ll} 1.0 & 20^\circ\mathrm{C} \\ 1.0037 - 0.0001\ T & 100^\circ\mathrm{C} \le T \le 500^\circ\mathrm{C} \\ 1.0266 - 0.0014\ T + 2.2 \times 10^{-6}\ T^2 & 600^\circ\mathrm{C} \le T \le 800^\circ\mathrm{C} \end{array} \right\} \tag{10}$$

where $\varepsilon_{cf}$ is the peak strain of fiber reinforced concrete. Figure 9 makes comparison between proposed relationship for peak strain against PP fiber volume fraction. Experimental results show that peak strain will be decrease by increasing PP fiber content. Comparison of peak strain of concrete with different fiber content shows that peak strain will increases 8.52%, 17.04%, and 21.30% by adding 0.1%, 0.2%, and 0.25% fiber to the concrete, respectively. Figure 10 makes comparison between PPFRC peak strain proposed relationship at different temperatures against published unstressed experimental test results [14, 17]. The experimental results indicate that peak strain decreases up to 4.65% at 400°C temperature and it rose to 31.46% at 800°C temperature. The proposed relationship is in agreement with the experimental test results.

## 9. Compressive Stress–Strain Relationship for PPFRC at Elevated Temperatures

In the structural design of heated concrete, the entire stress–strain curve, often in idealized form, must be considered as a function of temperature. In this study, a compressive stress–strain relationship for PPFRC at elevated temperatures that is based on modified Authors' [5, 6] model and is developed by using proposed

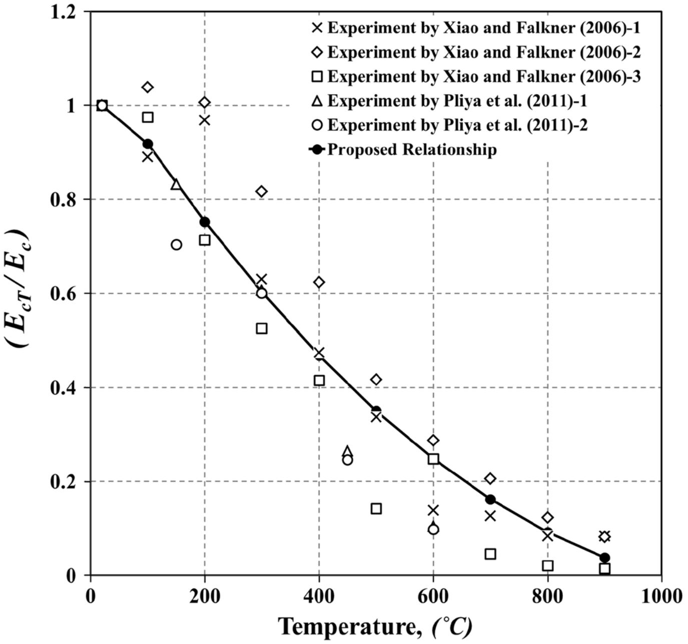

**Figure 8. Comparison between modulus of rupture proposed relationship of PPFRC with experimental test results.**

compressive strength [Equations (1) to (2)], elastic modulus [Equations (5) to (6)], and peak strain [Equations (9) to (10)] relationships.

$$\frac{\sigma_c}{f'_c} = \frac{n\left(\frac{\varepsilon_c}{\varepsilon'_c}\right)}{n-1+\left(\frac{\varepsilon_c}{\varepsilon'_c}\right)^n} \tag{11}$$

$$n = n_1 = [1.02 - 1.17(E_{\text{sec}}/E_c)]^{-0.74} \quad \text{if } \varepsilon_c \leq \varepsilon_c^{'} \tag{12}$$

$$n = n_2 = n_1 + (\lambda + 28 \times \mu) \quad \text{if } \varepsilon_c \geq \varepsilon_c^{'} \tag{13}$$

$$\lambda = \left(135.16 - 0.1744 f_c^{'}\right)^{-0.46} \tag{14}$$

$$\mu = 0.83 \exp\left(-911/f'_c\right) \tag{15}$$

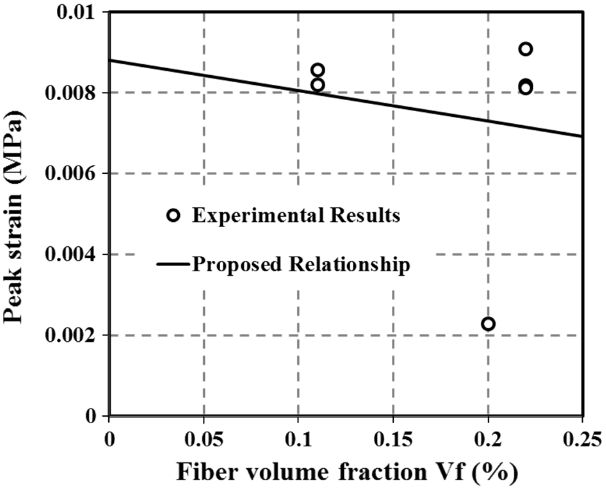

**Figure 9. Effect of fiber volume on peak strain.**

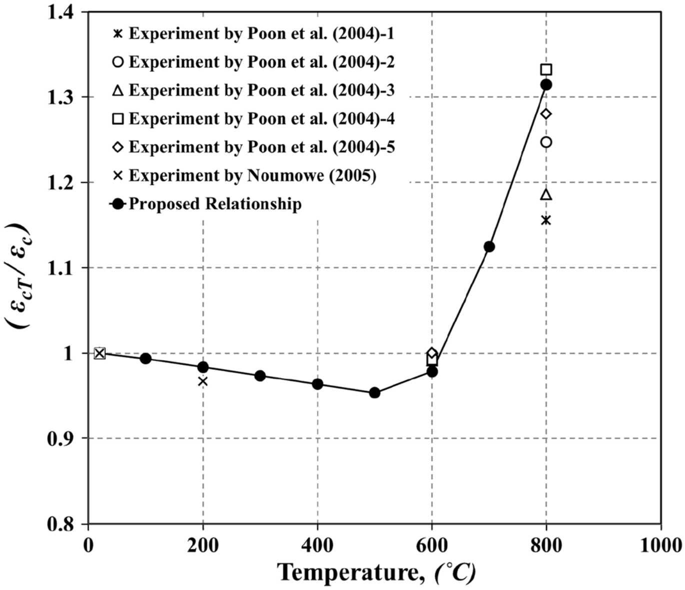

**Figure 10. Comparison between peak strain proposed relationship of PPFRC with experimental test results.**

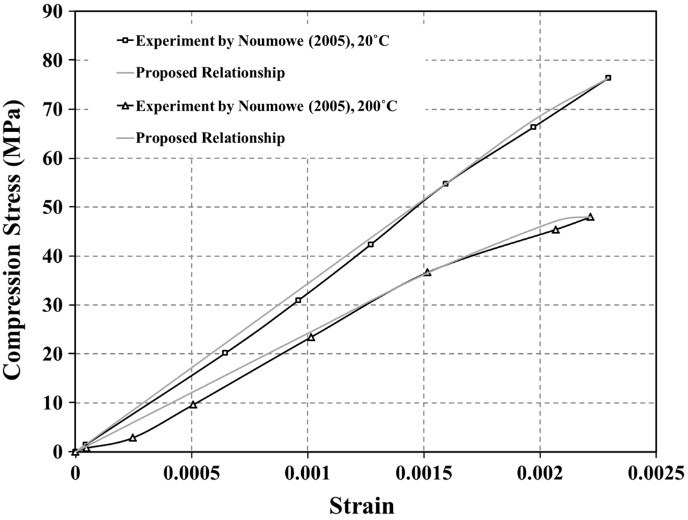

**Figure 11. Comparisons between proposed compressive stress–strain relationship for PPFRC against the experimental results Noumowe [14] at 20°C and 200°C.**

$$E_{\text{sec}} = f'_c/\varepsilon'_c \tag{16}$$

$$\varepsilon'_c = \left(\frac{f'_c}{E_c}\right)\left(\frac{\psi}{\psi - 1}\right) \tag{17}$$

$$\psi = \frac{f'_c}{17} + 0.8 \tag{18}$$

where $\sigma_{cf}$ is fibre reinforced concrete stress, $f'_{cf}$ is maximum compressive strength of fibre reinforced concrete, $n$ is material parameter that depends on the shape of the stress–strain curve, $\varepsilon_{cf}$ is fibre reinforced concrete strain, $\varepsilon'_{cf}$ is strain corresponding with the maximum stress $f'_{cf}$, $n_1$ is modified material parameter at the ascending branch, $n_2$ is modified material parameter at the descending branch, $E_{cf}$ is modulus of elasticity of fibre reinforced concrete, $E_{\text{sec}}$ is secant modulus of elasticity, $n_1$ is modified material parameter at the ascending branch, $n_2$ is modified material parameter at the descending branch, and $\lambda$, $\mu$ are coefficients of linear equation.

To account for transient creep effects, [4] considered that the total strain is composed of separate strain components. The thermal strain is a function of the temperature, and thus can be separated easily from the total strain. To calculate the transient creep strain, an assumption has to be made for the corresponding stress. This leads to an iterative solution. For more information regarding to thermal strain and/or transient strain and/or creep refer to Aslani [4].

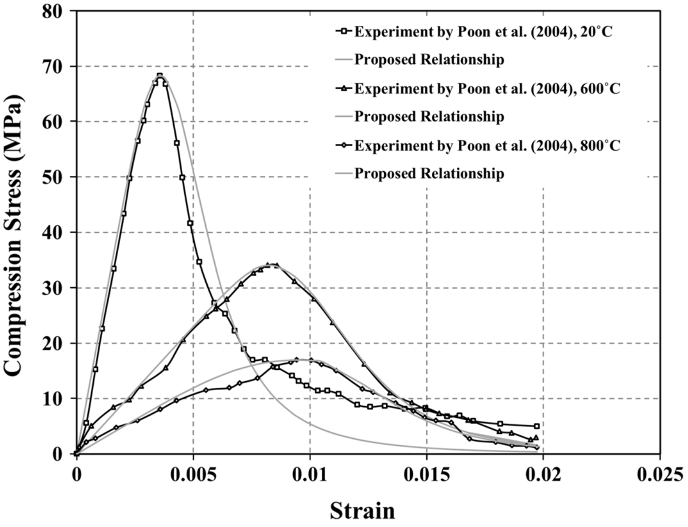

**Figure 12. Comparisons between proposed compressive stress–strain relationship for normal concrete against the experimental results Poon et al. [17] at 20°C, 600°C, and 800°C.**

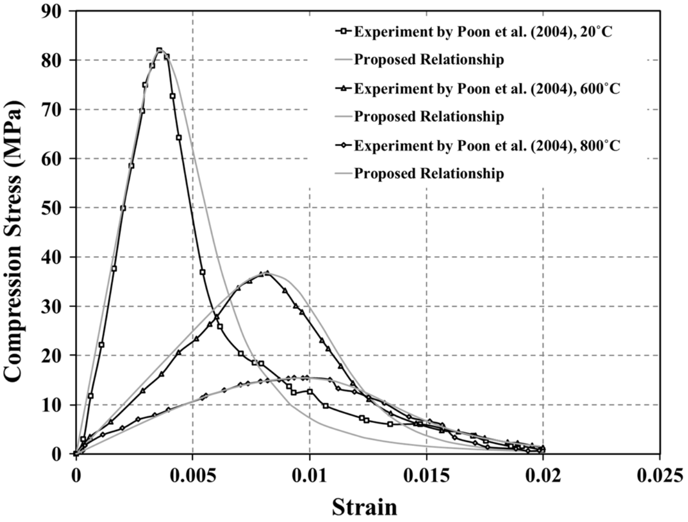

**Figure 13. Comparisons between proposed compressive stress–strain relationship for silica fume type I PPFRC against the experimental results Poon et al. [17] at 20°C, 600°C, and 800°C.**

Figure 11 shows comparisons between the proposed relationship for PPFRC against the unstressed experimental results at 20°C and 200°C reported by Noumowe [14]. Figures 12, 13, 14 show comparisons between the proposed relation-

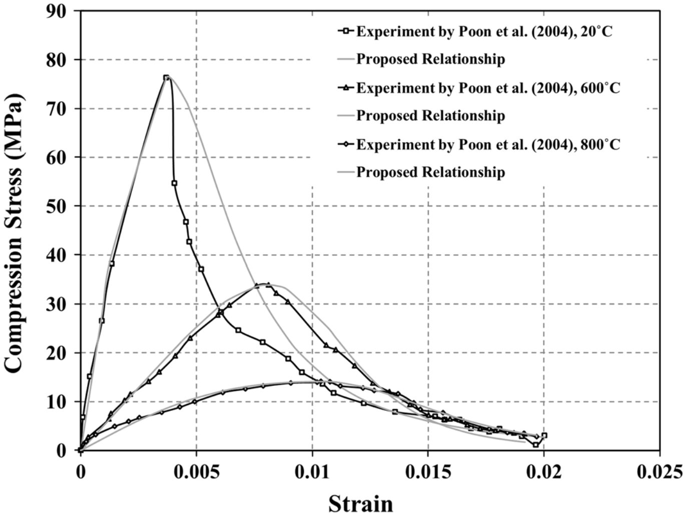

**Figure 14. Comparisons between proposed compressive stress–strain relationship for silica fume type II PPFRC against the experimental results Poon et al. [17] at 20°C, 600°C, and 800°C.**

ship for normal and silica fume (type I and II) PPFRC against the unstressed experimental results at 20°C, 600°C, and 800°C reported by Poon et al. [17]. The proposed compressive stress–strain relationship fits the experimental results at elevated temperature well.

Proposed models have following limitations: (1) these models did not include confinement effects, (2) they are applicable in the various range of compressive strength because normalized compressive strength is used, (3) PP fibre content is varied between 0.11% and 0.6%, (4) Common fine aggregate that is used in the database is natural river sand and type of coarse aggregate is varied, (5) heating rate range is between 0.5°C/min and 10°C/min, and (6) temperature that is used for different research is varied between 20°C and 900°C.

## 10. Conclusions

The following conclusions can be drawn from this study:

1. The proposed compressive stress–strain relationship of PPFRC at elevated temperature is based on authors' model with some modifications and is developed by using the proposed compressive strength, elastic modulus and peak strain relationships that is in good agreement with the experimental test results for PPFRC at different temperatures.

2. The proposed compressive stress–strain relationship is simple and reliable for modeling the compressive behavior of PPFRC at elevated temperatures. Also, using these relationships in the finite element method (FEM) is more simple and suitable.

3. The proposed relationships for the compressive and tensile strength, elasticity modulus, modulus of rupture, and peak strain of PPFRC with different content of fiber at elevated temperature are in good reasonable agreement with the experimental results. Also, the relationships for above mechanical properties are proposed that can calculate these properties related to the fiber content.

4. The paper stressed the fact that additional tests at different temperatures are needed to investigate the role of initial compressive and tensile stresses on the PPFRC compressive strength, strain at peak stress, modulus of elasticity, free thermal strain, load induced thermal strain, creep strain, transient strain, and fire spalling.

## References

1. Alhozaimy AM, Soroushian P, Mirza F (1996) Mechanical properties of polypropylene fiber reinforced concrete and the effect of pozzolanic materials. Cement Concr Compos 18(2):85–92
2. Allan ML, Kukacha LE (1995) Strength and ductility of polypropylene fiber reinforced grouts. Cem Concr Res 25(3):511–521
3. Aslani F, Bastami M (2011) Constitutive relationships for normal- and high-strength concrete at elevated temperatures. ACI Mater J 108(4):355–364
4. Aslani F (2012) Prestressed concrete thermal behaviour. Mag Concr Res 65(3):158–171
5. Aslani F, Jowkarmeimandi J (2012) Stress–strain model for concrete under cyclic loading. Mag Concr Res 64(8):673–685
6. Aslani F, Samali B (2013) Constitutive relationships for steel fiber reinforced concrete at elevated temperatures. Fire Technol. doi:10.1007/s10694-012-0322-5
7. Behnood A, Ghandehari M (2009) Comparison of compressive and splitting tensile strength of high-strength concrete with and without polypropylene fibers heated to high temperatures. Fire Saf J 44:1015–1022
8. Chen B, Liu J (2004) Residual strength of hybrid-fiber-reinforced high-strength concrete after exposure to high temperatures. Cem Concr Res 34(6):1065–1069
9. Fib Bulletin 46 (2008) Fire design of concrete structures—structural behaviour and assessment, Chap 6. In: Expertise and assessment of materials and structures after fire, State-of-art report
10. Giaccio GM, Zerbino RL (2005) Mechanical behaviour of thermally damaged high-strength steel fibre reinforced concrete. Mater Struct 38(3):335–342
11. Li M, Qian CX, Sun W (2004) Mechanical properties of high-strength concrete after fire. Cem Concr Res 34(6):1001–1005
12. Komonen J, Penttala V (2003) Effect of high temperature on the pore structure and strength of plain and polypropylene fiber reinforced cement pastes. Fire Technol 39(1):23–34
13. Malhotra HL (1982) Design of fire-resisting structures. Surrey University Press, London
14. Noumowe A (2005) Mechanical properties and microstructure of high strength concrete containing polypropylene fibres exposed to temperatures up to 200°C. Cem Concr Res 35:2192–2198
15. Peng GF, Yang WW, Zhao J, Liu YF, Bian SH, Zhao LH (2006) Explosive spalling and residual mechanical properties of fiber-toughened high-performance concrete subjected to high temperatures. Cem Concr Res 36:723–727

16. Pliya P, Beaucour AL, Noumowé A (2011) Contribution of cocktail of polypropylene and steel fibres in improving the behaviour of high strength concrete subjected to high temperature. Constr Build Mater 25(4):1926–1934
17. Poon CS, Shui ZH, Lam L (2004) Compressive behavior of fiber reinforced high-performance concrete subjected to elevated temperature. Cem Concr Res 34(12):2215–2222
18. Schneider U (1985) Properties of materials at high temperatures—concrete. RILEM Committee 44, PHT, University of Kassel, Kassel
19. Sideris KK, Manita P, Chaniotakis E (2009) Performance of thermally damaged fiber reinforced concretes. Constr Build Mater 23(3):1232–1239
20. Suhaendi SL, Horiguchi T (2006) Effect of short fibers on residual permeability and mechanical properties of hybrid fibre reinforced high strength concrete after heat exposition. Cem Concr Res 36:1672–1678
21. Xiao J, Falkner H (2006) On residual strength of high-performance concrete with and without polypropylene fibres at elevated temperatures. Fire Saf J 41:115–121