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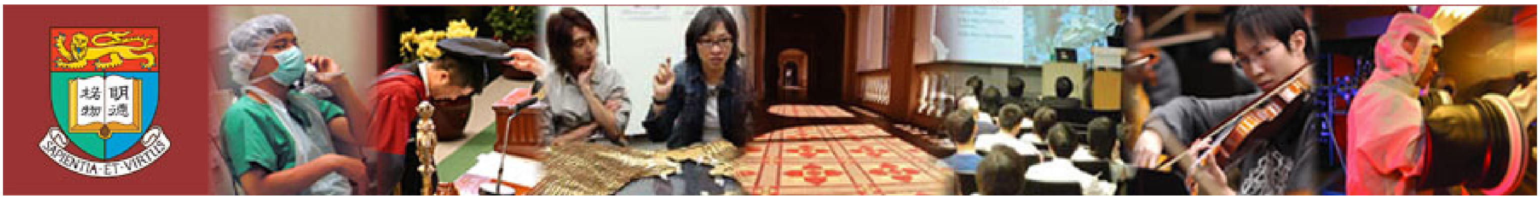

Title	Mechanical properties of prestressing steel in and after fire
Author(s)	ZHANG, L; WEI, Y; Au, FTK; Li, J
Citation	Magazine of Concrete Research, 2015
Issued Date	2015
URL	http://hdl.handle.net/10722/234542
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Magazine of Concrete Research
http://dx.doi.org/10.1680/jmacr.15.00267
Paper 1500267
Received 29/06/2015; revised 02/09/2015; accepted 15/09/2015

Mechanical properties of prestressing steel in and after fire

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Knowledge of the mechanical properties of prestressing steel at elevated temperatures and after cooling is essential to the fire resistance design and post-fire evaluation of the residual load-carrying capacity of prestressed concrete structures. Experiments were carried out using an accurate testing system for the development of empirical formulae to predict the deterioration of prestressing steel at elevated temperatures and after cooling. The helical structure of commonly used seven-wire strands allowed estimation of the mechanical properties of the strand based on those of the central wire. Only the central wire of the strand was thus tested, which enabled better clamping and control and hence more accurate measurements. Grade 1860 strands conforming to GB/T 5224, mostly used in Mainland China, and grade 1860 strands conforming to BS 5896, used in Europe and other countries, were tested. Consistent models for the reduction factors of various properties were developed. Some strands extracted from prestressed concrete specimens after fire testing were also tested for verification.

Notation

E	Young's modulus of prestressing wire at ambient temperature
$E(T)$	Young's modulus of prestressing wire at temperature T
$E_{ac}(T)$	Young's modulus of prestressing wire after cooling from temperature T
$f(T)$	reduction factor at temperature T
f_u	ultimate strength at ambient temperature
$f_u(T)$	ultimate strength at temperature T
$f_{uac}(T)$	ultimate strength after cooling from temperature T
$f_{yac}(T)$	yield strength of prestressing wire after cooling from temperature T
$f_{0\cdot2\%}$	0·2% proof stress at ambient temperature
$f_{0\cdot2}(T)$	0·2% proof stress at temperature T

Introduction

Prestressed concrete is often used to achieve large span to depth ratios, cost-effectiveness and enhanced load-carrying capacity, but it is prone to fire damage, particularly in thin slabs. Bailey and Ellobody (2009) conducted fire tests on unbonded one-way post-tensioned concrete slabs and investigated their overall structural behaviour in fire. Zhang *et al.* (2014) studied the behaviour of two-way reinforced concrete slabs in fire. A structural fire engineering assessment of the response in and after fire requires consideration of the thermal load, the thermal and mechanical properties of materials and their interaction. When prestressing steel is heated above 300°C, the structure is affected, possibly resulting in collapse. Although the Young's modulus of steel is not much affected after cooling, the 'yield' strength, ultimate strength and ductility will degrade depending on the peak temperature reached, and they thus need to be properly assessed.

Empirical equations for the Young's modulus and yield strength of grade 1670 prestressing wires used in China at temperatures up to 600°C were proposed by Fan and Lv (2001). Fan (2004) further tested grade 1860 prestressing strands under different cooling processes, and proposed cubic polynomials for Young's modulus, yield strength and ultimate strength after cooling. Hertz (2004, 2006) proposed an equation for the deterioration of quenched and tempered prestressing steel and of quenched and self-tempered reinforcement. Neves *et al.* (1996) conducted tests and found the residual strength of reinforcing and prestressing steel wires to depend on the cooling process. Atienza and Elices (2009) investigated the tensile strength of prestressing wires in and after fire up to 600°C. Gálvez *et al.* (2011) studied the strain rate effect on the tensile strength of prestressing wires at elevated temperatures. The ultimate strength and thermal creep effect of the central wires of prestressing strands conforming to BS 5896 (BSI, 2012) at elevated temperature were investigated by optical strain measurement (Gales *et al.*, 2012).

Performance-based design, instead of the simpler prescriptive-based design, is often adopted as it can achieve safety, economy and stability (Pang, 2006). BS EN 1992-1-2 (Eurocode 2) provides reduction factors for prestressing steel at elevated temperatures but not those for residual properties after cooling (BSI, 2004). The work described in this paper attempted to develop consistent models for predicting the mechanical properties of prestressing steel conforming to GB/T 5224 (SAC, 2003) and BS 5896 (BSI, 2012), used extensively in Mainland China and Europe respectively, at elevated temperatures and after cooling.

Axial response of straight seven-wire prestressing strands

Strands and wires are usually tested as straight specimens in regular testing. In applications of prestressed concrete structures, the cable curvature is normally small compared with the cable size and hence the test results will be applicable in this case. By studying the axial response of a straight seven-wire prestressing strand, it is possible to relate the response of the strand to that of the central wire.

Costello (1997) presented an analytical model to determine the axial static response of a simple straight strand by considering the respective contributions from the straight central wire and the outer helical wires. That analysis assumed an elastic response, frictionless contact between the wires and that the central wire was of sufficient size to prevent the outer wires touching each other. In the tested prestressing steel strand of nominal diameter 12·7 mm conforming to GB/T 5224, the diameter of the central wire was determined to be 4·35 mm. The diameter of the helical wire was measured and taken as the same although, strictly speaking, it should be slightly smaller in order to avoid the helical wires contacting each other. The pitch of the helical wires is defined as the axial distance along the length of strand that a helical wire twists around the central wire by one revolution. In this case, the pitch was taken as 15 times the nominal diameter of the strand, or 190·5 mm. Poisson's ratio of the prestressing steel was taken as 0·3. Analysis was carried out for this case according to the analytical model presented in chapter 3 of Costello's *Theory of Wire Ropes* (Costello, 1997). The loads carried by the helical wires and the central wire were determined to be 85·29% and 14·71% respectively of the total load applied. The share of each helical wire was 14·21% of the total load. The share of loading among wires was not uniform, but reasonably close to the average value of 14·29%. In the elastic stage, once the mechanical properties are determined from the central wire, it is possible to calculate those for the entire strand. However, since the deviation from the average stress is so small, estimation of the mechanical properties of a strand based on those of the central wire is reasonably accurate even beyond the elastic stage.

Experimental investigation

Test specimens and equipment

Two different kinds of seven-wire strands were tested – grade 1860 steel conforming to GB/T 5224 used in Mainland China and grade 1860 steel conforming to BS 5896 used in European countries. As it is difficult to measure the strain of a strand accurately due to its helical structure, extracted central wires were tested and this allowed better clamping and control. Table 1 shows the nominal dimensions and properties of the central wire specimens, while Table 2 shows their chemical compositions.

A material testing system (MTS 810) of 250 kN capacity was employed for the tests at The University of Hong Kong (HKU). The heating device was an MTS 653 high-temperature furnace with three heating chambers and a maximum heating temperature of 1400°C. The central 185 mm portion of the specimen was heated inside the furnace, which was monitored by a temperature controller (MTS model 409·83). The strain of the heated part of the specimen was measured by an axial extensometer for high-temperature testing (MTS 632·54F-11), having a gauge length of 25 mm and a maximum strain of 10%. The extensometer had two extension arms for convenient mounting. The centre-split design of the furnace allowed it to be opened slightly for the attachment and detachment of the extensometer while reducing adverse effects on the temperature inside the furnace. A thermocouple was placed in contact with the heated part of the specimen to measure its temperature.

	GB/T 5224	BS 5896
Diameter: mm	4·35	5·39
Area: mm^2	14·86	22·82
Density: kg/m^3	7800	7800
Total length: mm	800	800
Gripped length: mm	150	150
Clear length: mm	650	650
Young's modulus: GPa	200	204·1

Table 1. Nominal dimensions and properties of central wire specimens

	GB/T 5224	BS 5896
Chromium: %	—	0·13
Manganese: %	0·73	0·74
Silicon: %	0·2	0·41
Phosphorus: %	0·015	< 0·01
Carbon: %	0·8	0·8
Sulfur: %	0·008	0·016

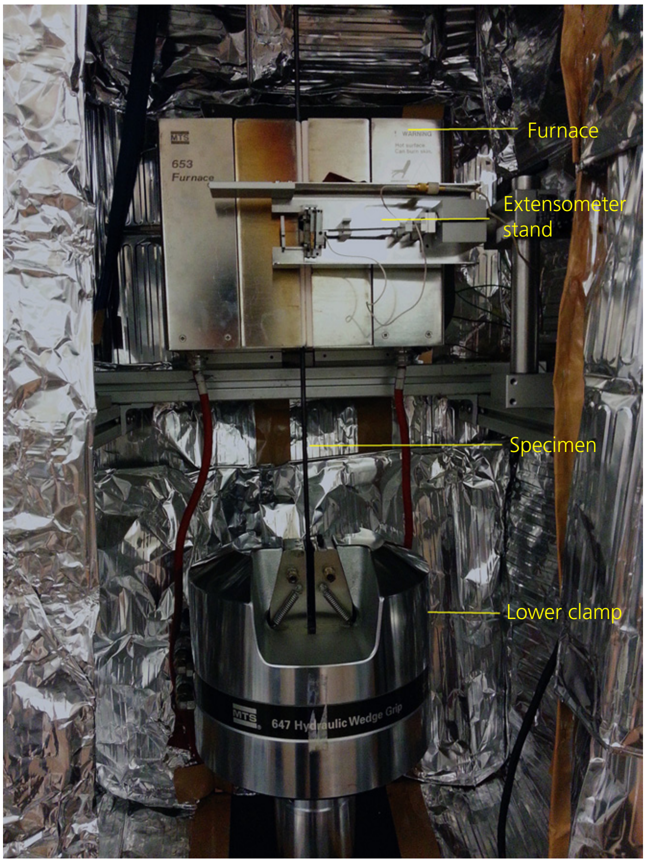
Table 2. Chemical compositions of prestressing steel wire

The whole testing system was covered with an aluminium foil heating shield for temperature stabilisation, as shown in Figure 1.

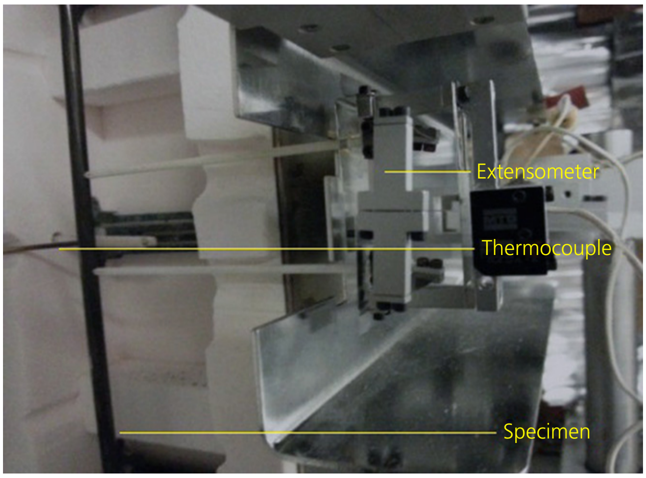
Test procedure

In the tensile tests at elevated temperatures, each specimen was heated to a target temperature (i.e. 100–800°C) and maintained for 15 min with one end gripped and the other end free. Free expansion of the specimen was allowed before applying load to avoid any influence of thermal expansion on strain measurements. Afterwards, the free end was gripped and the extensometer was attached to the heated part of the specimen. A constant displacement-controlled loading rate of 2 mm/min was applied until the specimen ruptured. The extensometer was detached before the specimen failed to protect the extension rods. The data obtained showed that the strain rate was approximately 0·003/min, which fell into the range of 0·005 ± 0·002/min as specified in ASTM E 21-09 (ASTM, 2009). The load and strain were recorded continuously by a computer at a sampling frequency of 5 Hz.

In the tensile tests after cooling, each specimen was first heated to the target temperature and maintained constant for 15 min for stabilisation, with one end gripped and the other end free. The furnace was then switched off and opened slightly, allowing the specimen to cool naturally to ambient temperature. When the specimen reached ambient temperature (25°C), the free end was gripped and a constant displacement-controlled loading rate of 2 mm/min was applied until failure, as before.



(a)



(b)

Figure 1. (a) MTS 810 material testing system with aluminium shield. (b) MTS 632·54F-11 axial extensometer

Test results

Mechanical properties at elevated temperatures

The stress obtained was engineering stress, assuming a constant cross-sectional area and ignoring the necking effect. Young's modulus E was taken as the tangent value of the initial proportional section of the stress–strain curve. The yield strength $f_{0{\cdot}2\%}$ was taken as the 0·2% proof stress (non-proportional elongation). The ultimate strength f_u was the maximum stress in the stress–strain curve. Their corresponding values at elevated temperature T °C were similarly defined, giving reduction factors (BSI, 2004) as $E(T)/E$, $f_{0{\cdot}2}(T)/f_{0{\cdot}2\%}$ and $f_u(T)/f_u$. The stress–strain curves of prestressing wires conforming to GB/T 5224 and BS 5896 at elevated temperatures are plotted in Figures 2 and 3 respectively. Young's modulus, yield strength and ultimate strength are affected differently by temperatures above 200°C. The corresponding reduction factors are shown in Table 3. They are also shown graphically in Figures 4–6 and compared with available results reported by Fan and Lv (2001, 2002), Fan (2004), Atienza and Elices (2009), Wang *et al.* (2010) and Gales *et al.* (2012) as summarised in Table 4.

Figure 4 shows that the Young's moduli of prestressing wires conforming to BS 5896 and GB/T 5224 showed similar degradation below 500°C, but the wire conforming to GB/T 5224 deteriorated more above 500°C. At temperatures of 600°C, 700°C and 800°C, the reduction factors for Young's modulus of prestressing wire conforming to BS 5896 were 46·6%, 20·5% and 18·2% respectively, while those for GB/T 5224 wire were only 37·9%, 7·3% and 3·6%. The BS 5896 prestressing steel wire showed better resistance above 500°C in terms of Young's

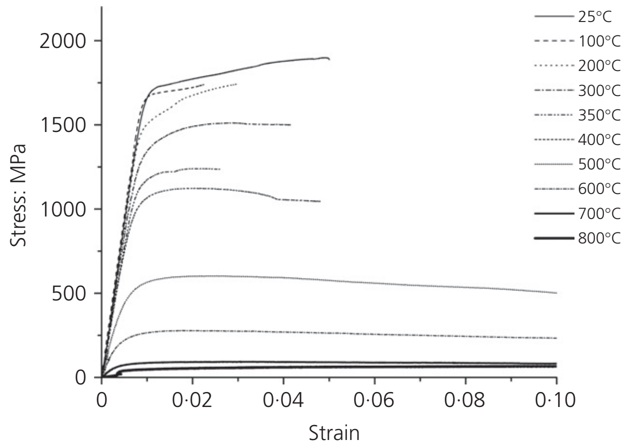


Figure 2. Stress–strain curves of prestressing wire conforming to GB/T 5224 at elevated temperatures

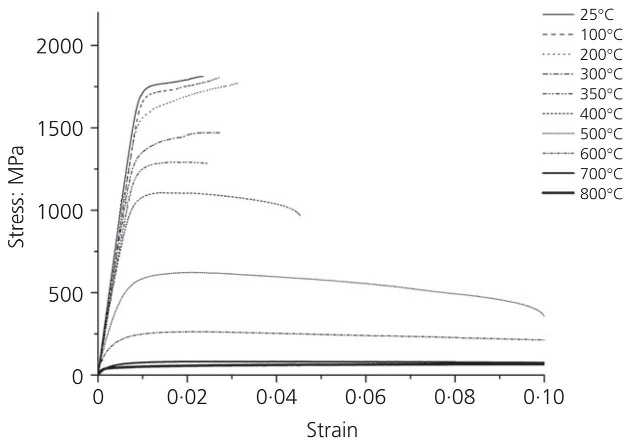


Figure 3. Stress–strain curves of prestressing wire conforming to BS 5896 at elevated temperatures

modulus at elevated temperature. The values specified in BS EN 1992-1-2 (BSI, 2004) are conservative at temperatures of 500–800°C compared with those for BS 5896, but the specified values are close to those for GB/T 5224. Most of the reduction factors for Young's modulus from other research works are lower at temperatures above 400°C.

Figure 5 shows generally good agreement between the reduction factors for the yield strength of prestressing wires conforming to GB/T 5224 and BS 5896. The reduction factors for yield strength specified by BS EN 1992-1-2 are conservative at temperatures of 200–500°C, but adequate for 500–800°C. Figure 6 shows less variability in ultimate strength at elevated temperatures compared with yield strength. BS EN 1992-1-2 (BSI, 2004) gives conservative reduction factors for ultimate strength at temperatures of 200–500°C, but agrees relatively well at other temperatures.

In general, a mechanical property $\xi(T)$ at temperature T °C can be expressed as

1. $$\xi(T) = \xi_0 \times f(T)$$

in terms of the mechanical property at ambient temperature ξ_0 and the corresponding mechanical reduction factor $f(T)$ (Hertz, 2004) given by

2. $$f(T) = k + \frac{1-k}{1 + (T/a) + (T/b)^2 + (T/c)^8 + (T/d)^{64}}$$

where the parameters k, a, b, c and d can be determined from experimental data.

The reduction factors for Young's modulus, yield strength and ultimate strength at elevated temperatures of the prestressing

Temperature: °C	GB/T 5224			BS 5896		
	Young's modulus	Yield strength	Ultimate strength	Young's modulus	Yield strength	Ultimate strength
20	1·000	1·000	1·000	1·000	1·000	1·000
100	1·013	0·985	0·998	0·944	0·974	0·984
200	0·97	0·888	0·965	0·94	0·906	0·949
300	0·886	0·792	0·796	0·858	0·779	0·754
350	0·853	0·677	0·654	0·817	0·717	0·662
400	0·829	0·607	0·591	0·798	0·607	0·568
500	0·578	0·295	0·318	0·571	0·301	0·319
600	0·379	0·131	0·147	0·466	0·116	0·135
700	0·073	0·049	0·049	0·205	0·033	0·042
800	0·036	0·027	0·035	0·182	0·025	0·034

Table 3. Reduction factors for mechanical properties of prestressing steel wires conforming to GB/T 5224 and BS 5896 at elevated temperatures

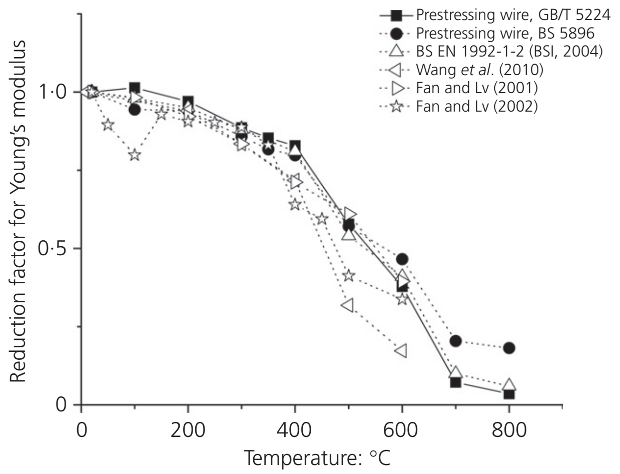


Figure 4. Reduction factors for Young's modulus at elevated temperatures

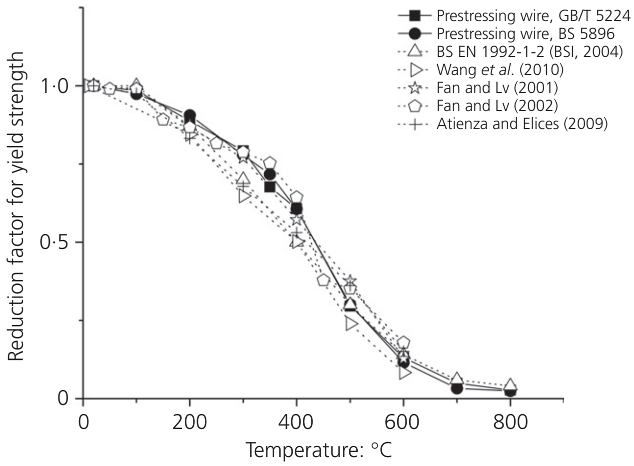


Figure 5. Reduction factors for yield strength at elevated temperatures

steels tested as obtained from curve fitting are shown in Figure 7. The values of adjusted R^2 for curve fitting are reasonably close to unity, indicating a good fit based on the experimental data. The corresponding parameters k, a, b, c and d of prestressing steel wires conforming to GB/T 5224 and BS 5896 prestressing steel are presented in Table 5.

Mechanical properties after cooling

The stress–strain curves of GB/T 5224 and BS 5896 prestressing wires after natural cooling from peak temperatures of 100–600°C to ambient temperature are shown in Figures 8 and 9 respectively. The mechanical properties are hardly affected by heating up to and cooling from 300°C, but the residual strengths degrade after cooling from peak temperatures above 400°C. As shown in Figure 10, upon cooling from

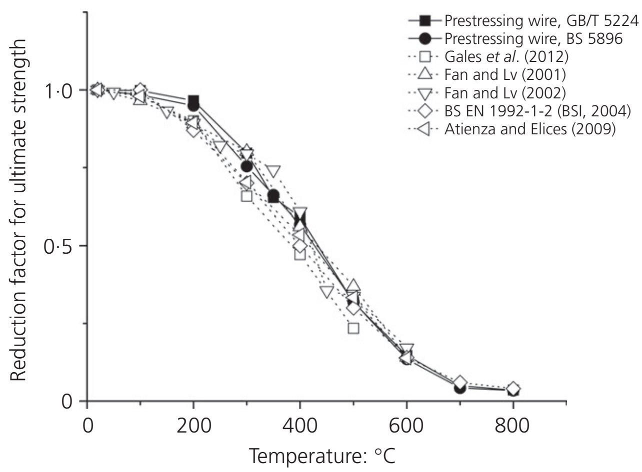


Figure 6. Reduction factors for ultimate strength at elevated temperatures

Author	Diameter: mm	Grade	Standard	Strand	Wire
Fan and Lv (2002)	—	1860	—	√	
Fan (2004)	—	1860	—	√	
Fan and Lv (2001)	5	1670	GB/T 5224		√
Atienza and Elices (2009)	5	—	—		√
Wang *et al.* (2010)	5	1670	GB/T 5224		√
Gales *et al.* (2012)	4	1670	BS 5896		√

Table 4. Previous tests of prestressing steel at elevated temperatures

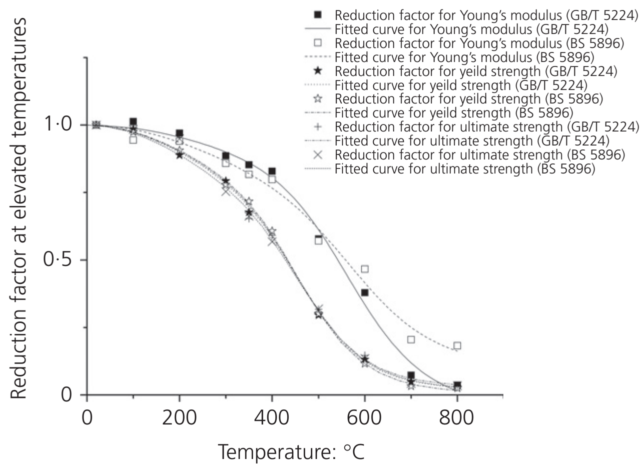


Figure 7. Reduction factors for mechanical properties of prestressing wire by curve fitting

	Steel	*k*	*a*	*b*	*c*	*d*
Young's modulus	GB/T 5224	−0·0572	$7{\cdot}00 \times 10^9$	950·37	580·74	100 000
	BS 5896	0·0965	$7{\cdot}00 \times 10^9$	724·35	589·82	100 000
Yield strength	GB/T 5224	0·0142	$7{\cdot}07 \times 10^9$	594·12	469·91	100 000
	BS 5896	0·0027	$7{\cdot}00 \times 10^9$	623·26	470·6	100 000
Ultimate strength	GB/T 5224	0·0257	$8{\cdot}00 \times 10^9$	602·83	467·09	100 000
	BS 5896	0·0159	$7{\cdot}00 \times 10^9$	564·32	473·03	100 000

Table 5. Parameters for reduction factors for mechanical properties at elevated temperatures

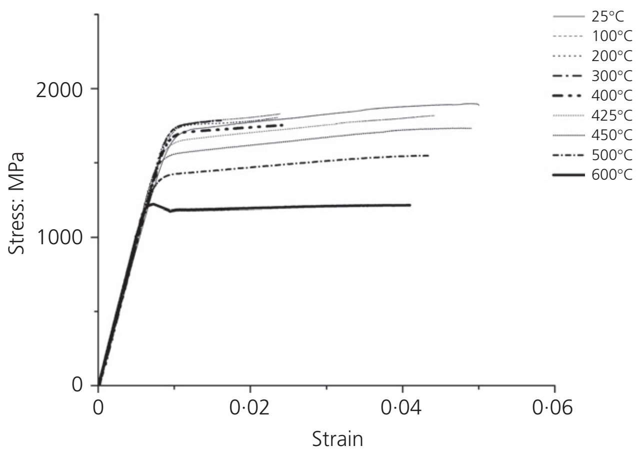


Figure 8. Stress–strain curves of prestressing wire conforming to GB/T 5224 after cooling from temperatures up to 500°C

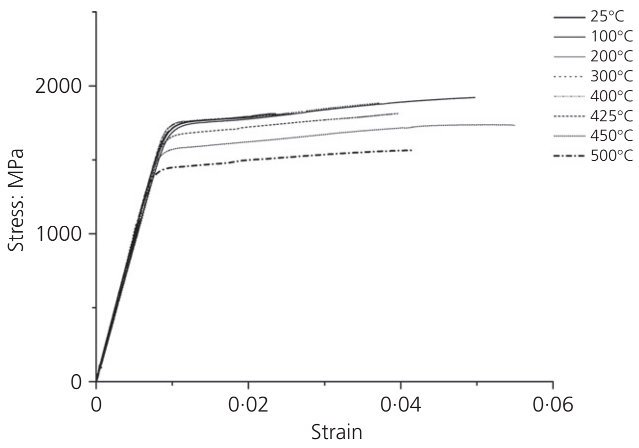


Figure 9. Stress–strain curves of prestressing wire conforming to BS 5896 after cooling from temperatures up to 500°C

temperatures of 600°C or above, the elastic range is adversely affected and plastic deformation begins earlier. This is probably because of the high-temperature exposure followed by slow cooling, which resembles annealing. After cooling from 800°C, the prestressing steel behaves similarly to high-yield steel.

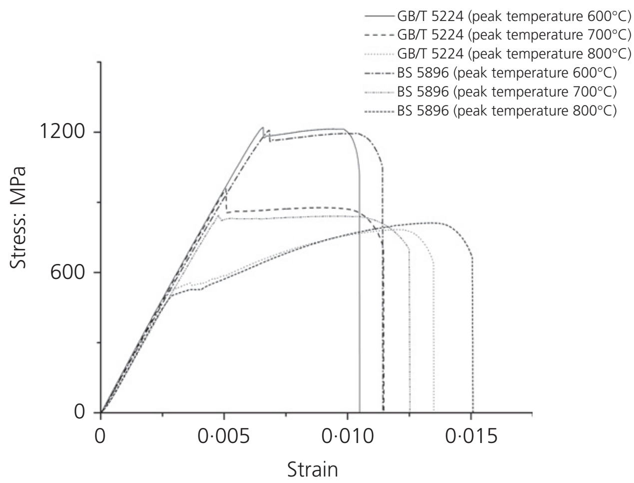


Figure 10. Stress–strain curves after cooling from temperatures of 600°C and above

To avoid damage to the extensometer by premature failure in tests after cooling from 600°C or above, the strain was estimated from cross-head displacement. Where both upper and lower yield points appeared, the yield strength was based on the lower. The reduction factors for Young's modulus, yield strength and ultimate strength after cooling are presented in Table 6.

Figure 11 compares the reduction factors for Young's modulus after natural cooling ($E_{ac}(T)/E$) with available results; $E_{ac}(T)$ is Young's modulus after cooling from the peak temperature T °C and E is that at ambient temperature. Among the cooling conditions investigated by Fan (2004) (natural cooling, water-spray cooling, in-furnace cooling and 72 h after natural cooling), only the results for natural cooling are included in Figure 11. In general, Young's modulus of prestressing steel is largely recoverable after exposure to elevated temperature and cooling.

The reduction factors for yield strength f_{yac} (T) of prestressing steel wire conforming to GB/T 5224 and BS 5896 after cooling from the peak temperature T °C in Figure 12 show an obvious decline for peak temperatures of 400°C or above but little effect below 400°C. The results from other sources show

Peak temperature: °C	GB/T 5224			BS 5896		
	Young's modulus	Yield strength	Ultimate strength	Young's modulus	Yield strength	Ultimate strength
20	1·000	1·000	1·000	1·000	1·000	1·000
100	1·032	1·026	1·024	0·956	0·984	0·985
200	1·052	1·022	1·028	0·98	0·996	0·966
300	1·043	1·028	1·019	1·007	1·012	0·997
400	1·049	0·995	0·985	1·007	1·015	0·982
425	1·032	0·964	0·966	0·992	0·967	0·939
450	1·064	0·912	0·913	1·012	0·917	0·89
500	1·055	0·83	0·818	1·023	0·845	0·805
600	1·073	0·689	0·643	1·014	0·693	0·619
700	1·028	0·497	0·504	0·946	0·484	0·433
800	1·056	0·343	0·413	0·978	0·334	0·416

Table 6. Reduction factors for mechanical properties of prestressing steel wires conforming to GB/T 5224 and BS 5896 after cooling

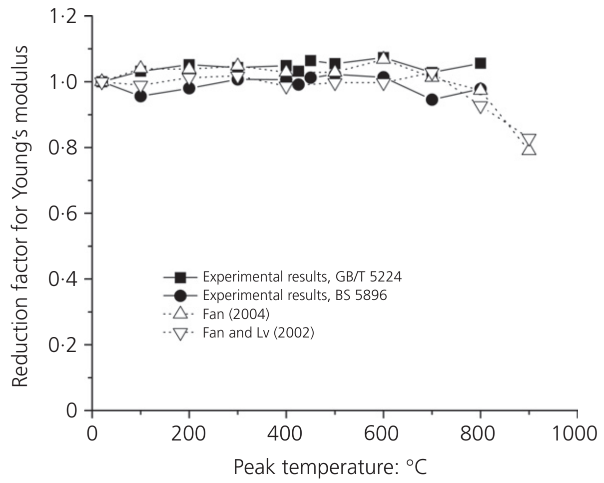


Figure 11. Reduction factors for Young's modulus after cooling

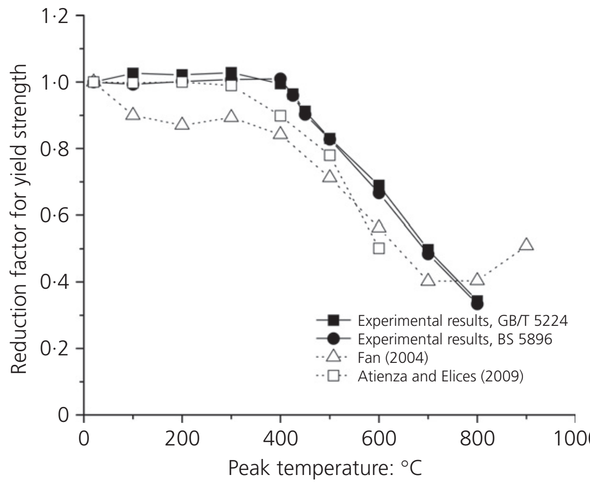


Figure 12. Reduction factors for yield strength after cooling

similar trends, but the present results appear more consistent. The reversed trend of results from Fan (2004) for cooling from temperatures above 700°C could be caused by strength enhancement because of martensite formation due to rapid cooling from the critical forming temperature 723°C (Meyers and Chawla, 2009). Similar trends can also be observed for the reduction factors for ultimate strength $f_{\mathrm{uac}}\ (T)$ of prestressing steel wire conforming to GB/T 5224 and BS 5896 after cooling from the peak temperature T °C, as shown in Figure 13.

Based on the test results, Young's modulus after cooling from peak temperature T can be regarded as unchanged, that is

3. $$E_{\mathrm{ac}}(T) = E_0$$

Based on the test results, piecewise linear functions were employed to describe the reduction factors for residual yield and ultimate strengths after cooling. The reduction factors for yield and ultimate strengths of prestressing steel wire conforming to GB/T 5224 are given respectively as

4. $$f_{\mathrm{yac}}(T) = \begin{cases} 1 & 20°\mathrm{C} < T < 400°\mathrm{C} \\ 1{\cdot}65469 - 0{\cdot}00164T & 400°\mathrm{C} \leq T \leq 800°\mathrm{C} \end{cases}$$

5. $$f_{\mathrm{uac}}(T) = \begin{cases} 1 & 20°\mathrm{C} < T < 400°\mathrm{C} \\ 1{\cdot}655 - 1{\cdot}64 \times 10^{-3}T & 400°\mathrm{C} \leq T \leq 700°\mathrm{C} \\ 1{\cdot}142 - 9{\cdot}175 \times 10^{-4}T & 700°\mathrm{C} \leq T \leq 800°\mathrm{C} \end{cases}$$

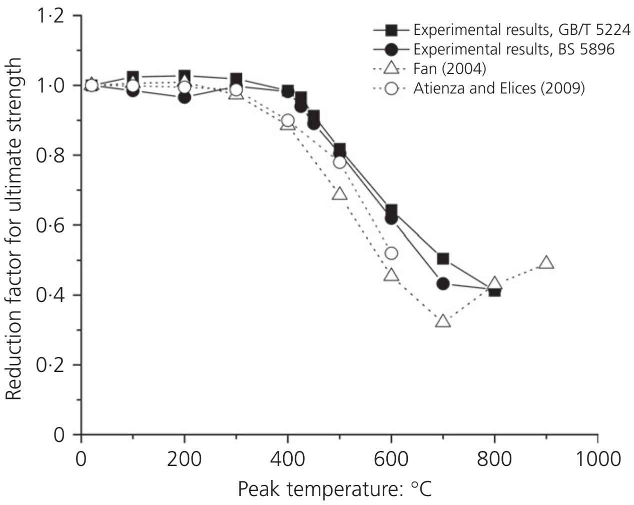


Figure 13. Reduction factors for ultimate strength after cooling

Similarly, those for prestressing steel wire conforming to BS 5896 are given respectively as

6. $$f_{\text{yac}}(T) = \begin{cases} 1 & 20°\text{C} < T < 400°\text{C} \\ 1{\cdot}707 - 1{\cdot}76 \times 10^{-3}T & 400°\text{C} \leq T \leq 800°\text{C} \end{cases}$$

7. $$f_{\text{uac}}(T) = \begin{cases} 1 & 20°\text{C} < T < 400°\text{C} \\ 1{\cdot}71708 - 1{\cdot}83 \times 10^{-3}T & 400°\text{C} \leq T \leq 700°\text{C} \\ 0{\cdot}55074 - 1{\cdot}684 \times 10^{-4}T & 700°\text{C} \leq T \leq 800°\text{C} \end{cases}$$

Effects of heating and cooling

Figure 14 compares the reduction factors for Young's modulus at elevated temperatures and after cooling, which is characterised by full recovery upon cooling. However, despite the full recovery of Young's modulus upon cooling, the reduction of Young's modulus during heating will have caused substantial loss of prestress, thereby affecting the load-carrying capacity even though the peak temperature may not be too high. Figures 15 and 16 show the corresponding comparisons for yield and ultimate strengths, which display striking similarity. The residual strengths of prestressing steel are essentially fully recovered if the peak temperature does not exceed 400°C.

Mechanical properties of strands in prestressed concrete after fire test

Under the same research project, fire tests on a number of unbonded post-tensioned two-way concrete slab specimens (Wei *et al.*, 2014) were carried out in a furnace at South China University of Technology (SCUT) to investigate their structural fire performance. Grade 1860 prestressing steel strands conforming to GB/T 5224 were used as tendons. After fire testing, samples of strands were reclaimed from the four specimens tested to determine their residual strengths after exposure to elevated temperatures. The length of each strand specimen was 1100 mm with a nominal cross-sectional area of 98·7 mm^2. Each strand had experienced different peak temperatures, as measured by thermocouples provided at key locations and recorded by a datalogger.

Additional precautions were necessary for the tensile tests at ambient temperature as the strand samples were imperfect. To avoid slipping at the grips, additional aluminium clamps

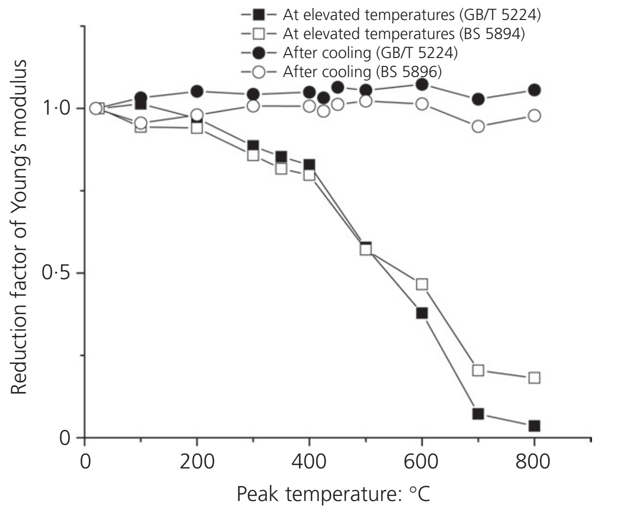


Figure 14. Reduction factors for Young's modulus at elevated temperatures and after cooling

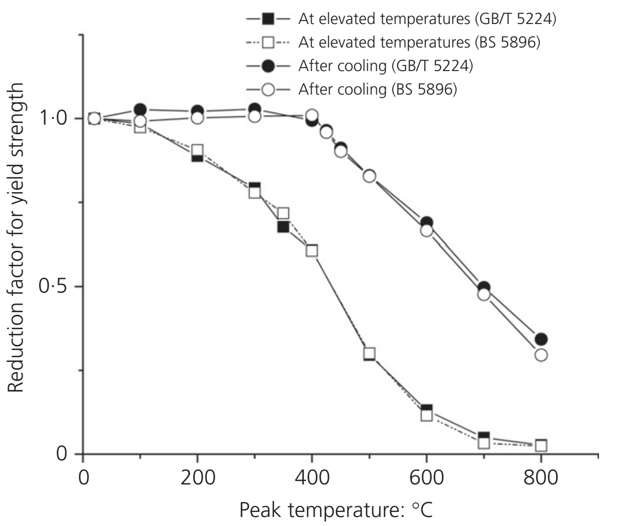


Figure 15. Reduction factors for yield strength at elevated temperatures and after cooling

roughened with ironsand at the surfaces were used. An extensometer of gauge length of 500 mm was used to monitor the strain. Each strand specimen was loaded until its ultimate strength was reached. The extensometer was detached before failure of the specimen for protection of the instrument. The yield and ultimate strengths obtained from the reclaimed strands (SCUT) are plotted against the peak temperatures experienced in Figure 17. Also shown in the figure are the corresponding values obtained from the testing of the central wire (HKU). In general, the trends agree well, but the degradation of the reclaimed strands appears to be more serious. The machine used for testing the strands was not as accurate as that used for testing the central wires, although this may not explain the higher degradation. The post-tensioned concrete specimens had been left outdoors for a year before fire testing,

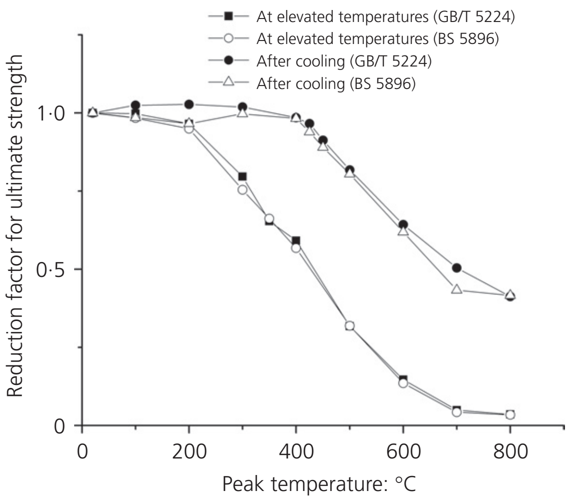


Figure 16. Reduction factors for ultimate strength at elevated temperatures and after cooling

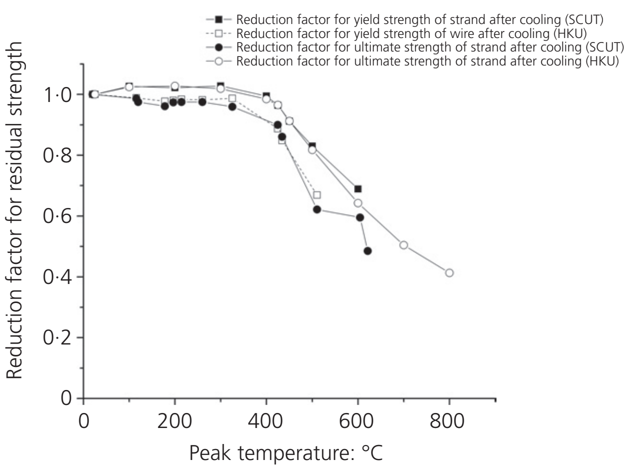


Figure 17. Comparison of residual strengths of prestressing strand and wire after cooling

during which some minor corrosion could have taken place, thus slightly reducing the cross-sectional area. Moreover, the slab specimen was exposed to fire at the soffit, creating a rather large thermal gradient; therefore, different wires of a strand experienced different peak temperatures. During subsequent tensile testing, the most affected wire could fail first and trigger earlier strand failure.

Conclusions

The mechanical properties of prestressing strands from two different sources in and after fire were investigated. The results are generally consistent with available results from the research literature and design codes. Empirical formulae based on a unified model are proposed for the degradation of Young's modulus, yield strength and ultimate strength of prestressing steel both at elevated temperatures and after cooling to ambient temperature. Although Young's modulus was found to be largely recoverable upon cooling to ambient temperature, both yield strength and ultimate strength suffered permanent degradation. To assist in post-fire assessments of prestressed concrete structures, it is recommended that reduction factors for the key mechanical properties after fire and cooling be incorporated in the relevant design codes.

Acknowledgements

The work described here was supported by the Research Grants Council (RGC) of the Hong Kong Special Administrative Region, China (RGC project no. HKU 710012E) and the State Key Laboratory of Subtropical Building Science of South China University of Technology, China (project no. 2011KA02). The authors are grateful to VSL Hong Kong Ltd for the provision of some strands and to Mr Ran Wang for assistance in the work.

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