Preloaded High-Temperature Constitutive Models and Relationships for Concrete

M. Bastani1,2 and F. Aslani1

Abstract. The behavior of concrete structures that are exposed to extreme thermo-mechanical loading is an issue of great importance in nuclear engineering. The structural fire-safety capacity of concrete is very complicated because concrete materials have considerable variations. Constitutive models and relationships for preloaded Normal and High Strength Concrete (NSC and HSC) subjected to fire are needed, which are intended to provide efficient modeling and to specify the fire-performance criteria of the behavior of preloaded concrete structures exposed to fire. In this paper, formulations for estimating the parameters affecting the behavior of unconfined preloaded concrete at high temperatures are proposed. These formulations include residual compressive strength, initial modulus of elasticity, peak strain, thermal strain, transient creep strain, and the compressive stress-strain relationship at elevated temperatures. The proposed constitutive models and relationships are verified with available experimental data and existing models. The proposed models and relationships are general and rational, and have good agreement with the experimental data. More tests are needed to further verify and improve the proposed constitutive models and relationships.

Keywords: Preloaded concrete; Constitutive models and relationships; Normal and high strength concrete; Fire; High temperature.

INTRODUCTION

Concrete is a heterogeneous material with a wide variety of usage in structural design.1 Modeling of the mechanical behavior of concrete at temperatures above ambient is necessary in the analysis of hypothetical accidental situations in a nuclear reactor or in other accidental fire situations. The design of fire-resistant structural elements requires realistic knowledge on the behavior of concrete at high temperatures. When concrete is exposed to high temperatures, there may be considerable variations in physical and mechanical properties with an irreversible loss of stiffness and strength including the possibility of increased ductility in the post-peak regime. The fire resistance of concrete can be determined by three test methods, available for finding the residual compressive strength of concrete at elevated temperatures: stressed, unstressed, and unstressed residual strength tests. The stressed and unstressed tests are compatible for assessing the strength of concrete during high temperatures, while the unstressed residual strength test is excellent for finding residual properties after elevated temperatures. In the stressed test, specimens are restrained by a preload prior to, and throughout, the heating process. In the unstressed test, the specimens are heated without restraint. Both stressed and unstressed specimens are loaded to failure under uni-axial compression when the steady-state temperature is reached at the target temperature. The unstressed residual property test method is designed to provide the property data of concrete at room temperature after exposure to elevated temperatures.2,3

At present, using prescriptive approaches is generally established for the fire resistance of Reinforced Concrete (RC) members, which are based on either empirical calculation methods or standard fire resistance tests. These approaches do not provide a rational and realistic fire safety assessment and have

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major drawbacks. New codes are moving towards performance-based design, and temperature-dependent calculations are expected to be required to satisfy certain performance criteria. There is an increased focus on the use of numerical methods for evaluating the fire performance of structural members, which depends on the properties of the constituent materials. Knowledge of the high-temperature properties of concrete is critical for fire resistance assessment under performance-based codes [4].

The parameters that control concrete behavior are: compressive strength, tensile strength, peak strain, modulus of elasticity, creep strain, thermal conductivity and thermal strain, which are nonlinear functions of temperature. Also, aggregate types of concrete influence concrete behavior exposed to fire [5]. Many compressive and tensile constitutive models for concrete at normal temperatures are proposed. The constitutive laws of concrete materials under fire conditions are complicated, and knowledge of current thermal properties is based on the limited material properties. There are either limited test data for some elevated temperature properties, or there are considerable differences and inconsistencies in the elevated test data for other properties of concrete [2,6,7]. These differences and inconsistencies are mainly due to the differences in test methods, condition of procedures, and the environmental parameters accompanying the tests [8]. Thus, at present, there are no well-founded constitutive relationships in codes and standards for many of the high-temperature properties of concrete [2]. Although the computational methods and techniques for estimating the performance of structural members of buildings are proposed, research studies that provide inputting data, such as the constitutive laws of concrete materials, into these computational methods, has not kept pace [9]. Much of the information in ACI216R [10] is based on experimental data on concrete at elevated temperatures from the 1950s and 1960s that contain no comprehensive constitutive relationships [4].

In this study, constitutive models and relationships are proposed for preloaded Normal and High Strength Concrete (NSC and HSC) at elevated temperatures, which are compared to available ones and verified with previous experimental data. Regression analyses are conducted on experimental data to propose residual compression strength, initial modulus of elasticity, peak strain, thermal strain and transient creep strain. In the present paper, at first, the models that were proposed for residual compression strength, initial modulus of elasticity, peak strain, thermal strain and creep strain are verified with experimental data. Secondly, compressive stress-strain relationships for NSC and HSC at elevated temperatures are proposed and verified with the experimental data.

**COMPRESSIVE STRENGTH OF PRELOADED NSC AND HSC AT HIGH TEMPERATURES**

Several models have been proposed to estimate unloading concrete compressive strength at high temperatures. The model for the preloaded concrete compressive strength of concrete at high temperatures is the Hertz [11] model. Hertz [11] proposed a model (Equation 1) that recognizes the variation of $f'_{cT}$ with the type of aggregate:

$$f'_{cT} = f'_{c} \left[ 1 + \left( \frac{T}{T_1} \right)^2 + \left( \frac{T}{T_2} \right)^{8} + \left( \frac{T}{T_3} \right)^{60} \right].$$

Siliceous aggregate:

- $T_1 = 15000$, $T_2 = 800$,
- $T_3 = 570$, $T_4 = 1000$.

Lightweight aggregate:

- $T_1 = 100000$, $T_2 = 1100$,
- $T_3 = 800$, $T_4 = 940$.

Other aggregates:

- $T_1 = 100000$, $T_2 = 1080$,
- $T_3 = 690$, $T_4 = 1000$.

In this study, a model is proposed for the preloaded compressive strength of normal, high strength (siliceous aggregate), carbonate and lightweight aggregate preloaded concretes at elevated temperatures; regression analyses for which are proposed and conducted on existing experimental data, as expressed in Equations 2 to 6, respectively.

Normal strength concrete (Siliceous aggregate):

$$f'_{cT} = f'_{c} \begin{cases} 1.0 \\ 1.00 + 0.00045 \times 10^{-6} \times T^2 + 8 \times 10^{-10} \times T^3 \\ 0.44 - 0.0004 \times T \\ 0 \end{cases}$$

$$20^\circ C \leq T \leq 200^\circ C$$
$$200^\circ C < T \leq 800^\circ C$$
$$900^\circ C \leq T \leq 1000^\circ C$$
$$T > 1000^\circ C$$

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High strength concrete (Siliceous aggregate):

\[
f'_{cT} = f'_c \begin{cases} 
  1.0 & \text{if} \quad 0^\circ \text{C} \leq T \leq 20^\circ \text{C} \\
  0.83 + 0.0019 T - 5.2 \times 10^{-3} T^2 + 3 \times 10^{-6} T^3 & \text{if} \quad 20^\circ \text{C} \leq T \leq 100^\circ \text{C} \\
  0 & \text{if} \quad 100^\circ \text{C} < T \leq 900^\circ \text{C} \\
  0 & \text{if} \quad T > 900^\circ \text{C}
\end{cases}
\]

Carbonate aggregate concrete:

\[
f'_{cT} = f'_c \begin{cases} 
  1.00537 - 2.0 \times 10^{-4} T & \text{if} \quad 0^\circ \text{C} \leq T \leq 1.0 \\
  1.05 - 0.0017 T + 5 \times 10^{-6} T^2 - 5 \times 10^{-6} T^3 & \text{if} \quad 1.0 \leq T \leq 400^\circ \text{C} \\
  0 & \text{if} \quad 400^\circ \text{C} < T \leq 900^\circ \text{C} \\
  0 & \text{if} \quad T > 900^\circ \text{C}
\end{cases}
\]

Lightweight aggregate concrete:

\[
f'_{cT} = f'_c \begin{cases} 
  1.003158 - 1.57 \times 10^{-4} T & \text{if} \quad 0^\circ \text{C} \leq T \leq 1.0 \\
  1.035 - 0.0015 T + 5 \times 10^{-6} T^2 - 5 \times 10^{-6} T^3 & \text{if} \quad 1.0 \leq T \leq 200^\circ \text{C} \\
  0 & \text{if} \quad 200^\circ \text{C} < T \leq 900^\circ \text{C} \\
  0 & \text{if} \quad T > 900^\circ \text{C}
\end{cases}
\]

The proposed models at elevated temperatures are compared separately with experimental data and the Hertz [11] model as shown in Figures 1 to 4. Figure 1 makes a comparison between the Hertz [11] model and the proposed model for preloaded NSC at different temperatures, against the experimental results of Abrams [12] and Phan and Carino [6]. The proposed model has good accuracy with the experimental results. Figure 2 shows the proposed model for preloaded HSC at different temperatures, against the experimental results of Castillo and Durrani [13], Khoury et al. [14] and Phan and Carino [6], which indicates that the model fits well with experimental results. The model is unique and no other model has been found for HSC, which is very important due to the widespread usage of HSC around the world especially in high-rise buildings that are faced with structural fire-safety problems. The compressive strength of HSC varies differently and more unfavorably with temperature compared to
that of NSC. The differences are more pronounced in the temperature range between 25°C to about 400°C, where HSC sustains markedly higher strength loss than NSC. Differences become less significant at temperatures above 400°C. The variations of compressive strength with temperature may be characterized by an initial stage of strength loss (25°C to approximately 100°C), followed by a stage of stabilized strength and recovery (100°C to approximately 400°C), and a stage above 400°C characterized by a monotonic decrease in strength with increasing temperature. The strength recovery stage of HSC occurs at higher temperatures than NSC [2]. Figure 3 shows a comparison of the Hertz [11] model and the proposed model for preloaded carbonate aggregate concrete against the experimental results of Abrams [12]. The proposed model has good accuracy with the experimental results in comparison to the Hertz [11] model. Figure 4 represents a comparison between the proposed model for preloaded lightweight aggregate concrete, the Hertz [11] model and the experimental results of Abrams [12]. The proposed model is more rational with the experimental results in comparison with the Hertz [11] model especially for temperatures above 400°C.

**INITIAL MODULUS OF ELASTICITY AT ELEVATED TEMPERATURES (PRELOADED CONCRETE)**

The elastic modulus of concrete could be affected primarily by the same factors influencing its compressive strength [15,16]. The most important available models for the elastic modulus of preloaded concrete at high temperatures are summarized in Table 1. In this paper, a model for the elasticity modulus of concrete at elevated temperatures is proposed, regression analyses for which are conducted on existing experimental data to propose it, and which is expressed as Equation 6:

\[
E_{etT} = E_e \begin{cases} 
1.0 & \text{for } T < 20^\circ C \\
1.03 - 0.00025 (T - 9 \times 10^{-7} T^2) & 20^\circ C < T \leq 800^\circ C \\
0 & T > 800^\circ C \end{cases}
\]

Figure 5 provides a comparison between Table 1 models and the proposed model for the elasticity modulus of preloaded concrete at elevated temperatures against the experimental results of Anderberg and Theandersson [17] and Khoury et al. [14]. The proposed model fitted well with most of the experimental results.

**Table 1. Elastic modulus models at elevated temperatures (preloaded concrete).**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Elastic Modulus at Elevated Temperatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anderberg and Theandersson [17]</td>
<td>(E_{etT} = \frac{f_{et}}{f_e}) 1.0</td>
</tr>
<tr>
<td>Schneider [18]</td>
<td>Normal weight concrete:</td>
</tr>
<tr>
<td></td>
<td>(E_{etT} = (0.0001552 T + 1.03104)gE_e, 20^\circ C \leq T \leq 600^\circ C)</td>
</tr>
<tr>
<td></td>
<td>(F_{etT} = (-0.00095 T + 0.25)gE_e, 600^\circ C \leq T \leq 1000^\circ C)</td>
</tr>
<tr>
<td>Schneider [18]</td>
<td>Lightweight concrete:</td>
</tr>
<tr>
<td></td>
<td>(g = 1 + \frac{L_t}{f_e}, \quad \frac{L_t}{f_e} \leq 3.0)</td>
</tr>
<tr>
<td></td>
<td>(E_{etT} = (0.00102 T + 1.0204)gE_e, 20^\circ C \leq T \leq 1000^\circ C)</td>
</tr>
<tr>
<td>Kehmnan and Baker [19]</td>
<td>For preloaded concrete:</td>
</tr>
<tr>
<td></td>
<td>(F_{etT} = (0.000034 T + 1.012673)E_e, 20^\circ C &lt; T &lt; 525^\circ C)</td>
</tr>
<tr>
<td></td>
<td>(E_{etT} = (0.002036 T + 1.749091)E_e, 525^\circ C \leq T \leq 800^\circ C)</td>
</tr>
</tbody>
</table>
PEAK STRAIN AT HIGH TEMPERATURES (PRELOADED CONCRETE)

The most important models for the peak strain of preloaded concrete at high temperatures are the Khennane and Baker [19] and Terro [20] models. Khennane and Baker [19] studied the experimental results provided by Anderberg and Thelandersson [17] and proposed the following equation for the peak strain of concrete, having an initial compressive stress during the heating process,

$$\varepsilon_{\text{max}} = 0.00000167T + 0.002660 \geq 0.003,$$

if $T \leq 800^\circ C$. \hfill (7)

Terro [20] proposed the following equation for the peak strain of concrete that accounts for the initial compressive stress level,

$$\varepsilon_{\text{max}} = (50\lambda_L^L - 15\lambda_L + 1)\varepsilon'_{c1} + 20(\lambda_L - 5\lambda_L^L)\varepsilon'_{c2} + 5(10\lambda_L - \lambda_L)\varepsilon'_{c3},$$

$$\varepsilon'_{c1} = 2.05 \times 10^{-2} + 3.08 \times 10^{-1} T + 6.57 \times 10^{-8} T^2 + 6.58 \times 10^{-12} T^3,$$

$$\varepsilon'_{c2} = 2.03 \times 10^{-2} + 1.27 \times 10^{-1} T + 2.17 \times 10^{-8} T^2 + 1.64 \times 10^{-12} T^3,$$

$$\varepsilon'_{c3} = 0.002.$$ \hfill (8)

In this paper, a much simpler model for the peak strain of preloaded concrete at elevated temperatures is proposed, regression analyses for which are conducted on existing experimental data in order to propose it, and which is expressed as Equation 9:

$$\varepsilon_{\text{max}} = 0.0028 + 2 \times 10^{-6} T,$$

$$20^\circ C \leq T \leq 800^\circ C.$$ \hfill (9)

Figure 6 provides a comparison between Khennane and Baker [19] and Terro [20] models and the proposed model for peak strain preloaded concrete, against the experimental results of Anderberg and Thelandersson [17]. The proposed model has good accuracy with experimental results in comparison with others.

THERMAL STRAIN (UNLOADED AND PRELOADED CONCRETE)

The free thermal expansion is predominantly affected by the aggregate type. The free thermal expansion is not linear with respect to temperature. The presence of free moisture will affect the result below 150°C, since the water being driven off may cause net shrinkage. Traditionally, it is expressed by a linear function of temperature by employing a thermal expansion coefficient, $\alpha$ [21].

$$\varepsilon_{\text{th}} = \alpha(T - 20^\circ C).$$ \hfill (10)

For concrete with siliceous or carbonate aggregates, $\alpha$ can be taken equal to $19 \times 10^{-6}$ or $12 \times 10^{-6}$ per °C [22]. The most important available models for the thermal strain of unloaded concrete at high temperatures are summarized in Table 2. In this study, models for the thermal strain of unloaded siliceous, carbonate and

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<table>
<thead>
<tr>
<th>Reference</th>
<th>Thermal Strain Models (Unloaded Concrete)</th>
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</table>
| Lie [23]  | Siliceous and Carbonate Aggregate:  
|           | $\varepsilon_{th} = 0.0004(T^2 - 400) + 6(T - 20) \times 10^{-6}$, |
|           | Lightweight:  
|           | $\varepsilon_{th} = 7.5 \times 10^{-6}(T - 20^\circ C)$, |
|           | $\varepsilon_{th} = \begin{cases} 
-1.8 \times 10^{-4} + 9 \times 10^{-5} T + 3.3 \times 10^{-11}(T)^3 \\
14 - tems10^{-3} 
\end{cases}$,  
$20^\circ C \leq T \leq 700^\circ C$  
$700^\circ C \leq T \leq 1200^\circ C$, |
|           | Carbonate Aggregate:  
|           | $\varepsilon_{th} = \begin{cases} 
-1.2 \times 10^{-4} + 6 \times 10^{-5} T + 1.4 \times 10^{-11}(T)^3 \\
12 \times 10^{-3} 
\end{cases}$,  
$20^\circ C \leq T \leq 805^\circ C$  
$805^\circ C \leq T \leq 1200^\circ C$, |
|           | Lightweight:  
|           | $\varepsilon_{th} = 8 \times 10^{-6}(T - 20^\circ C)$, |

lightweight aggregate concretes at elevated temperatures are proposed, regression analysis for which are conducted on the existing experimental data in order to propose it, and which are expressed as Equations 11 to 14:

Siliceous aggregate concrete:

$$\varepsilon_{th} = 0.0004(T^2 - 400) + 6(T - 20) \times 10^{-6} T^2,$$

$100^\circ C \leq T \leq 800^\circ C,$  
\[ (11) \]

$$\varepsilon_{th} = \alpha(0.00045 + 1 \times 10^{-6} T + 2 \times 10^{-8} T^2),$$

$100^\circ C \leq T \leq 800^\circ C.$  
\[ (12) \]

Compressive Strength range:

$20^\circ C - 60^\circ C, \quad \alpha = 1$,  
$C70 \quad \alpha = 0.85$,  
$C80 \quad \alpha = 0.75$,  
$C90 \quad \alpha = 0.65$,  
$C100 \quad \alpha = 0.5$.

Carbonate aggregate concrete:

$$\varepsilon_{th} = 0.0001 + 5 \times 10^{-7} T + 2 \times 10^{-8} T^2,$$

$100^\circ C \leq T \leq 800^\circ C.$  
\[ (13) \]

Lightweight aggregate concrete:

$$\varepsilon_{th} = 0.00045 + 8 \times 10^{-6} T,$$

$100^\circ C \leq T \leq 800^\circ C.$  
\[ (14) \]

Figure 7 provides a comparison between thermal strain models of normal strength unloaded siliceous aggregate concrete at elevated temperatures with experimental data.

Figure 7 shows a comparison between Lie [23] and EN 1992-1-2 [24] models and the proposed model for the thermal strain of normal strength unloaded siliceous aggregate concrete against the experimental results of Abrams [12], Khoury et al. [25], Lie [23], and Gawan et al. [26]. Figure 8 represents a comparison between Lie [23] and EN 1992-1-2 [24] models and the proposed model for the thermal strain of unloaded siliceous aggregate concrete against the experimental results of Gawan et al., 90 MPa [26]. Figures 9 and 10 provide a comparison between Lie [23] and EN 1992-1-2 [24] models and the proposed model for the thermal strain of unloaded carbonate and lightweight aggregate concretes separately against the experimental results of Abrams [12], Khoury et al. [25] and Lie [23]. The proposed models have good accur-
Figure 8. Comparison between thermal strain models of high strength unloaded siliceous aggregate concrete at elevated temperatures with experimental data.

Figure 9. Comparison between thermal strain models of unloaded carbonate aggregate concrete at elevated temperatures with experimental data.

Figure 10. Comparison between thermal strain models of unloaded lightweight aggregate concrete at elevated temperatures with experimental data.

For 15%-30% preloaded:
\[
\varepsilon_{th} = -0.00047 - 7.2 \times 10^{-6} T + 6 \times 10^{-8} T^2
- 10^{-10} T^3,
\]
\[100^\circ C \leq T \leq 800^\circ C.\] (16)

For 30%-45% preloaded:
\[
\varepsilon_{th} = -0.0001 - 1.8 \times 10^{-5} T + 6 \times 10^{-8} T^2
- 9 \times 10^{-11} T^3,
\]
\[100^\circ C \leq T \leq 800^\circ C.\] (17)

For 45%-60% preloaded:
\[
\varepsilon_{th} = -0.0007 - 10^{-5} T + 5 \times 10^{-8} T^2 - 8 \times 10^{-11} T^3,
\]
\[100^\circ C \leq T \leq 800^\circ C.\] (18)

Figure 11 provides a comparison between the proposed models for the thermal strain of preloaded concrete against the experimental results of Gaiw et al. [26] for unloading 15%, 30%, 45% and 60% preloading cases, respectively. The proposed models fit very well with most of the experimental results, which indicate more preloading percentage and more reduction of thermal strain. This figure also indicates the trend of thermal strain-temperature curves, which is entirely a function of the preloading percentage.

CREEP STRAIN AT ELEVATED TEMPERATURES

It was observed that preloaded concrete elements experience a characteristic marked increase in strains during
Table 3. Creep strains models.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Creep Strains</th>
</tr>
</thead>
</table>
| Anderberg and Theandersson [17] | \( \varepsilon_{tr} = k_{tr} \left( \frac{232}{T} \right)^{2\gamma_{th} \gamma_{th}} \),  
  \( T \leq 550^\circ C \),  
  \( \frac{\varepsilon_{tr}}{T_{ref}} = 0.0006 \left( \frac{232}{T} \right)^{2\gamma_{th} \gamma_{th}} \),  
  \( T \geq 550^\circ C \),  
  \( 1.8 \leq k_{tr} \leq 2.35 \)                                           |
| Schneider [18]             | \( \varepsilon_{tr} = \frac{\phi}{\varepsilon_{tr}} \),  
  \( \phi = g\{ C_1 \gamma_{th}(T - 20^\circ C) + C_2 \gamma_{th}(T - T_w) + C_3 \} + \frac{375}{T_{ref}} \frac{T - 20^\circ C}{T_{ref}} \),  
  \( \frac{\varepsilon_{tr}}{T_{ref}} \leq 3.0 \),  
  \( \gamma_{th} = (0.3u + 2.2) \times 10^{-5} \),  
  where \( u \) is the moisture content and \( C_1, C_2, C_3, \gamma_{th} \) and \( T_w \) are constants  
  with values equal to 2.60, 1.40, 1.40, 0.0026 and 720 for concrete with  
  siliceous aggregates, 2.60, 2.60, 2.60, 0.0076 and 650 for concrete with  
  carbonate aggregates, and 2.60, 3.00, 3.00, 0.0076 and 600 for concrete  
  with lightweight aggregates.                                                     |
| Diederichs [27]            | \( \varepsilon_{tr} = \frac{3.3 \times 10^{-11} (T - 20^\circ C)^3 - 1.72 \times 10^{-7} (T - 20^\circ C)^2 + 0.0412 \times 10^{-3} (T - 20^\circ C)}{1.5} \). |
| Terce [20]                 | \( \varepsilon_{tr} = \varepsilon_{2.3} \times \left( \frac{0.32 + 3.296 \frac{1}{T_{ref}}}{1.5} \right)^{0.5},  
  \frac{\varepsilon_{2.3}}{T_{ref}} \leq 3.0 \),  
  \( \varepsilon_{2.3} = -43.87 \times 10^{-6} + 2.73 \times 10^{-5} T + 6.35 \times 10^{-8} T^2 - 2.19 \times 10^{-10} T^3 + 2.77 \times 10^{-13} T^4 \),  
  \( \varepsilon_{0.3} = -1625.78 \times 10^{-6} + 58.03 \times 10^{-5} T - 0.6364 \times 10^{-5} T^2 + 3.6112 \times 10^{-5} T^3 - 9.796 \times 10^{-12} T^4 + 8.806 \times 10^{-15} T^5 \). |
| Nielsen et al. [28]        | \( \varepsilon_{tr} = 0.000038(v_{ref}/f_{c}^{0.6}) \).                        |

Figure 11. Comparison between thermal strain models of preloaded concrete at elevated temperatures with experimental data.

![Thermal strain vs Temperature](image)

This increase significantly exceeds expected creep strains and was termed as a transient creep strain [22,23,30]. The most important models for the creep strain of concrete at high temperatures are summarized in Table 3. In this study also models for the creep strain of preloaded concrete at elevated temperatures are proposed, regression analyses for which are conducted on existing experimental data in order to propose it, and which are expressed as Equations 19-21:

For 10%-20% preloaded:

\[ \varepsilon_{tr} = 0.0006 - 3.8 \times 10^{-5} T + 7.25 \times 10^{-8} T^5, \]

\[ 100^\circ C \leq T \leq 600^\circ C. \]  

(19)

For 20%-40% preloaded:

\[ \varepsilon_{tr} = 0.00095 - 6 \times 10^{-6} T + 3 \times 10^{-8} T^2, \]

\[ 100^\circ C < T < 600^\circ C. \]  

(20)

For 40%-60% preloaded:

\[ \varepsilon_{tr} = -8 \times 10^{-5} + 4.1 \times 10^{-5} T + 3 \times 10^{-8} T^2, \]

\[ 100^\circ C \leq T \leq 600^\circ C. \]  

(21)

Figures 12 to 14 show the proposed models fit well with most of the experimental results, as well as Nielsen's model [28], which is linear and rational with the experimental results of temperatures less than 500°C. It can be used if simplified calculations are required. Schneider's model [18] provides a lower bound for the experimental results.

**COMPRESSION STRESS-STRAIN RELATIONSHIPS AT ELEVATED TEMPERATURES**

The most important available compressive stress-strain relationships for concrete at high temperatures are summarized in Table 4. In this study, a compressive
Table 4. Compressive stress-strain relationships at elevated temperatures.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Compressive Stress-Strain Relationships at Elevated Temperatures</th>
</tr>
</thead>
</table>
| Anderberg and Thelandersson [17]       | \[
\sigma_{ct} = \sigma_0 + \frac{1}{f_{ct}} \left( 1 - \left( \frac{\varepsilon_{ct} - \varepsilon_{cmax}}{\varepsilon_{cmax}} \right)^{1/2} \right)^2 ; \quad \varepsilon_{ct} \leq \varepsilon_{cmax} \\
\varepsilon_1 = \varepsilon_{cT} \left( 1 - \frac{\varepsilon_{cmax}}{\varepsilon_{cT}} \right) \quad \sigma_0 = E_{ct} \left( \varepsilon_{cT} - \frac{\varepsilon_{cmax}}{\varepsilon_{cT}} \right) ; \quad \varepsilon_{cT} \leq \varepsilon_{cmax} \]
| Lie and Lin [31]                       | \[
\sigma_{ct} = \sigma_0 + \frac{1}{f_{ct}} \left( 1 - \left( \frac{\varepsilon_{ct} - \varepsilon_{cmax}}{\varepsilon_{cmax}} \right)^{1/2} \right)^2 ; \quad \varepsilon_{ct} \leq \varepsilon_{cmax} \\
\varepsilon_1 = \varepsilon_{cT} \left( 1 - \frac{\varepsilon_{cmax}}{\varepsilon_{cT}} \right) \quad \sigma_0 = E_{ct} \left( \varepsilon_{cT} - \frac{\varepsilon_{cmax}}{\varepsilon_{cT}} \right) ; \quad \varepsilon_{cT} \leq \varepsilon_{cmax} \]
| Schneider [18]                         | \[
\sigma_{ct} = \sigma_0 + \frac{1}{f_{ct}} \left( 1 - \left( \frac{\varepsilon_{ct} - \varepsilon_{cmax}}{\varepsilon_{cmax}} \right)^{1/2} \right)^2 ; \quad \varepsilon_{ct} \leq \varepsilon_{cmax} \\
\varepsilon_1 = \varepsilon_{cT} \left( 1 - \frac{\varepsilon_{cmax}}{\varepsilon_{cT}} \right) \quad \sigma_0 = E_{ct} \left( \varepsilon_{cT} - \frac{\varepsilon_{cmax}}{\varepsilon_{cT}} \right) ; \quad \varepsilon_{cT} \leq \varepsilon_{cmax} \]
| Terro [20]                             | \[
\sigma_{ct} = \frac{3\varepsilon_{ct} F_0}{\varepsilon_{cmax}} \left( \frac{\varepsilon_{ct}}{\varepsilon_{cmax}} \right)^n ; \quad \varepsilon_{ct} \leq \varepsilon_{cmax} \]
\sigma_{ct} = \frac{3\varepsilon_{ct} F_0}{\varepsilon_{cmax}} \left( \frac{\varepsilon_{ct}}{\varepsilon_{cmax}} \right)^n ; \quad \varepsilon_{ct} \leq \varepsilon_{cmax} \]
| Kodur et al. [32]                      | \[
\sigma_{ct} = \begin{cases} 
\sigma_0 + \frac{1}{f_{ct}} \left( 1 - \left( \frac{\varepsilon_{ct} - \varepsilon_{cmax}}{\varepsilon_{cmax}} \right)^{1/2} \right)^2 ; \quad \varepsilon_{ct} \leq \varepsilon_{cmax} \\
\sigma_0 + \frac{1}{f_{ct}} \left( 1 - \left( \frac{\varepsilon_{ct} - \varepsilon_{cmax}}{\varepsilon_{cmax}} \right)^{1/2} \right)^2 ; \quad \varepsilon_{ct} \geq \varepsilon_{cmax} 
\end{cases} \\
\varepsilon_1 = \varepsilon_{cT} \left( 1 - \frac{\varepsilon_{cmax}}{\varepsilon_{cT}} \right) \quad \sigma_0 = E_{ct} \left( \varepsilon_{cT} - \frac{\varepsilon_{cmax}}{\varepsilon_{cT}} \right) ; \quad \varepsilon_{cT} \leq \varepsilon_{cmax} \]
| Chang et al. [33]                      | \[
M = \frac{F_T}{E_T} ; \quad M_0 = \frac{F_T}{E_T} \\
\sigma_{ct} = \frac{\varepsilon_{ct} F_0}{1 + (M - M_0) \left( \frac{1}{\varepsilon_{cmax}} + (\frac{\varepsilon_{ct}}{\varepsilon_{cmax}}) \right)^n M \left( \frac{\varepsilon_{ct}}{\varepsilon_{cmax}} \right) \quad \sigma_0 = E_{ct} \left( \varepsilon_{cT} - \frac{\varepsilon_{cmax}}{\varepsilon_{cT}} \right) ; \quad \varepsilon_{cT} \leq \varepsilon_{cmax} \]
| Youssef and Moustah [34]               | \[
1. \quad \varepsilon_{ct} \leq \varepsilon_{cT} + \varepsilon_T ; \quad \sigma_{ct} = K_{ct} \frac{f_{ct}'}{f_{ct}} \left[ 2.0 \left( \frac{\varepsilon_{ct}}{\varepsilon_{cT} + \varepsilon_T} \right) - \left( \frac{\varepsilon_{ct}}{\varepsilon_{cT} + \varepsilon_T} \right) \right] ; \\
\varepsilon_{cT} \geq \varepsilon_{cT} + \varepsilon_T ; \quad \sigma_{ct} = K_{ct} \frac{f_{ct}'}{f_{ct}} \left[ 1 - Z \left( \varepsilon_{ct} - \varepsilon_{cT} - \varepsilon_T \right) \right] \geq 0.2 K_{ct} \frac{f_{ct}'}{f_{ct}} ; \\
Z = 0.5 / (\varepsilon_{cT} + \varepsilon_T) ; \quad \sigma_{ct} = K_{ct} \frac{f_{ct}'}{f_{ct}} \left[ \varepsilon_{cT} - \varepsilon_T \right] \quad \sigma_{ct} = K_{ct} \frac{f_{ct}'}{f_{ct}} \left[ \varepsilon_{cT} - \varepsilon_T \right] ; \quad \varepsilon_{cT} = \varepsilon_{ct} \times K_{ct} , \\
K_{ct} = 1 + \frac{2\varepsilon_{ct}}{f_{ct}'} ; \quad \varepsilon_{cT} \geq \varepsilon_T \left[ \varepsilon_{cT} \geq \varepsilon_T \right] ; \quad \sigma_{ct} = K_{ct} \frac{f_{ct}'}{f_{ct}} \left[ 1 + 5 \left( \frac{\varepsilon_{ct}}{f_{ct}'} - 1 \right) \right] ; \\
2. \quad \varepsilon_{cT} = \varepsilon_{ct} \left[ \varepsilon_{cT} = \varepsilon_T \left[ \varepsilon_{cT} + \varepsilon_T \right] \left( \frac{1}{\varepsilon_{cT} + \varepsilon_T} \right) \left( 1 + \frac{\varepsilon_{ct}}{\varepsilon_{cT} + \varepsilon_T} \right) \right] ; \\
f_{ct} = 2f_{ct} \varepsilon_{ct} / \left( \varepsilon_{cT} + \varepsilon_T \right) \left( \frac{1}{\varepsilon_{cT} + \varepsilon_T} \right) \left( 1 + \frac{\varepsilon_{ct}}{\varepsilon_{cT} + \varepsilon_T} \right) ; \\
f_{ct} = f_{ct} \left[ \frac{1.254 + 2.254}{1 + \frac{3.5f_{ct}}{f_{ct}'}} - \frac{2f_{ct}'}{f_{ct}'} \right] ; \quad f_{ct} = K_{ct} \frac{2K_{ct} A_{ct}}{d_{ct} h}, \right. 
\]
stress-strain relationship for NSC and HSC at elevated temperatures (which is based on Carreira and Chmi's [35] model with several modifications, and is developed by using the proposed residual compression strength, the initial modulus of elasticity, peak strain, thermal strain and transient creep strain) is expressed as Equation 99:

\[
\frac{\sigma_c T}{f'_c} = \frac{\beta_{mT} \left( \frac{\varepsilon_c}{\varepsilon_{\text{max}}} \right)}{\beta_{mT} - 1 + \left( \frac{\varepsilon_c}{\varepsilon_{\text{max}}} \right)^{\beta_{mT}}},
\]

\[
\beta_{mT} = \beta_{mT,0} \left( \text{fitted} \right) = \left[ 1.02 - 1.17 \left( E_p/E_c \right) \right]^{0.74},
\]

if \( \varepsilon_{\text{r}} \leq \varepsilon_{\text{max}} \)

\[
\beta_{mT} = \beta_{mT,0} \left( \text{fitted} \right) + \left( a \cdot b \cdot t \right),
\]

if \( \varepsilon_{\text{r}} \geq \varepsilon_{\text{max}} \)

\[
a = 2.7 \times \left( 12.4 - 1.66 \times 10^{-2} f'_c \right)^{-0.45},
\]

\[
b = 0.83 \exp \left( -911/f'_c \right).
\]

Figures 15 to 17 provide a comparison between the proposed relationship for 20\% preloaded NSC against the experimental results of Purkiss and Bali [36] at 200°C, 550°C, and 700°C, which indicates the proposed model has good agreement with experimental results. Figures 18 to 21 provide a comparison between the proposed relationship for 60\% preloaded NSC against the experimental results of Purkiss and Bali [36] at 200°C.
200°C, 575°C and 700°C. The proposed relationship has good accuracy with the experimental results at elevated temperatures. Figures 21 to 25 provide a comparison between the proposed relationship for 20% preloaded HSC against the experimental results of Khoury et al. [14] at 20°C, 100°C, 300°C, 500°C and 600°C. The proposed relationship is rational and fits well with the experimental results.

CONCLUSIONS

The fire performance of RC structural members is affected by the high-temperature properties of concrete materials. There is a major changeability in the reported test data on the high-temperature properties of concrete. Therefore, there are large discrepancies in the current constitutive models for the thermal and mechanical properties of concrete. The main parameters of concrete that affect the stress-strain relationship of preloaded concrete at high temperatures are: residual compression strength, initial modulus of elasticity, peak strain, thermal strain and transient creep strain. Initial compressive stresses will cause a reduction in the concrete compressive strength and peak strain at high temperatures while increasing transient creep strains. In this paper, constitutive models and relationships for preloaded NSC and HSC subjected to fire are proposed, which are intended to provide efficient modeling and specify the fire-performance criteria of the behavior.
of concrete structures exposed to high temperatures. Attempts were made towards achieving rational and well-founded constitutive models and relationships for preloaded NSC and HSC at elevated temperatures. The major conclusions derived from the present work are:

1. The proposed models for compressive strength at elevated temperatures for preloaded NSC and HSC (siliceous), carbonate and lightweight aggregate concretes verify well the experimental results.
2. The proposed model for the elastic modulus of preloaded concrete at elevated temperatures is rational and compatible with the experimental results.
3. The proposed model for the peak strain of preloaded concrete at high temperatures has good agreement with experimental results, but further experimental tests are needed to further verify and improve the proposed model.
4. The free thermal strain models that are proposed for unloaded and preloaded concrete at high temperatures verify well with experimental results.
5. The creep strain models for preloaded concrete at high temperatures have good agreement with experimental results.
6. The proposed compressive stress-strain relationship for concrete is made, based on well-established relationships for concrete at elevated temperatures, which has a good conformity with the experimental test results of NSC and HSC at different high temperatures.

7. Additional tests at different temperatures are needed to study the influence of first compressive on the preloaded concrete compressive strength, concrete peak strain, and the initial modulus of elasticity of preloaded concrete. Tests are also required to assess the tension properties of preloaded concrete at elevated temperatures.

![Graph](image1.png)

**Figure 24.** Comparison between the proposed relationship for 20% preloaded HSC against experimental results of Khouy et al. [14] at 500°C.

![Graph](image2.png)

**Figure 25.** Comparison between the proposed relationship for 20% preloaded HSC against experimental results of Khouy et al. [14] at 600°C.

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**NOMENCLATURE**

- $\sigma_c$: concrete compressive stress at ambient temperature
- $f_c'$: concrete compressive strength at ambient temperature
- $f_{ic}$: initial compressive stress before heating
- $f_{c1}$: stress at the point of intersection of the two equations defining the stress strain curve of concrete
- $f_{yT}$: yield strength of reinforcing bars at elevated temperature
- $\sigma_{cT}$: concrete compressive stress at elevated temperature
- $f_{cT}'$: concrete compressive stress at elevated temperature
- $f_{cT}'$: compressive strength of confined concrete at elevated temperature
- $f_{IT}'$: effective lateral confining stress at elevated temperature
- $\varepsilon_c$: concrete strain at ambient temperature
- $\varepsilon_c'$: strain at maximum stress for concrete at ambient temperature
- $\varepsilon_{cu}$: ultimate strain for concrete at ambient temperature
- $\varepsilon_C$: strain at the elastic limit in compression cracking strain
- $\varepsilon_{tu}$: strain at point of intersection of the two equations defining the stress strain curve of concrete
- $\varepsilon_{\text{max}}$: strain at maximum stress of concrete at elevated temperature
- $\varepsilon_{cT}'$: strain at maximum stress of confined concrete at elevated temperature
- $\varepsilon_{c1}', \varepsilon_{c2}', \varepsilon_{c3}'$: strain at maximum stress as function of temperature for 0%, 10% and 20% initial stress level
- $\varepsilon_{tr}$: transient creep strain
- $\varepsilon_{th}$: unrestrained thermal strain
- $\varepsilon_{c3}$: transient creep strain for initial stress of 0.3 $f_c'$
strain component that takes into account effect of concrete strength on the slope of the descending branch of unconfined concrete at elevated temperature

strain component that gives the additional ductility due to rectangular transverse reinforcement

initial modulus of elasticity at ambient temperature

initial modulus of elasticity at elevated temperature

initial tangent stiffness to the stress-displacement curve

stiffening parameter

constants to account for aggregate type in evaluating transient creep strain

function to account for increase in modulus of elasticity due to external loads

a non-dimensional factor that accounts for effect of the weight of concrete on the shape of the stress-strain curve

fire temperature in degree Celsius

constants describing the reduction in the concrete compressive strength for different aggregate types

slope of the decaying branch of the concrete stress-strain curve

volume fraction of aggregate used to evaluate the transient creep strain

constant (1.8 to 2.35) used to evaluate transient creep strain

confinement factor at elevated temperature

confinement effectiveness coefficient

cross sectional area of transverse reinforcement

diameter of the transverse reinforcing bars

center-to-center spacing of the transverse reinforcement

factor accounting for the initial compressive stress level

function to evaluate transient creep strain

constant to account for aggregate type in evaluating transient creep strain

Function to account for the effect of moisture content on transient creep strain

modified material parameter at the ascending branch

modified material parameter at the descending branch

material parameter that depends on the shape of the stress-strain curve

modified material parameter at the ascending branch at elevated temperature

modified material parameter at the descending branch at elevated temperature

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