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Effect of temperature on mechanical properties of prestressing bars

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HIGHLIGHTS

- Effect of temperature on mechanical properties of prestressing bar is discussed.
- Critical temperature of prestressing bar is derived.
- Relations for high-temperature mechanical properties of prestressing bars is developed.

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ABSTRACT

Properties of prestressing reinforcement deteriorate with rise in temperature and hence the effect of temperature on mechanical properties is critical for evaluating the fire response of prestressed concrete structures. To develop such temperature dependent properties, a series of steady-state tensile strength tests were carried out on prestressing bar specimens to evaluate tensile strength, elastic modulus and stress–strain response in 20–800 °C temperature range. Results from these tests indicate that prestressing bar exhibits slower loss of strength and stiffness than conventional prestressing steel strands and wires throughout the temperature range of 20–800 °C. Data generated from tensile strength tests are utilized to develop empirical relations for expressing strength, elastic modulus and stress–strain response of prestressing bar as a function of temperature. The proposed relations can be used as input data in computer models for evaluating fire response of prestressed structures that incorporate prestressing bars.

1. Introduction

In recent years, significant research and development activities in the field of metallurgy have led to new types of steel reinforcement with improved properties. Prestressing bar (usually called steel bar for prestressed concrete) is one such type of newly developed medium strength (with a characteristic strength f_{pk} = 970 - MPa) prestressing steel and is increasingly used as reinforcement in prestressed concrete (PC) structures, high-rise buildings, bridge piers and rail-road ties. Examples of recent buildings utilizing prestressing bar include Shanghai International Exhibition Center and Shenzhen Convention and Exhibition Center (China).

Prestressing bars possess medium strength (in the range of 800–970 MPa) as compared to very high strength in prestressing steel strands (in the range of 1770–1960 MPa). The strength in prestressing bar is derived by increasing carbon content (as compared to reinforcing steel) and adding other alloy elements, and through quenching and tempering process [1,2]. The increased interest in the use of prestressing bar is due to a number of benefits it offers over conventional prestressing steel strands and wires. Further, when traditional prestressing steel strands (with characteristic strengths of f_{pk} = 1770–1960 MPa) are used in medium span (6–9 m) slabs and beams, the reinforcement ratio is usually dominated by the ultimate limit state consideration (moment carrying capacity). In such cases, deformation and cracking in slabs and beams under serviceability limit state are difficult to control due to low reinforcement ratio resulting from very high strength of prestressing steel strands. On the contrary, such deformation and crack control could easily be facilitated in PC structures reinforced with medium strength prestressing bars. Further, the strength of prestressing bar can be effectively utilized to the maximum extent. In addition, as compared to traditional prestressing steel strands, there is no acid washing in prestressing bar production, and thus industrial wastewater resulting from production during fabrication is reduced. Thus, prestressing bars are finding increasing application in recent construction projects due to above mentioned advantages.

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Nomenclature

E_s	elastic modulus at room temperature
$E_{s,T}$	elastic modulus at temperature T
f_{pk}	characteristic strength at room temperature
f_u	ultimate strength at room temperature
$f_{u,T}$	ultimate strength at temperature T
$f_{0.2}$	yield strength at strain levels of 0.2% offset at room temperature
$f_{0.2,T}$	yield strength at strain levels of 0.2% offset at temperature T
l_0	length of prestressing bar between two grips
l_1	the length of prestressing bar in elevated temperatures range
T	temperature
ε_T	strain at temperature T
$\varepsilon_{k,T}$	failure strain at temperature T
ε_u	strain at ultimate strength at room temperature
$\varepsilon_{u,T}$	strain at ultimate strength at temperature T
$\varepsilon_{0.2}$	strain at yield strength at room temperature
$\varepsilon_{0.2,T}$	strain at yield strength at temperature T
Δ_T	measured displacement at temperature T
σ_k	rupture point at room temperature
$\sigma_{k,T}$	rupture point at temperature T
σ_p	proportional limit at room temperature
$\sigma_{p,T}$	proportional limit at temperature T
σ_T	measured stress in prestressing bar at temperature T

Fire represents one of the extreme conditions encountered by structural members and hence PC structures have to meet relevant fire resistance ratings specified in building codes [3,4]. Knowledge of mechanical properties of prestressing bar at elevated temperatures is critical for evaluating fire resistance of concrete structures [5]. However, there have been no studies on the effect of temperature on mechanical properties of prestressing bar.

To develop such property data, an experimental program was carried out to evaluate strength and stiffness of prestressing bar at various temperatures. Steady-state tensile strength tests were carried out to evaluate variation of stress–strain response, yield and ultimate strength, proportional limit, rupture point and elastic modulus as a function of temperature.

2. Mechanical properties of prestressing steel at elevated temperatures

Ultimate strength and stress–strain relationship of prestressing steel strand (wire) are of primary importance in evaluating the fire response of PC structures. Prestressing bar, similar to prestressing steel strand (wire), does not have a clearly demarked yield plateau at ambient or elevated temperatures, which differentiates it from that of reinforcing steel bar. The definition for determining the yield strength of steel at elevated temperatures varies in different design codes of practice. EC3 [6] and SAC 2003 [7] recommends evaluating yield strength based on a strain level of 0.2% offset, while EC2 [8] recommendation is based on a strain level of 0.1% offset. As shown in Fig. 1, the 0.2% offset yield strength is the intersection point of the stress–strain curve and the proportional line offset by 0.2% strain. In BS 5950 [9] different reduction factors are given according to three nominal strain levels of 0.5%, 1.5% and 2.0% for different types of steels. A typical representation of stress–strain curve of prestressing steel strand (wire) at elevated temperature is shown in Fig. 1. The ultimate strength represents the maximum (peak) value of stress in the stress–strain curve. The proportional limit corresponds to the point on stress–strain curve till which response is elastic. The rupture point corresponds to the point on stress–strain curve at which rupture of prestressing steel strand (wire) occurs.

A review of literature indicates that many experimental studies have been carried out on the effect of temperature on strength properties of reinforcing steel [10–13]. Most of these studies were conducted for evaluating strength and stiffness properties of conventional reinforcing steel bars with yield strength in the range of 235–520 MPa. There is limited test data on temperature induced strength deterioration on prestressing steel strands (wires). Abrams [14] conducted tensile strength tests on cold drawn prestressing steel strands (with a characteristic strength f_{pk} = 1860 MPa) under steady-state conditions. Zheng et al. [15,16] conducted tensile strength tests on low relaxation prestressing steel wires (characteristic strengths in the range of 1770–1860 MPa) using both steady-state and transient-state fire test methods. Based on these tests, stress–strain relationships for prestressing steel wires at elevated temperatures were proposed. Gales and Bisby [17,18] conducted high-temperature tensile strength tests on prestressing steel tendons under sustained load to simulate creep effect. New creep parameters were developed to improve the accuracy of stress relaxation constitutive models. These test results highlight the importance of accounting for reliable creep parameters for modelling stress relaxation in heated prestressing steel tendons.

The mechanical properties of steel not only degrade with temperature, but also vary with chemical composition and type of heat treatment [1,19]. The chemical compositions of different steels used as reinforcement are tabulated in Table 1. There are two types of treatment that is used in production of prestressing steel strands/wires, namely cold drawn or quenched and tempered [20,21]. The chemical composition of prestressing bar is different from that of prestressing steel strands/wires, and reinforcing steel bar. Hence, high-temperature properties of prestressing bar is envisioned to be different. Current guidelines in ACI [3], EC2 [4] and PCI handbook [22] are based on property data generated from prestressing steel strands and wires (cold drawn or quenched and

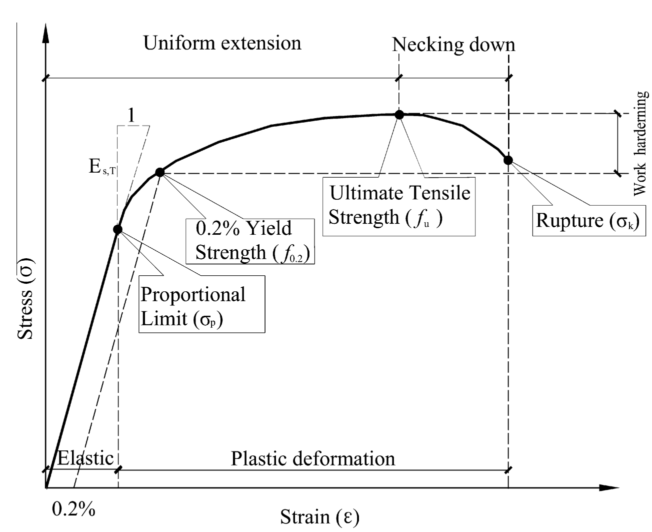

Fig. 1. Typical representation of stress–strain curve of prestressing steel strand (wire).