Stress relaxation properties of prestressed steel wires

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Abstract

In this study, stress relaxation phenomenon has been examined generally. Experiments were carried out on carbon steel wires with diameter 8 mm which are particularly used in prestressed concrete composites. Thermomechanically heat treatment was also carried out on this wire in order to relieve the residual stresses accumulated after the cold work. The heat treatment temperature and the stretch ratio, which are the parameters of thermomechanical heat treatment, were changed. Thermomechanical heat treatment experiments have been performed under two separate groups. In one of the groups, stretch ratios were changed at a constant temperature of 350°C. In the other group, the heat treatment temperature was changed while the strain ratio was constant at 40%. The optimum thermomechanical heat treatment conditions have been determined by changing the heat treatment temperature and stretch ratio and by observing the effect of these changes of tensile stress and stress relaxation behaviour of the cold drawn steel wires.

It is not always feasible to perform stress relaxation experiments in long periods of time as 1000 h. The general conditions of the laboratories are not suitable to permit this period of time. In this study, the results of the relaxation experiments are emphasised with empirical formulas.

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1. Introduction

In prestressed concrete composites, steel wires with higher elastic limit and tensile strength are required. Concrete has lower tensile strength as compared to its higher compression strength. Steel tendons are used to improve tensile strength of concrete. Higher strength steel wires naturally serve to increase the strength of whole concrete composite. In prestressed concrete composite, steel wires are embedded in concrete in tension and during its use there should not be a loss of tension. Therefore, steel wires should have a low relaxation property [1,2].

In industrial applications, steel wires are cold drawn to achieve high strength. Interior stresses developed during the cold drawn produce some important changes in tensile strength, Hook slope, elongation, etc. of the material. In order to minimise the effects of residual stresses, thermomechanical treatments should be induced [3].

By definition, stress relaxation under the creep conditions refers to the decrease in stress at a constant deformation. When stress relaxation occurs, the stress needed to maintain a constant total deformation decreases as a function of time [4–6].

Stress relaxation could also defined as decrement in stress as a function of time while the material length remains constant. However, creep is defined as elongation in material when subjected to constant stress. An adequate formulation, which gives the relationship between these two, has not been derived yet. Therefore, although it is easy to perform creep tests when stress relaxation data is required, stress relaxation experiments should be done [6–8].

Carbon steel wires which are used in the production of prestressed concrete composites with 4–14 mm diameters are cooled in a controlled atmosphere after the hot rolling process which results in a relatively homogeneous pearlite type structure. Heating up to temperatures of 400°C and stretching up to 50% are applied to cold drawn wires, which have high hardness and strength. This thermomechanical treatment is done to improve the mechanical properties [8–12].

Researches done so far have proved that relaxation losses are dramatically reduced after re-stretching. For this reason, relaxation at plastic elongation in the longitudinal direction will decrease primary creep considerably, and this will lead to a decreased stress loss at the beginning of the relaxation test.
Stress relaxation decrease, seen in reloading in relaxation tests done at room temperature, is greater than decreases observed at elevated temperatures. Thus, to relieve creep more stable achievements can be realised at elevated temperatures. This process, which is called low temperature heat treatment (LTHT) has been used in the production of steel wires with low stress relaxation [13].

The effect of LTHTs on relaxation resistance is rather high. LTHT is applied for relieving residual stresses and stabilising mechanical properties of materials. LTHT applied on carbon steel and stainless steels cause the development of tension and torsion properties of materials. Fig. 1 shows the effect of LTHT temperatures on patented cold drawn carbon steels. When LTHT temperatures increase, relaxations continuously decrease at low stress levels. At higher stress levels, around 350 °C, relaxation decreases to a minimum level and then it rises again [13].

2. Experimental study

During the experiments stretch ratio and heat treatment temperature, which are the parameters of thermomechanical heat treatment (stress relieving—stretching), have been changed. Specimens prepared with various parameters have been used for tensile strength and stress relaxation experiments. In the experimental work, 8 mm diameter steel wires were used. Its chemical composition is given in Table 1.

Thermomechanical heat treatment experiments have been performed under two separate groups. In one of the groups, stretch ratios were changed at constant temperature of 350 °C. While the strain ratio was constant at 40%, heat treatment temperature was changed. Parameters for thermomechanical heat treatment are summarised in Table 2. For each group, three test specimens were chosen for tensile testing which has been performed at Zwick Universal Test Machine and their strength (the yield stress at 0.1% total elongation, \(R_{p0.1}\), the yield stress at 0.2% total elongation, \(R_{p0.2}\) and ultimate tensile strength, \(R_{m}\)) and elongation values have been determined.

Tensile test results are shown in Fig. 2, which are obtained with 40% constant stretch ratio and various heating temperatures. Fig. 3 shows the tensile test results that specimens were prepared at constant temperature and various stretch ratios. Specimens with 1.20 m length from each group have

<table>
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<th>Table 2 Parameters of thermomechanical heat treatmenta</th>
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<tr>
<td>Constant (T), 350 °C</td>
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<tr>
<td>Non-treated</td>
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<tr>
<td>20% stretch</td>
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<td>30% stretch</td>
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<td>40% stretch</td>
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<td>50% stretch</td>
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<td>Table 1 Chemical composition range of the steels tested</td>
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<tr>
<td>Element</td>
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<tr>
<td>Carbon</td>
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<tr>
<td>Silicon</td>
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<td>Manganese</td>
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<td>Sulphur</td>
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<td>Phosphorus</td>
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Fig. 1. Effect of LTHT on stress relaxation behaviour of patented cold drawn carbon steel.

Fig. 2. The relationship between tensile properties and temperature for a constant stretch ratio of 40%.

Fig. 3. The relationship between tensile properties and stretch ratio for a constant temperature of 350 °C.
been placed in to a 30 t capacity machine chamber with \( \pm 20 \degree C \) temperature control precision and experiments are done with Metro-Com relaxation test equipment for 100–200 h. As an initial strength 80% of tensile strength of first pieces from each group are taken. Results are plotted in log time vs. relaxation \( \left( 100 \left( P_0 - P_1 \right) / P_0 \right) \) in the diagrams, where \( P_0 \) is the initial load and \( P_1 \) the ultimate load. Stress relaxation test results are shown in Fig. 4. Here the specimens are prepared with constant stretch ratio and various temperatures. In Fig. 5 also the result is shown where the specimen are prepared at a constant temperature \( (T = 350 \degree C) \) and various stretch ratios.

A typical cold drawn wire microstructure is shown in Fig. 6. As it can be seen from the light microscope micrograph the whole microstructure consists of fine pearlite. The structure shows a heavy deformation where the pearlite grains are elongated in the deformation direction. Some of the cementite lamella lying unfavourable to the deformation direction are broken. The tensile behaviour of this sorbitic microstructure can be seen from Figs. 2 and 3, where the specimens had their highest \( R_p 0.1, R_p 0.2 \) and \( R_m \) values in the temperature range of 350–400 \( \degree C \). A possible explanation of this behaviour is that in the cold drawn wire the diffusion is faster at elevated temperatures. Generally, small carbon and nitrogen atoms move fast at low temperatures and they are locked in the dislocations. This is the reason of increased strength. Studies done at higher temperatures compared to this work show that there is a decrease of strength in the higher temperatures due to the decrease of cold work effect [13]. In Fig. 3, it is shown that the results from the thermomechanical heat treatments in constant temperature and various stretch ratios are shown that \( R_p 0.1, R_p 0.2 \), and \( R_m \) values are maximum at 40–50% stretch ratio.

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Fig. 4. The relationship between the relaxation and time for a constant stretch ratio of 40% and varying temperatures.

Fig. 5. The relationship between the relaxation and time for a constant temperature of 350 \( \degree C \) and varying stretch ratios.
Relaxation behaviour of the specimens is shown in Fig. 4 for constant stretch ratio and different temperatures. The increased relaxation resistance was observed in specimens, which were heat treated at 400 °C range. And also, for the specimens treated at the constant temperature of 350 °C and different stretch ratios, it is seen in Fig. 7, that the specimens with 40–50% applied stretch have the high stress relaxation resistance values. It can be seen that heating and stretching treatments eliminate the residual stresses and that explains the increase in the relaxation resistance of cold worked wires [14].

In cases of continuous production, more samples are to be tested. For this reason, some equations are put forward to determine the relaxation rate. Eqs. (1) and (2) which are recommended by Stussi, and (3) recommended by Maura, Sözen and Sies are used and compared with the experimental results [15–17]:

\[
\sigma = \frac{\sigma_0}{1 + 10^n} \quad (1)
\]

\[
n = -1.3 + \frac{\log t}{3} \left( \frac{\sigma_0}{\sigma_A} - 0.99 \right) \quad (2)
\]

\[
\frac{\sigma}{\sigma_0} = 1 - \frac{\log t}{10} \left( \frac{\sigma_0}{\sigma_A} - 0.55 \right) \quad (3)
\]

where \( n \) is a function, depending on time and the initial stress; \( \sigma_A \) the yield stress at 0.1% total elongation; \( \sigma_0 \) the initial stress; and \( t \) the time (h).

The results derived from the equations of Stussi are similar to the experimental results. However, those found by using Maura, Sözen, and Sies’s equations differed from our results with 4%. As the recommended equation (3)

![Fig. 6. The cold drawn wire microstructure, fine pearlite, light microscopical image. The structure is etched with nital.](image)
covers all types of steel, and is unchanged for normal and lower relaxation in the steel, a new constant is determined by the equation formed from the program which is given in Appendix A [15].

Equations for normal (4) and lower relaxation (5) samples are given below:

\[
\frac{\sigma}{\sigma_0} = 1 - \frac{\log t}{10} \left( \frac{\sigma_0}{\sigma_A} - 0.67 \right) \quad (4)
\]

\[
\frac{\sigma}{\sigma_0} = 1 - \frac{\log t}{10} \left( \frac{\sigma_0}{\sigma_A} - 0.73 \right) \quad (5)
\]

Values derived from these equations are compared with the experimental results. In Figs. 7 and 8, comparison of the experimental results with the values derived from the equations of Stussi et al., and our modified equations are shown. The experimental results are similar to those derived from the equations of Stussi, as it is seen from the figures.

3. Conclusions

This study is an attempt to show the effects of thermomechanical heat treatment on cold drawn carbon steels. The conclusions of this study are shown below:

- During the thermomechanical heat treatments which have been carried out at various temperatures and at constant stretching, it is observed from Fig. 2 that the specimens had their highest \(R_{p0.1}, R_{p0.2}, R_m\) values in the temperature range of 350–400 °C.
- Results from the thermomechanical heat treatments at constant temperature and various stretch ratios show that \(R_{p0.1}, R_{p0.2}, R_m\) values were maximum at 50% stretch ratio.
- For constant stretch ratio and various temperature ranges, the lowest stress relaxation value are observed in specimens, which were heat treated at 400 °C.
- For specimens treated at a constant temperature and different stretch ratios, it was seen that the specimens
with 40–50%-applied stretch have the lowest stress relaxation values.

- It is evident that the relaxation rate can be determined by the extrapolation of the figures using Eqs. (1)–(5), without the requirement of 1000 h test or the whole period of servicing. These equations shall prevent time consumption by providing a preliminary idea during production and planning.

Appendix A
References