Acta Polytechnica CTU Proceedings **53**:24–27, 2025
https://doi.org/10.14311/APP.2025.53.0024
© 2025 The Author(s). Licensed under a CC-BY 4.0 licence
Published by the Czech Technical University in Prague

EFFECT OF HYDROGEN EMBRITTLEMENT ON MECHANICAL PROPERTIES OF NON-STRESSED PRESTRESSING STEEL

Tomáš Chobotský*, Martin Kubový, Andrea Milerová, Adam Čítek

Czech Technical University in Prague, Klokner Institute, Šolínova 7, 160 00 Praha, Czech Republic

* corresponding author: tomas.chobotsky@cvut.cz

Abstract. The aim of this paper is to elucidate the effect of hydrogen on the structure of commonly used prestressed concrete steel strand (PC strand) of concrete bridges and other structures in the non-stressed state to determine the general behaviour of the characteristic steel material, which would lead to further investigation of specimens in the prestressed state. For the experimental part of the research, a system was set up for saturating the samples with hydrogen, which diffuses into the steel structure in atomic form. These specimens were then subjected to tensile testing according to EN ISO 15630-3 to reveal the reduced mechanical properties of the prestressed concrete steel strand specimen caused by the diffusion of hydrogen into the material structure. After the tensile tests, the fracture surfaces were analysed on a scanning electron microscope to verify the effect of hydrogen.

Keywords: Prestressing steel, diffusion, hydrogen embrittlement, corrosion, ductility.

1. Introduction

The phenomenon of hydrogen embrittlement has been known since the last century and until recently was an often overlooked problem in high strength materials such as prestressed concrete steel strand in concrete structures. Also very important is the knowledge that material failure generally occurs with a delay.

Speaking about prestressed concrete steel strand, should be mentioned that it is a structural element reaching ultimate tensile strength values of around 1 900 MPa (yield strength of around 1 640 MPa), i.e. a very strong steel material, which according to the aforementioned theories, should be very susceptible to hydrogen embrittlement. It is a tensile steel rope twisted from seven wires, which is supposed to bind all the segments and create a prestress in the concrete structure. Using this type of bridge structure reinforcement, it is possible to create noticeably larger spans in the reinforced concrete structure that cannot be realized with conventional bundled profiled reinforcement.

It should be noted that the motivation behind the hydrogen embrittlement theory on prestressed concrete steel strand is the uncertain explanation of the causes of collapse of several bridge structures in Europe and Asia. The collapse of a structure is usually a combination of several adverse factors, like a electrochemical corrosion, and it is possible that hydrogen embrittlement may be one of them. It is necessary to discuss the synergistic effect of this corrosion damage mechanism together with the action of supercritical amounts of chloride anions from the spreading salts (localized pitting corrosion damage).

2. Experimental part

In the experimental part, the susceptibility of commonly used prestressed concrete steel strand to hydrogen embrittlement was investigated. The PC strand samples were exposed in aqueous sodium sulfate solution in the framework of cathodic surface polarization under hydrogen evolution. In the experimental part, the susceptibility of commonly used prestressed concrete steel strand to hydrogen embrittlement was investigated. The PC strand samples were exposed in aqueous sodium sulfate solution in the framework of cathodic surface polarization under hydrogen evolution. By this electrolytic decomposition of water for predetermined intervals and after a subsequent minor technological delay, the samples were subjected to tensile testing. The PC strands were connected as cathode in the system (the anode was a stainless steel mesh of the corresponding surface area), thus hydrogen was generated on the samples, during the time of current passage, which could freely diffuse into the steel structure. The following sections describe the course of the experiment [1, 2].

Chemical composition of prestressing steel					
C	Mn	Si	P	S	N
0.83	0.73	0.26	max. 0.008	max. 0.008	max. 0.004

Table 1. Chemical composition of samples.

3. Exposure of samples

A system of experimental design was proposed to provide the necessary values of current densities for water decomposition. The diagram shows a block diagram of a direct current power source intended to supply the electrode system used for sample exposure.

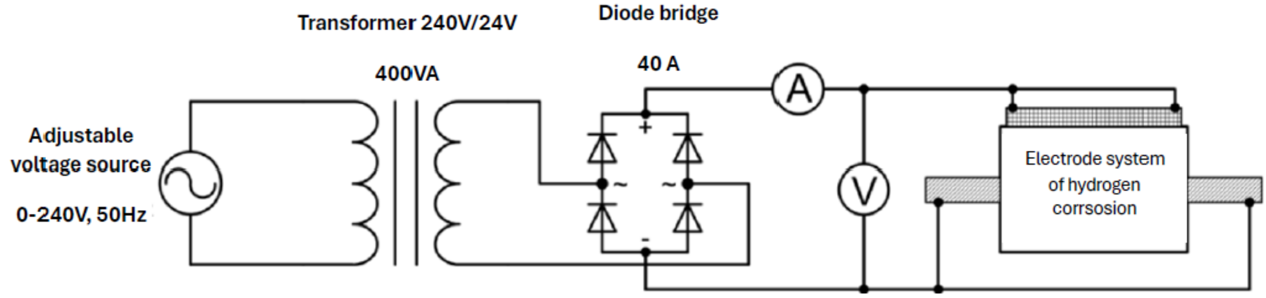

FIGURE 1. Wiring diagram of the electrode system.

The required effective DC value for this electrode system was determined to be 18 A at an effective voltage of 10 V. This corresponds to an impedance value of the electrode system of approximately 0.5 Ω. This value assumes the use of an electrolyte in the form of a saturated aqueous sodium sulphate solution.

The rectifier circuit is powered from a regulated AC voltage source from 0 to 240 V with a mains frequency of 50 Hz. The regulated voltage is fed to the input of a toroidal transformer with a nominal conversion of 240 V/24 V and an output of 400 V A. The output voltage of the transformer is connected to the AC input of a rectifying bridge (Graetz bridge) designed to rectify currents up to 40 A. The development of hydrogen on the exposed surface of the reinforcement is ensured by the acceleration of the corrosion kinetics under the reduction of hydrogen from water, see Equation 1, due to the cathodic corrosion reaction in the cathodic polarization mode of the causative surface. The actual cathodic polarization takes place in the galvanostatic regime [1, 3].

$$2\,H_2O + 2\,e^- \longrightarrow H_2 + 2\,OH^- \tag{1}$$

Due to cathodic polarization, by wiring the exposed sample of the prestressing steel as the (–) pole in the implementation of the electrolyzer circuit, the corrosion of the steel surface is accelerated under reducing conditions for the development of hydrogen gas with a significant partial pressure of the gas over the free surface of the exposed sample. If there was no polarization of the reinforcement steel surface due to the involvement of a DC current source, the surface of the reinforcement steel would corrode gradually in an aqueous environment under a cathodic corrosion reaction, the reduction of atmospheric oxygen, see Equation 2.

$$2\,H_2O + 4\,e^- + O_2 \longrightarrow 4\,OH^- \tag{2}$$

4. The course of the exposition

In the experiment, a box of polymer material of optimal dimensions is used, where holes were drilled in the sides of the centres to accommodate the prestressing reinforcement specimen (exposure of only the central part of the 1.7 m long PC strand). An AISI 316L stainless steel mesh was inserted into the sides of the plastic box up to the walls. This pair of fine meshes served as a sacrificial anode within the electrolyser wiring. The actual surface pattern of the prestressing steel was routed between these meshes.

From previously obtained experimental data related to the cathodic protection of steel pipelines placed in soil, it is clear that the supercritical current density, when hydrogen is formed on the steel surface, is approximately $100\,\mathrm{mA\,cm^{-2}}$ depending on the type of electrolyte. On this basis, a stationary current density of $120\,\mathrm{mA\,cm^{-2}}$ was chosen for this experiment, which guarantees a sufficiently significant acceleration of the kinetics of atomic hydrogen formation on the surface of the reinforcement steel [3–5].

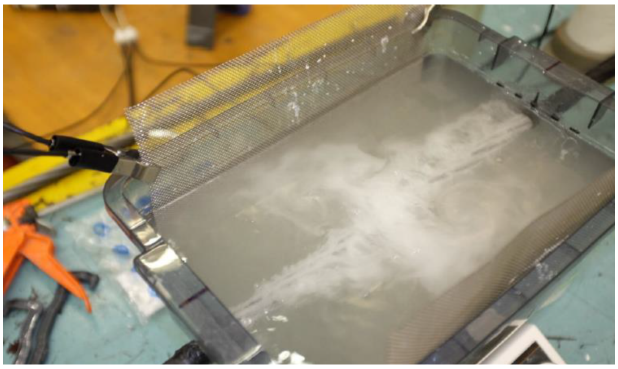

FIGURE 2. Formation of hydrogen on the sample surface.

5. Tensile test

After the PC strands were finished and removed from the bath, the samples had to be immediately subjected to tensile testing based on the standard EN ISO 15630-3 for testing steel for reinforcement and prestressing, i.e. for a duration of at least 30 s. The fact is that hydrogen, which diffuses into the steel structure during water decomposition, tends to escape very quickly, especially at elevated temperatures. At this point, there is a discrepancy among experts as to the rate at which hydrogen escapes from the structure. However, it is safe to say that the faster the tensile test is performed, the more hydrogen remains in the structure. In addition, it is also necessary to discuss the local alkalization (Equation 1) of the prestressing steel surface on the diffusion of hydrogen gas into the material structure.

The samples were divided into two groups according to the length of exposure and the third group was the samples without hydrogen as a reference. Group A was exposed for 20 minutes and group B was exposed for 60 minutes. The longer time is unjustified according to the articles of foreign authors, because after a certain time the same amount of hydrogen diffuses into the structure as escapes from the structure, and therefore there is no increase in the amount of hydrogen in the structure.

The measured data were processed into a Stress-Strain diagram and from them the ultimate strenght R_m, the contractual yield strength $R_{p0.1}$ and $R_{p0.2}$, the ductility A_{gt} and the elastic modulus E were derived. The elastic modulus was calculated by interlacing a straight line by the least squares method through the linear region of the Stress-Strain diagram in the range 300 to 1 350 MPa [6–8].

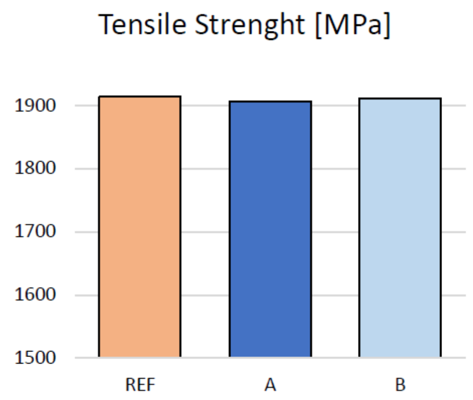

Figure 3. Comparison of mean tensile strenght of each group of specimens.

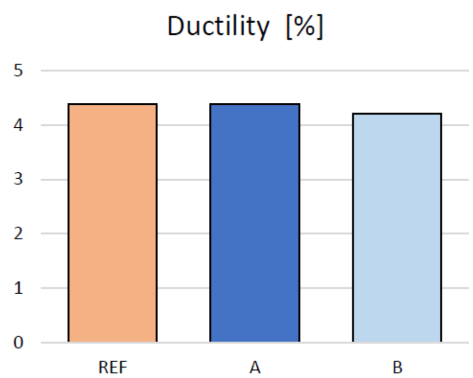

Figure 4. Comparison of mean ductility of each group of specimens.

The above Figures 3 and 4 show that there is no decrease in ultimate strength and no change in ductility compared to the reference samples, which would confirm the presence and influence of hydrogen on the structure and mechanical properties of the tested samples. Table 2 also shows the other observed values that do not show any influence of hydrogen on the structure [8, 9].

Group	R_m [MPa]	$R_{p0.1}$ [MPa]	$R_{p0.2}$ [MPa]	A [%]	E [GPa]
REF	1 913.73	1 723.22	1 757.69	4.38	203.81
A	1 906.13	1 708.29	1 752.91	4.38	209.35
B	1 911.14	1 705.01	1 752.68	4.21	205.91

Table 2. Mean mechanical properties of each group of specimens.

6. Analysis of fracture surfaces

After the tensile test, individual wires that were broken during the test were removed from the specimens. Typically, there was one, at most two, broken wires out of seven on each specimen. In no specimen were all seven wires in the PC strand broken. These wires were then subjected to fracture surface analysis on an electron microscope.

The fractographic analysis of the fracture surfaces on the reference samples and groups A and B did not reveal even minimal indications of characteristic brittle fracture facets initiated by the presence of hydrogen in the structure. In the majority of cases, the fractures were of the ductile fracture pattern characteristic of high-strength steels. Shear failure was observed on three samples across the groups, but with the same mechanical properties as other specimens.

Group	Fractography Sample	Fractography Fracture Surface
REF	1	Ductile with hole
	2	Ductile
	3	Shear
	4	Ductile
	5	Ductile
A	1	Ductile
	2	Ductile with hole
	3	Ductile
	4	Shear
	5	Ductile
B	1	Ductile
	2	Ductile
	3	Ductile
	4	Ductile
	5	Shear

Table 3. Type of fracture surface.

No areas with indications of brittle fractures were found during the inspection of the areas under the microscope. After evaluation of all images, it can be assumed that in these cases hydrogen had no effect on the fracture behaviour [1, 2, 6, 7].

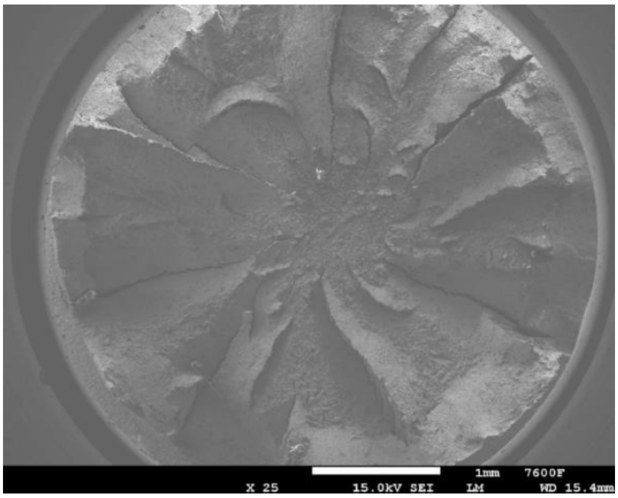

Figure 5. Fracture surface of sample B3.

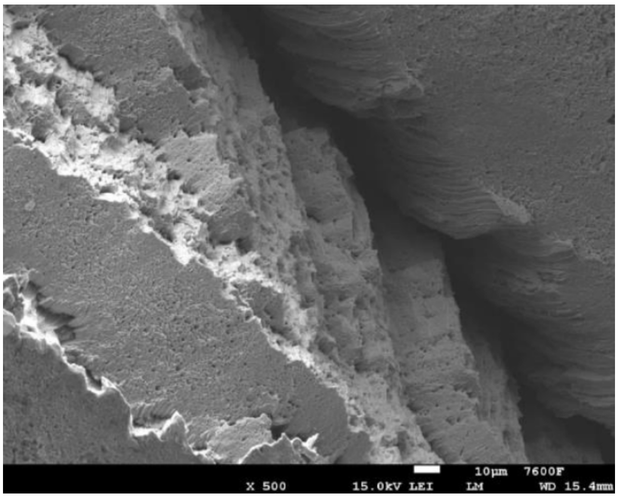

Figure 6. Detail of surface crack.

7. Conclusion

Even though this is a high-strength material probably susceptible to hydrogen embrittlement, it cannot be said from the above data that hydrogen would cause significant hydrogen embrittlement of the material. The fundamental finding remains that most of the specimens cracked after tensile testing outside the exposed zone, i.e. outside the middle zone, where preferential failure should occur. This phenomenon leads to the conclusion that there are random defects in the material structure from the manufacturing process, e.g. from melting or subsequent forming, which have a much greater influence on the strength of the structure than hydrogen diffusion and subsequent embrittlement. This assertion cannot be confirmed in any definite way by the above experiment and its results, but it seems to be a plausible explanation for this phenomenon.

In the light of previous scientific work, the possible influence of the corrosion products formed (the natural protective passive layer of steel in an alkaline environment) on the majorite-based Fe_3O_4 magnetite, which even in an amorphous very thin layer are able to block very effectively the entry of hydrogen into the steel, can be discussed. The reason for this is the very low diffusion coefficient for atomic hydrogen through the Fe_3O_4 crystal lattice. This fact may have occurred in the case of this experiment as well. Research on the effect of hydrogen embrittlement on prestressing steel will continue in the future, as not all possibilities of specimen exposure have yet been tested to explain the phenomena of excentric cracking.

Acknowledgements

This research was supported by the Czech Science Foundation under grant no. 24-12783S.

References

[1] S. P. Lynch. Hydrogen embrittlement (HE) phenomena and mechanisms. In *Stress Corrosion Cracking*, p. 90–130. Elsevier, 2011. https://doi.org/10.1533/9780857093769.1.90

[2] K. Shiozawa, Y. Morii, S. Nishino, L. Lu. Subsurface crack initiation and propagation mechanism in high-strength steel in a very high cycle fatigue regime. *International Journal of Fatigue* **28**(11):1521–1532, 2006. https://doi.org/10.1016/j.ijfatigue.2005.08.015

[3] L. M. Quej-Aké, R. Galván-Martínez, A. Contreras-Cuevas. Electrochemical and tension tests behavior of API 5L X60 pipeline steel in a simulated soil solution. *Materials Science Forum* **755**:153–161, 2013. https://doi.org/10.4028/www.scientific.net/msf.755.153

[4] B. Yanachkov, Y. Mourdjeva, K. Valuiska, et al. Effect of hydrogen content on the microstructure, mechanical properties, and fracture mechanism of low-carbon lath martensite steel. *Metals* **14**(12):1340, 2024. https://doi.org/10.3390/met14121340

[5] P. Pokorný, T. Chobotský, N. Prodanovic, et al. Bond strength and corrosion protection properties of hot-dip galvanized prestressing reinforcement in normal-strength concrete. *Journal of Composites Science* **8**(10):407, 2024. https://doi.org/10.3390/jcs8100407

[6] H. Birnbaum, P. Sofronis. Hydrogen-enhanced localized plasticity – a mechanism for hydrogen-related fracture. *Materials Science and Engineering: A* **176**(1–2):191–202, 1994. https://doi.org/10.1016/0921-5093(94)90975-x

[7] A. S. Kholtobina, R. Pippan, L. Romaner, et al. Hydrogen trapping in bcc iron. *Materials* **13**(10):2288, 2020. https://doi.org/10.3390/ma13102288

[8] A. Miyamoto, K. Tei, H. Nakamura, J. W. Bull. Behavior of prestressed beam strengthened with external tendons. *Journal of Structural Engineering* **126**(9):1033–1044, 2000. https://doi.org/10.1061/(asce)0733-9445(2000)126:9(1033)

[9] J. A. Morales, J. Torres, N. Rebolledo, J. Sánchez. Experimental and statistical analysis of the corrosion in tendons in contact with water. *Frontiers in Materials* **6**, 2019. https://doi.org/10.3389/fmats.2019.00167