

Dependence of Time to Fracture due to Hydrogen Embrittlement on Stress, Hydrogen Content, and Temperature in Rebar for Prestressed Concrete

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ABSTRACT

We conducted a constant load test to evaluate how stress, hydrogen content, and temperature affect time to fracture due to hydrogen embrittlement in rebar for prestressed concrete. We experimented on tempered martensitic steel rebar taken from prestressed concrete structures prepared for the test. Hydrogen charging was performed by cathodic charging at a current density of 10 A/m² in a 1 M NaHCO₃ solution with ammonium thiocyanate (NH₄SCN) added. The sub-surface hydrogen content was controlled by changing the NH₄SCN concentration in the solution. The experimental results showed that the time to fracture decreased with increasing applied tensile stress in a power law relationship. The time to fracture and sub-surface hydrogen content also demonstrated a power law relationship, while stress and hydrogen content had no effect on the respective power indexes. Temperature affected the coefficient of power law and the power index of hydrogen content, but the power index of tensile stress was mostly independent of temperature.

Key words: Hydrogen embrittlement, Infrastructure

INTRODUCTION

Rebars used in prestressed concrete structures are constantly subjected to tensile stress, and some rebars have been reported to fracture due to hydrogen embrittlement.¹ It is important to know the hydrogen embrittlement behavior in rebars to prevent fractures. The effects of environmental conditions such as tensile stress, hydrogen content, and temperature on time to fracture have been evaluated individually,^{2,3} however, their combined effects have not been clarified. The purpose of this study is to

experimentally clarify the relationship between time to fracture due to hydrogen embrittlement and environmental conditions to which the rebars are subjected.

EXPERIMENTAL PROCEDURE

Specimen

The specimens were tempered martensitic steel rebar taken from prestressed concrete structures prepared for the test. The rebar was in accordance with Japanese Industrial Standard (JIS) G 3137 SBPDN 1275/1420, with a nominal cross-sectional area of 40 mm². The specified tensile strength was at least 1420 MPa, and the specified chemical composition was at most 0.030% for P, at most 0.035% for S, and at most 0.30% for Cu. The rebar had been welded to other rebar when it was used in prestressed concrete structures, so there were welding marks on the surface of the specimens at roughly 90-mm intervals (Figure 1). The length of each specimen was 500 mm, and they were masked with epoxy so that the area for hydrogen charging was 180 mm long and contained two welding marks.

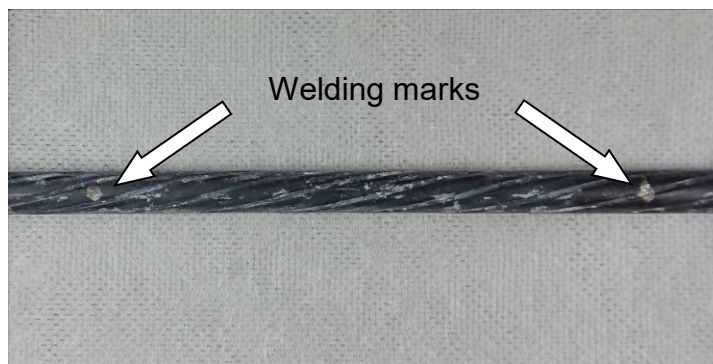


Figure 1: Appearance of specimen.

Measurement of time to fracture due to hydrogen embrittlement

The time to fracture due to hydrogen embrittlement was measured using the constant load test (CLT), in which the specimen was charged with hydrogen under a constant tensile stress. The tensile stress range was 710 MPa to 994 MPa. Hydrogen charging was performed by cathodic charging at a current density of 10 A/m² in a 1 M NaHCO₃ solution with ammonium thiocyanate (NH₄SCN) added. The sub-surface hydrogen content was controlled by changing the NH₄SCN concentration in the solution in the range of 2.6 mol/L to 5.8 mol/L. The test temperature was kept constant by circulating water in the outer layer of the test cell. The temperature range was 278 K to 313 K. Tests were conducted on 10 specimens for each test condition.

Measurement of sub-surface hydrogen content

When hydrogen penetration into the specimen is dominated by diffusion, the sub-surface hydrogen content and the equilibrium hydrogen content of the specimen are the same. Thus, the relationship between the NH₄SCN concentration in the solution and the sub-surface hydrogen content was determined by measuring the equilibrium hydrogen content of the specimen by thermal desorption analysis (TDA) using a gas chromatograph. The specimens were cut into 3-cm lengths and charged with hydrogen for 72 hours at various NH₄SCN concentrations, and then the hydrogen content was measured by TDA at a heating rate of 100°C/h in the temperature range of -100°C to 400°C.

RESULTS AND DISCUSSION

Sub-surface hydrogen content

The relationship between the NH_4SCN concentration in the solution and the sub-surface hydrogen content measured by TDA is shown in Figure 2. The hydrogen content increased as the NH_4SCN concentration increased, and the following empirical equation was obtained by fitting with the least-squares method:

$$C_H = \ln(C_{AT} + 6.46 \times 10^{-4}) + 7.80, \quad (1)$$

where C_H [mass ppm] is the sub-surface hydrogen content and C_{AT} [mol/L] is the NH_4SCN concentration in the solution. Hereafter, the test conditions for CLT will be described by the sub-surface hydrogen content converted from the NH_4SCN concentration.

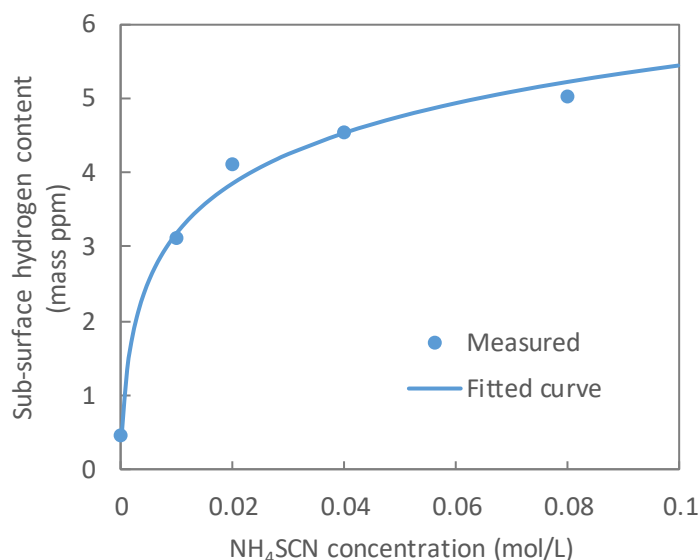


Figure 2: Relationship between NH_4SCN concentration in solution and sub-surface hydrogen content.

Effect of tensile stress and hydrogen content on time to fracture

The results of time to fracture due to hydrogen embrittlement measured by changing the tensile stress and the sub-surface hydrogen content at a temperature of 298 K are shown in Figures 3 and 4, respectively. The time to fracture varied significantly in each set of conditions, but the average time to fracture showed a linear relationship with both tensile stress and sub-surface hydrogen content on both logarithmic graphs. This indicates that tensile stress and the sub-surface hydrogen content have a power law relationship with average time to fracture. Therefore, the relationship between average time to fracture, tensile stress, and sub-surface hydrogen content can be expressed by the following equation:

$$t = S^\alpha \times C_H^\beta \times \gamma, \quad (2)$$

where t is average time to fracture [h], S is tensile stress [MPa], α and β are the slopes of the dotted lines in Figures 3 and 4, respectively, and γ is a coefficient of the power law. From Figures 3 and 4, we can obtain $\alpha = -3.80$, $\beta = -3.15$, and $\gamma = 3.95 \times 10^{13}$ at 298 K.