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Stress-Strain Behavior of Confined Concrete during Cooling after Heating to High Temperature

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Abstract: The stress-strain behavior of confined concrete under heating and residual conditions has been preliminarily addressed in previous research; however, its behavior at subsequent cooling temperatures after being heated to peak temperature has yet to be thoroughly investigated. It is crucial for determining confined concrete structures' post-fire performance and burnout resistance. The paper presents the fundamental behavior of the confined concrete constitutive parameters and stress-strain curve at subsequent cooling temperatures after being heated to peak temperature. The study includes the stress-stress relationship of a 200 mm diameter cylinder with two distinct confinement spacings of 60 mm and 120 mm. The constitutive parameters for confined concrete were initially determined for a peak heating temperature of 750 °C and then modified to establish the stress-strain relationship for successive cooling temperatures of 500 °C, 250 °C, and ambient temperature. The study results show that confinement has a considerable impact on compressive strength, stiffness, and ductility at ambient and fire conditions. After being heated to peak temperature, the confined concrete compressive strength recovers during successive cooling temperatures, with the recovery dependent on confinement spacing. The established stress-strain relationship can assist in better comprehending structural performance and capacity degradation for different tie spacings, and is useful for the analysis and design of confined RC (reinforced concrete) elements during and after a fire.

Key words: Confined concrete, stress-strain relationship, elevated temperature, heating and cooling, fire.

Notations

f_{cT}	Confined concrete compressive stress at elevated temperature
f'_{cT}	Unconfined concrete compressive strength at elevated temperature
f'_{ccT}	Confined concrete compressive strength at elevated temperature
$f'_{c,\theta c}$	Unconfined concrete compressive strength at a subsequent cooling temperature
$f'_{c,\theta max}$	Unconfined concrete compressive strength at maximum temperature
$f'_{cr,\theta a}$	Unconfined concrete compressive strength after complete cooling down
f_{yh}	Yield strength of the transverse reinforcement at elevated temperature
f'_{lx} and f'_{ly}	Effective lateral confining stress in *x* and *y* direction, respectively
ρ_s	Volume ratio of the transverse confining steel to the volume of the confined concrete core
K_e	Confinement effectiveness coefficient
f_y	Yield strength of reinforcing steel at ambient temperature
θ_{max}	Maximum (or peak) temperature during a fire
θ_c	Fire temperature during cooling
$\varepsilon_{oc}T$	Confined concrete strain at peak stress at elevated temperature
$\varepsilon_o T$	Unconfined concrete strain at peak stress at elevated temperature
ε_{tr}	Fire-induced transient creep strain in concrete
$\varepsilon_{c,\theta}$	Instantaneous stress-related strain at elevated temperature
$\varepsilon_{0,\theta c}$	Concrete strain at peak stress at a subsequent cooling temperature
$\varepsilon_{0,\theta max}$	Concrete strain at peak stress at maximum temperature

1. Introduction

The performance of reinforced concrete (RC) structures is more crucial in fire-prone environments. Concrete exposed to high temperatures undergoes both

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chemical and physical changes, accelerating the material's deterioration [1-3]. The structural elements experience an excessive loss of strength and stiffness due to the severe deterioration of their mechanical characteristics [4, 5]. The provided confinement to improve load capacity at ambient conditions becomes ineffective with periods of fire due to losses in steel and concrete characteristics. Understanding how confined concrete behaves at elevated temperatures is crucial for assessing its fire performance during heating and the post-heating state. Generally, building fire comprises a prolonged cooling phase after heating or could involve extended heating and cooling [5, 6]. The structural integrity of a RC (reinforced concrete) building is jeopardized once the cooling process begins due to a progressive increase in temperature within the inner core of the concrete elements [7, 8]. The building remains vulnerable to collapse for several hours after completely extinguishing the fire. As a result, structural design requirements during increasing and cooling temperatures become critical. However, the characteristics of RC influence structural behavior as temperatures rise and then fall; therefore, sufficient input parameters are crucial for accurately predicting load capacities and response.

In recent decades, RC has been extensively discovered at elevated temperatures and in its residual state by conducting uniaxial compression tests on prismatic unconfined concrete specimens [3, 9, 10]. The temperature-dependent constitutive parameters were determined, and an entire stress-strain relationship was developed based on the test data. Several studies have investigated the stress-strain behavior of confined concrete at the residual state [11, 12]; however, there is still a lack of data on confined concrete during heating and cooling. There are not enough experimental data for unconfined and confined concrete to gain insights into concrete behavior throughout sequential cooling temperatures. The information about confined concrete properties during a fire is useful for designing confined concrete elements for a specified fire resistance rating and examining the safety of existing structures in a fire's heating and cooling phases. In this study, a stress-strain relationship of confined concrete is established for a peak heating temperature of 750°C and a subsequent cooling temperature. The Eurocode 4 [13] approach is employed to determine the constitutive properties of confined concrete at the consecutive cooling temperature.

2. General Stress-Strain Relationship for Confined Concrete

The degree of confinement given by the transverse reinforcement has a significant impact on the compression behavior of concrete. Several models have been established to account for the confinement effect in the stress-strain relationship by testing confined concrete under monotonic compression loading. Park et al. [14], Sheikh and Uzumeri [15], and Mander et al. [16] are some of the well-known models. Of the most often used adaptive stress-strain models at ambient temperatures, by Mander et al. [17]. Mander et al. [17] offers the theoretical stress-strain relationship for uniaxial compression testing on concrete cylinders and has been thoroughly tested with various confinement configurations such as circular hoop and rectilinear confinement. Youssef and Moftah [3] used literature data to develop the constitutive parameters for unconfined and confined concrete at ambient temperature and proposed suitable stress-strain relationships for concrete in compression as a function of temperature, as given in Eq. (1). This can be used to compute stress (f_{cT}) in confined concrete for a concrete strain ($\mathcal{E}_{cT}$) within a maximum strain limit ($\mathcal{E}_{oT}$) at desired temperature. Eqs. (2) and (3) were used to compute confined concrete compressive strength (f'_{ccT}) and strain at peak stress ($\mathcal{E}_{ocT}$). The lateral confining pressure (f'_{lt}) is calculated by appropriately considering the degradation of confining steel at elevated temperatures. The effective lateral confining stress, f'_{lT}, can be accounted for equal to $\frac{K_e \rho_s f_{yh}}{2}$. Based on the confinement supplied in two perpendicular directions (f'_{lx} and f'_{ly}), the graph presented by Mander et al. [17] can be used to derive the rectilinear confinement, f'_{ccT}.

Confined concrete stress (f_{cT}):

$$f_{cT} = \frac{2.f'_{ccT}.\varepsilon_c T}{(\varepsilon_o T+\varepsilon_{tr}).\left[1+\left(\frac{\varepsilon_c T}{\varepsilon_o T+\varepsilon_{tr}}\right)^2\right]} \quad (1)$$

Confined concrete compressive strength (f'_{ccT}):

$$f'_{ccT} = f'_{cT}.\left[-1.254 + 2.254.\sqrt{1+\frac{7.94.f'_{lT}}{f'_{cT}}} - \frac{2.f'_{lT}}{f'_{cT}}\right] \quad (2)$$

Concrete strain at peak stress ($\varepsilon_{oc}T$):

$$\varepsilon_{oc}T = \varepsilon_o T.\left[1+5\left(\frac{f'_{ccT}}{f'_{cT}}-1\right)\right] \quad (3)$$

2.1 Validation of Model

The modified Youssuf model [3] is employed to generate the stress-strain relationship and then compared with Mander et al. [16, 17] experimental and analytical data at ambient temperature to ensure modelling fidelity. The experimental program conducted Mander et al. [16, 17] included cylinders with diameters of 500 mm and heights of 1,500 mm. The cylinders were loaded axially on a hydraulically controlled testing machine. Four concrete cylinders with different confinement spacing were validated, and stresses were calculated, accounting for the confinement effect for various strain increments. Columns had identical longitudinal steel with 12 deformed bars of a diameter of 16 mm and different numbers and sizes of transverse spiral reinforcement, resulting in confining reinforcement volumetric ratios ranging from 0.006 to 0.025. The unconfined concrete and steel strengths were 28 MPa and 275 MPa, respectively. The confinement spacings for the four columns C1, C2, C3, and C4 were 41 mm, 69 mm, 103 mm, and 119 mm, respectively. Transverse reinforcement has a diameter of 12 mm for the first three columns of C1 to C3 and 10 mm for C4. Fig. 1 depicts the stress-strain curve results for various confinement configurations, demonstrating the good agreement between predicted and experimental results at ambient conditions.

3. Proposed Approach for Confined Concrete during Cooling

The constitutive parameters of the stress-strain relationship of confined concrete are obtained during heating, which is then modified to execute the stress-strain relationship at a subsequent cooling temperature using the Eurocode theoretical approach [13]. Eurocode emphasizes the theoretical approach for the concrete constitutive parameters such as compressive strength, strain at peak stress, and ultimate strain when determining the stress-strain relationship at subsequent cooling temperature. These constitutive parameters at consecutive cooling temperatures are derived from the previously occurred peak heating temperature (Θ_{max}) of fire and the current cooling temperature (Θ_c). The concrete compressive strength ($f'_{c,\theta c}$) at cooling temperature can be determined by establishing the linear relationship between the compressive strength at the peak temperature ($f'_{c,\Theta max}$) and the corresponding residual strength ($f'_{cr,\theta a}$). Eurocode 4 [13] suggests that the strain at peak stress ($\varepsilon_{0,\theta c}$) remains unchanged for their successive cooling temperatures, i.e., $\varepsilon_{0,\theta c} = \varepsilon_{0,\theta max}$. There is no subsequent change in strain at peak stress during cooling. The confined concrete stress-strain relationship at subsequent cooling temperature was determined by substituting modified constitutive parameters into the Youssef and Moftah [3] model. A similar strategy to that described for concrete is employed to model the longitudinal and confined steel during the cooling. The residual strength of concrete and steel was calculated using the model of Chang et al. [18] and Tao et al. [19] respectively.

3.1 Study Parameters

A circular section with a diameter of 200 mm was

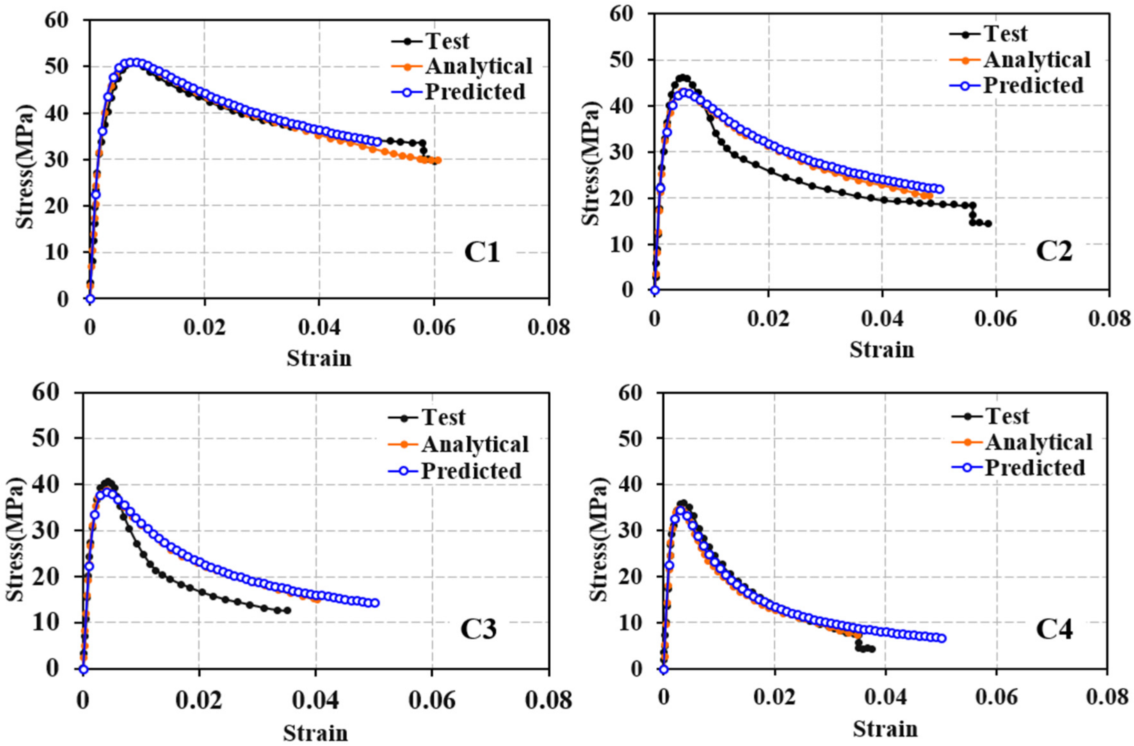


Fig. 1 Validation of the predicted stress-strain relationship of confined concrete with the Mander et al. [16,17] at ambient conditions.

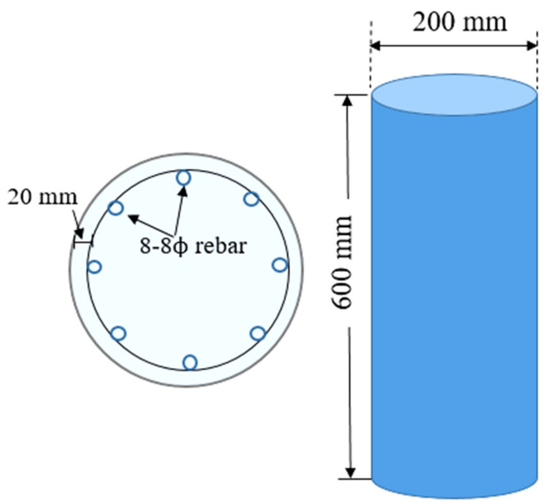
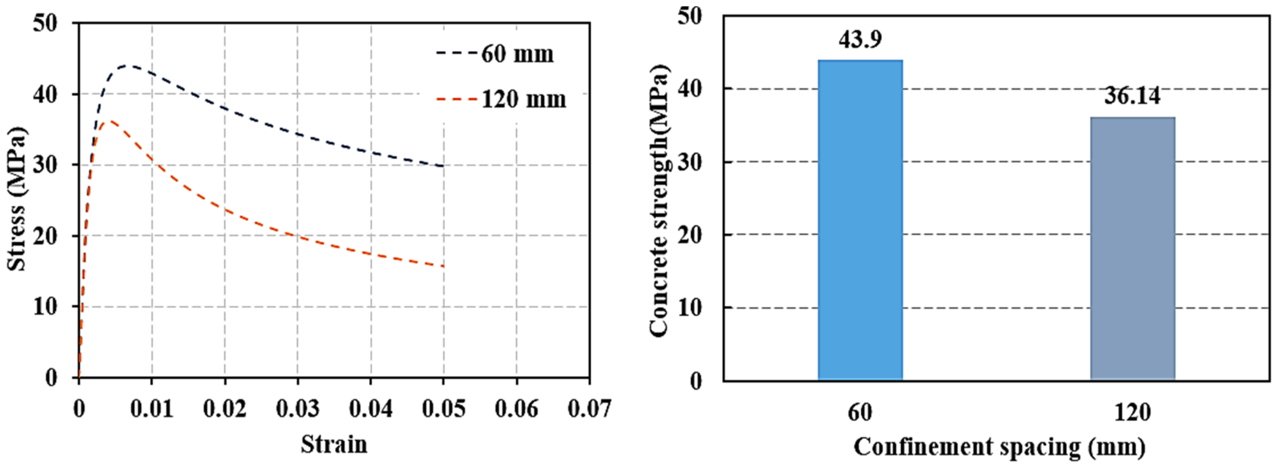


Fig. 2 Sectional and reinforcement details of the specimen.

considered, with two different confinement spacings of 60 mm and 120 mm. The 8 mm diameter of eight rebars was used for longitudinal reinforcement, and 6 mm diameter rebars were considered for transverse reinforcement. The sectional and reinforcement details of the specimen are shown in Fig. 2. The concrete and steel strengths were 30 MPa and 500 MPa, respectively. The strain corresponding to peak stress for unconfined concrete at ambient circumstances was considered 0.002 [17]. The maximum heating temperature of 750 °C was considered, with the stress-strain relationship calculated for following cooling temperatures of 500 °C, 250 °C, and ambient conditions.

4. Result and Discussion

The results demonstrate that confined concrete's compressive strength increases significantly compared to unconfined concrete at ambient conditions, as seen in Fig. 3b. If concrete is confined by transverse reinforcement, it expands due to axial compression, resulting in passive lateral pressure. Thus, confined steel provides a resistance against the lateral pressure exerted due to axial compression, consequently capacity improves. The compressive strength of unconfined concrete was 30 MPa. However, it increases by 20.46% and 46.33% for 120 mm and 60 mm confinement spacing, respectively, as seen in Fig. 3. In terms of ductility, the strain at peak stress at ambient conditions was 0.002,



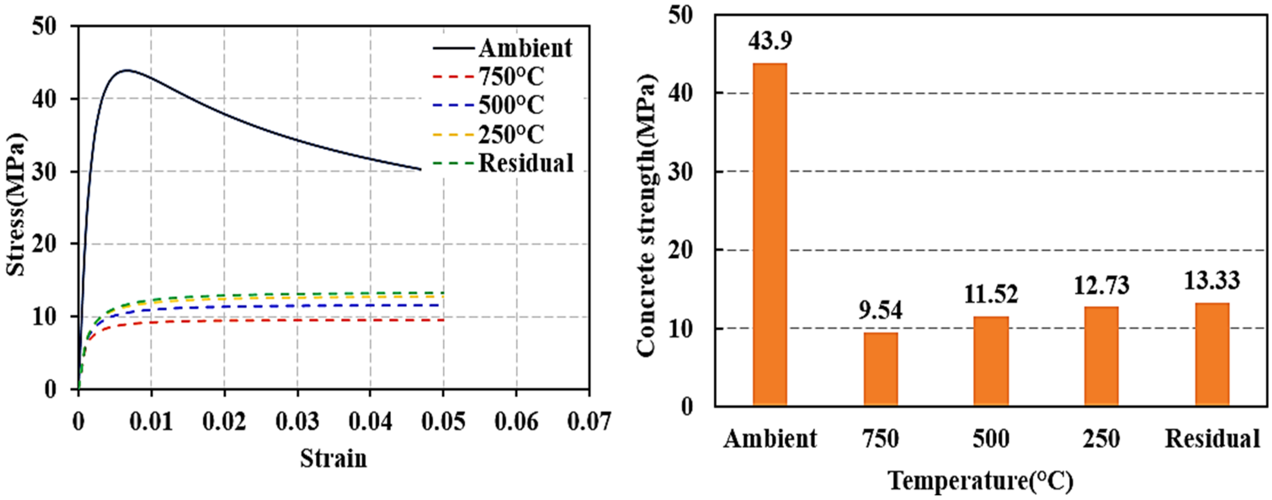
(a) Stress-strain relationship (b) Compressive strength

Fig. 3 Confined concrete stress-strain relationship at ambient temperature for confinement spacing of 60 and 120 mm.

whereas the strain improved by 150% and 200% for confinement spacings of 120 mm and 60 mm at ambient conditions. As seen in Fig. 3a, the overall behavior of the stress-strain curve of confined concrete improves due to an increase in strength, stiffness, and ductility. The improved ductility will allow structural elements to deform significantly during extreme loading events.

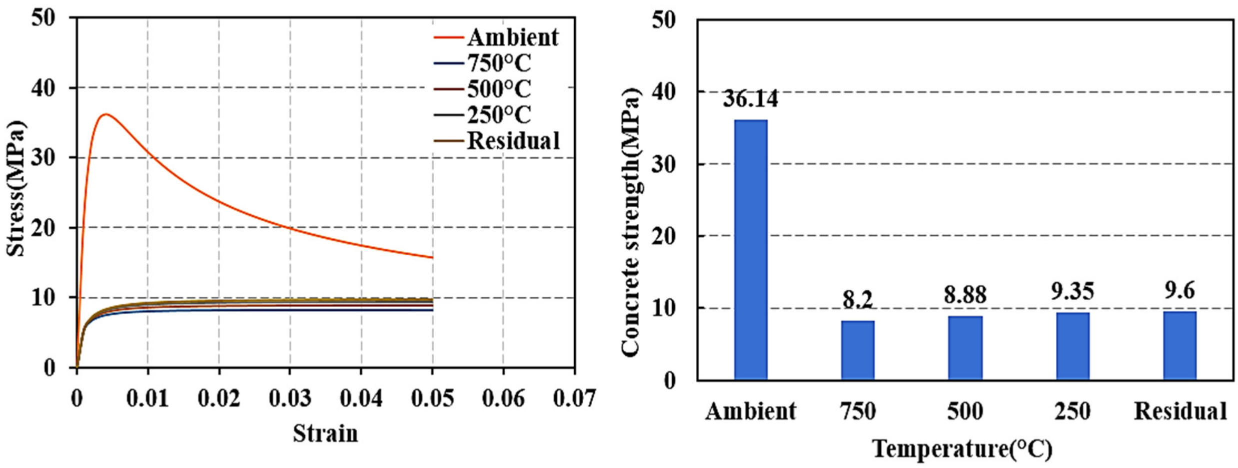
When exposed to a temperature of 750 °C, the strength of unconfined concrete drops by 76% compared to ambient circumstances. Similarly, confined concrete compressive strength reduces to 78.26% and 77.31% for 60 mm and 120 mm confinement spacing, respectively, as shown in Figs. 4b and 5b. High-temperature exposure may result in notable losses in the mechanical properties of steel and concrete. Therefore, confinement's ability to increase stiffness and strength could become less effective at high temperatures. In a similar manner, the strength of unconfined concrete is also significantly affected, potentially resulting in a substantial loss of load capacities (both axial and flexural) during a fire [20, 21]. The stress-strain curve shown in Figs. 4a and 5a also demonstrated that the stiffness of confined concrete decreased dramatically. However, as confinement spacing increases, strength and stiffness decrease dramatically. At a peak heating temperature of 750 °C, the strength of confined concrete for a confinement spacing of 60 mm is 16.34% higher than that of a confinement spacing of 120 mm. Similarly, ductility improved dramatically with temperature and confinement space.

After heating to a peak temperature of 750 °C, the confined concrete compressive strength improved on consecutive cooling temperatures of 500 °C, 250 °C, and ambient, as seen in Figs. 4 and 5. This can be attributed to recovered steel characteristics during cooling temperature. However, compressive strength declined with subsequent cooling temperatures. The maximum recovery occurs after complete cooling (residual state). Concrete with confinement of 60 mm apparently recovered 39.72% more strength than that obtained at 750 °C, while 120 mm confinement spacing brought 17.07% strength at the residual stage. Figs. 4 and 5 illustrate that the overall stress-strain curve improves with successive cooling temperatures as stiffness and strength recover. Recovery in confinement of spacing 60 mm is more significant than recovery in confinement spacing of 120 mm over successive cooling temperatures. Maximum recovery in lower confinement spacing can be attributed to the impact of restoring steel characteristics in the maximum confinement area. However, due to the significant transverse spacing, 120 mm spacing acts more similarly to unconfined concrete and has no



(a) Stress-strain relationship (b) Compressive strength

Fig. 4 Confined concrete stress-strain relationship at heating and subsequent cooling temperatures for confinement spacing of 60 mm.



(a) Stress-strain relationship (b) Compressive strength

Fig. 5 Confined concrete stress-strain relationship at heating and subsequent cooling temperature for confinement spacing of 120 mm.

substantial effect on compressive strength enhancement. The study's findings highlight the fact that after the concrete is heated to its maximum temperature, it can significantly affect its load capacity [8].

5. Conclusion

The study investigates the effect of peak heating temperature on the constitutive characteristics of confined concrete. In addition to that, attempts are made to incorporate the fundamental approach behind the constitutive relationship at the subsequent cooling temperature suggested by Eurocode 4. The stress-strain relationship for confined concrete with 60 mm and 120 mm confinement spacings is established by appropriately incorporating confinement and cooling temperature effects. The findings indicate that after accounting for the impact of confinement, compressive strength improves significantly at ambient and elevated temperature.

Confined concrete retains 32.50% and 13.89% more strength than unconfined concrete at a peak heating temperature of 750 °C for confinement spacings of 60 mm and 120 mm, respectively. After being heated to a peak temperature of 750 °C, confined concrete improves strength and stiffness at cooling temperatures of 500°C, 250 °C, and ambient temperature. The maximum recovery appeared to take place in confinement spacing of 60 mm over consecutive cooling temperatures following heating to 750°C, as compared to 120 mm confinement spacing. The highest recovery occurs after complete cooling to ambient temperature in both confinement spacing. The increase in compressive strength across successive cooling temperatures is due to the recovery in steel characteristics.

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