Impact of atmospheric corrosion on the mechanical properties of B235 steel rods

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Abstract. It is well known that atmospheric corrosion greatly affects the stress-strain properties of reinforcing steel. To be able to assess and forecast the remaining service life of constructions which have been subjected to atmospheric corrosion, it is necessary to have good knowledge of this effect. Research is often complicated to do due to the lack of accurate information on the initial dimensions of the steel parts and the properties of the material of which those parts are made. In this paper an attempt is made to overcome this obstacle. Reinforcing steel rods are tested. Those rods have been subjected to natural atmospheric conditions in a temperate climate zone for 25 years, in vertical orientation. To determine the initial stress-percentage extension curve of those rods test pieces have been made by machining on a lathe – to remove the corrosion layer and to set a standard diameter. The chemical composition and the density of the material are determined by appropriate experiments. The yield strength, the ultimate strength, the percentage elongation after fracture are determined by standard tensile testing. To determine the final stress-percentage extension curve, tensile tests are carried out with the corroded rods without any treatment. A comparison of both curves and analysis of the atmospheric corrosion effect on the stress-strain behavior is made.

1. Introduction

It is often necessary to assess the remaining service life of corroded constructions after their prolonged service in an aggressive environment. This assessment is often difficult to make due to the lack of information about the initial properties of the materials and about the exact shape and dimensions of the parts.

The inconvenience caused by the lack of information about the initial properties of the materials can be easily overcome by removing the corrosion layer from the corroded parts followed by machining of standard test pieces which are subjected to a tensile test in standard conditions.

When the mechanical properties of real corroded constructions must be assessed the only possible approach is to cut off the test pieces from the investigated construction. Usually the reinforcing rods are extracted from concrete constructions which have stayed for long period of time (20-40 years) in an atmospheric or an artificial aggressive environment [1, 2] or parts are cut off from steel constructions which have worked in similar conditions [3].

When the goal is to determine the amount of corrosion and the rate of corrosion in order to predict how long the construction may be used in an aggressive environment, it is necessary to know the initial shape and dimensions of the parts. The inability to measure them with great accuracy is compensated by some approximation using data from the accompanying technical documentation. If such information is not available the problem of determining the rate and the amount of corrosion is impossible to solve.
The object of this research are corroded smooth rods of reinforcing steel with nominal diameter of 6.5 mm. The rods have stayed outdoors for 25 years (atmospheric corrosion) oriented vertically in a temperate climate zone. The chemical composition (table 1) is studied in a specialized laboratory. The steel is determined as grade B235 in accordance with the acting Bulgarian standard BDS 4758:2008 [4]. This steel with some approximation can be accepted as an analog for the widely used structural steel S235JR [5]. The European standard dedicated to reinforcing steels is EN 10080:2005 [6]. The standard does not discuss specific grades of steel or compositions, but the upper limits for the quantities of some chemical elements are given. The composition of the major alloying elements is taken into account by calculating the equivalent amount of carbon using the following formula, in which the values from table 1 are entered:

$$C_{eq} = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} = 0.2 + \frac{1.18}{6} + \frac{0.20}{5} + \frac{0.28 + 0.62}{15} = 0.48.$$ (1)

The value of $C_{eq}$ is lower than the standard upper limit of 0.50 [6] which means that the amount of alloying elements in the tested steel complies with the requirements of the standard.

**Table 1.** Chemical composition of the tested rods.

| Element | Amount, % | No grade, EN 10080:2005, | B235, BDS 4758:2008, | S235JR, EN 10025-2:2004, |
|---------|-----------|--------------------------|----------------------|--------------------------|
| C       | 0.2000    | ≤ 0.24                   | ≤ 0.20               | ≤ 0.19                   |
| $C_{eq}$| 0.48      |                          |                      |                          |
| Mn      | 1.1800    |                          | ≤ 0.50               | ≤ 1.50                   |
| Cu      | 0.6200    | ≤ 0.85                   |                      | ≤ 0.60                   |
| Ni      | 0.2800    |                          |                      |                          |
| Si      | 0.2300    |                          |                      |                          |
| Cr      | 0.1200    |                          |                      |                          |
| As      | 0.0585    |                          |                      |                          |
| S       | 0.0450    | ≤ 0.055                 | ≤ 0.040             | ≤ 0.045                 |
| P       | 0.0240    | ≤ 0.055                 | ≤ 0.040             | ≤ 0.045                 |
| N       | 0.0075    | ≤ 0.014                 | ≤ 0.014             | ≤ 0.014                 |

The goal of this paper is to make an assessment of the impact of atmospheric corrosion on the mechanical properties of reinforcing steel B235, analog of structural steel S235. To investigate this effect two sets of tensile tests have been done. The first set is with cleaned test pieces cut off from the corroded rods and without additional treatment. The second set is with standard test pieces machined on lathe to a diameter of 4 mm.

### 2. Test pieces for tensile testing

On figure 1 the different stages of preparation of the test pieces are shown. The corroded rod in its original appearance is shown in figure 1 (a). Its surface is covered with a dense layer of corroded products with high mechanical strength, which is hard to remove. Figure 1 (b) shows a rod after several cycles of chemical cleaning according to EN ISO 8407:2014 standard [7]. The uneven nature of corrosion can be observed with multitude of pittings and patches, and a large amount of residual corrosion products. On figure 1 (c) a photograph of a fully cleaned rod is shown. A combination of mechanical cleaning (scrubbing with brush) and chemical cleaning is used. The surface texture is preserved as much as possible. The piece is ready for measurement, weighing and mechanical testing. On figure 1 (d) a standard test piece for tensile testing [8] is shown. The test piece is made from the corroded rod by machining it to a diameter of 4 mm. The purpose of this test piece is to get the stress-percentage extension curve of the uncorroded material.
3. Properties of the test pieces

3.1. Density of the steel
As the initial mass (before the beginning of the corrosion) of the rods is not known it is necessary to know the exact density of the material to be able to calculate the mass of the rods knowing their dimensions.

The density of the steel is determined experimentally. A cylindrical piece with accurate dimensions – 4 mm diameter and 10 mm length – is machined using a lathe. The final dimensions of the same piece are measured with a micrometer and its volume is calculated. It is also weighed with 0,001 g accuracy. Finally the steel density is calculated to be 7745 kg/m$^3$.

3.2. Initial dimensions and mass
The initial dimensions and mass of the studied corroded rods are unknown. It is known that these are reinforcing rods manufactured in accordance with BDS 4758:1984 standard, which is a predecessor to [4]. This means that the initial diameter of the rods is $d_1 = 6.5$ mm. If the diameter and the density are known, it is very easy to calculate the initial parameters of the test piece with a 100 mm length – volume $V_1 = 3318.31$ mm$^3$; surface area $S_1 = 2108.4$ mm$^2$; mass $m_1 = 25.7$ g.

3.3. Final dimensions and mass
The diameter of a set of three pieces of cleaned corroded test pieces with a length of 100 mm as shown in figure 1 (c) is measured with a micrometer in four cross-sections. The average diameter $d_{av}$ and the final mass $m_2$ of the test pieces are determined. The results are given in table 2.

| №    | Measured diameter $d$, mm | $d_{av}$, mm | $m_2$, g |
|------|--------------------------|--------------|----------|
|      | section 1     | section 2     | section 3     | section 4     |               |
| 1    | 6.25          | 6.21          | 6.21          | 6.17          | 6.210         | 22.888       |
| 2    | 6.24          | 6.18          | 6.20          | 6.18          | 6.200         | 22.483       |
| 3    | 6.25          | 6.18          | 6.18          | 6.21          | 6.205         | 22.479       |

| $d_{av}$ | $m_2$     |
|----------|-----------|
| 6.205    | 22.617    |

Table 2. Determination of average diameter $d_{av}$ and average final mass $m_2$ of the corroded test pieces.
3.4. Mass loss
Mass loss for the 25-year period of corrosion in natural atmospheric conditions is calculated in three different forms:

- **absolute mass loss of a 100 mm long rod:**
  \[
  \Delta m = m_1 - m_2 = 25.7 - 22.617 = 3.083 \text{ g};
  \]

- **specific mass loss:**
  \[
  \frac{\Delta m}{S_1} = \frac{3.083}{2108.4 \times 10^{-6}} = 1462.25 \frac{\text{g}}{\text{m}^2};
  \]

- **percentage mass loss:**
  \[
  \frac{\Delta m}{m_1 - 100} = \frac{3.083}{25.7} \times 100 = 12\%.
  \]

3.5. Corrosion rate
The corrosion rate \( k \) is one of the most important parameters of the corrosion behavior, because it allows the remaining service life prediction in case of operation in corrosive environment. In our case:

\[
    k = \frac{\Delta m}{S_1 t} = \frac{3.083}{2108.4 \times 10^{-6} \times 9125} = 0.16 \frac{\text{g}}{\text{m}^2 \text{days}}; 
\]

where \( t = 25 \times 365 = 9125 \) days is the number of days in 25 years.

4. Tensile testing
The tensile tests are made using enhanced universal testing machine ZD10 with a lead screw loading mechanism which makes it possible to use precise digital control of loading [9] in accordance with EN ISO 6892-1:2016 standard [8].

A set of three proportional test pieces of each type, shown in figure 1 (c) and (d), are tested. The machined test piece has the behavior of non-corroded material. To measure extension, extensometers with gauge length equal to the original gauge length of the test pieces are used, as given in table 3. The mechanical properties upper yield strength \( R_{eH} \), ultimate strength \( R_m \) and percentage elongation after fracture \( A \) are taken from experimentally obtained stress-percentage extension curves, like ones shown on figure 2. The stress rate was 6 MPa/s.

| Table 3. Mechanical properties in accordance with [8]. |
|-------------------------------------------------------|
| **Type of test piece** | **Nominal diameter, mm** | **Gauge length, mm** | **№** | **\( R_{eH} \), MPa** | **\( R_m \), MPa** | **\( A \), %** |
|------------------------|--------------------------|---------------------|-------|---------------------|---------------------|-------------|
| Non-corroded (machined from corroded) | 4 | 20 | 1  | 314  | 391 | 27.8 |
| | | | 2 | 312 | 390 | 29.9 |
| | | | 3 | 314 | 395 | 28.5 |
| | | | **Average** | 313 | 392 | 28.7 |
| Corroded (25 years atmospheric corrosion), percentage loss of mass 12% | 6.5 | 32.5 | 1 | 272 | 346 | 20.2 |
| | | | 2 | 266 | 340 | 21.4 |
| | | | 3 | 268 | 345 | 20.8 |
| | | | **Average** | 269 | 344 | 20.8 |
5. Analysis of the obtained results

Corrosion leads to loss of material and loss of area of the carrying cross sections. As a result the strength properties of the corroded piece decrease. In our case we can observe the expected decrease in the yield strength $R_{	ext{eff}}$ by 14.06% and the ultimate strength $R_m$ – by 12.24% in the corroded test pieces. At 12% mass loss, the measured yield strength is above the minimal value set in standards [4, 5], but the ultimate strength is less than the lower limit set in the same standards.

The corrosion worsens the quality of the surfaces in contact with the aggressive environment. A large number of surface defects with complex and irregular shape and varying depth occur. In tensile testing these defects are stress concentrators, from where cracks are easily developed. This worsens not only the strength, but also the deformational properties of the corroded piece. In our case a significant decrease of plasticity of the examined test pieces is observed – at 12% mass loss the elongation after fracture $A$ is reduced by 27.53% to a value which is significantly below the value prescribed in [4, 5].

The results presented in this paper are going to be compared with results from an accelerated corrosion test.

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