Fungal Influenced Corrosion in Post-Tension Structures

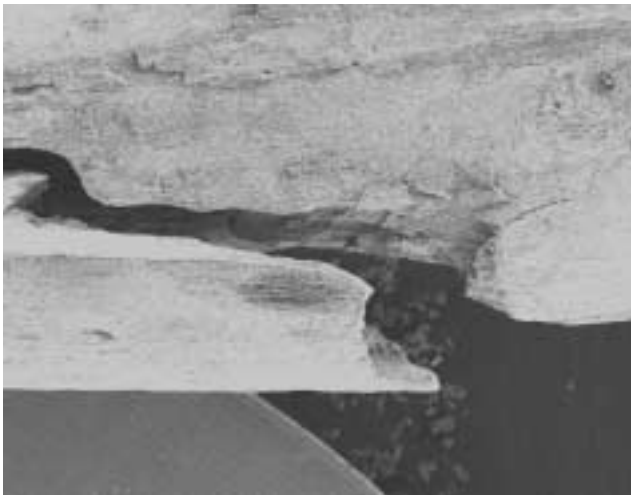
by Brenda Little and Roger Staehle

This paper describes the effect of fungi on the integrity of post-tensioned tendons with respect to the occurrence of stress corrosion cracking (SCC). The occurrence of SCC is interpreted in terms of organic acids produced by fungal metabolic activity.

Post-tension construction is used in buildings, parking garages, bridges, high-pressure water lines and nuclear power plants.[1] Typically, wire, strand, or bar tendons are inserted into pre-placed ducts in a structure and are post tensioned from one or both ends after the concrete has achieved sufficient strength. Hydrocarbon-based lubricants are used to facilitate the insertion. Anchor plates are attached at both ends. Uniform surface corrosion or more localized pitting has been reported in post-tensioned buildings and parking structures, but SCC is the predominant mode of cable failure.[2] In most instances, localized corrosion of post-tensioned cables is attributed to the presence of rainwater in the grease caps[1] or chloride contamination.[3] Embrittlement has been reported in post-tensioning strands in completely enclosed, climate controlled high-rise buildings.[1]

This study was undertaken after the failure of a single post-tensioned cable in a multi-story building. Figures 1a and b indicate typical fractured surfaces found on wires of tendons taken from the building. Filamentous fungi, including *Fusarium* sp., *Penicillium* sp., and *Hormoconis* sp., were isolated from the lubricating grease and the grease was consistently acidic as measured with pH indicating paper. Experiments were designed to determine the role of *in situ* fungi in the observed SCC.

(a)



(b)

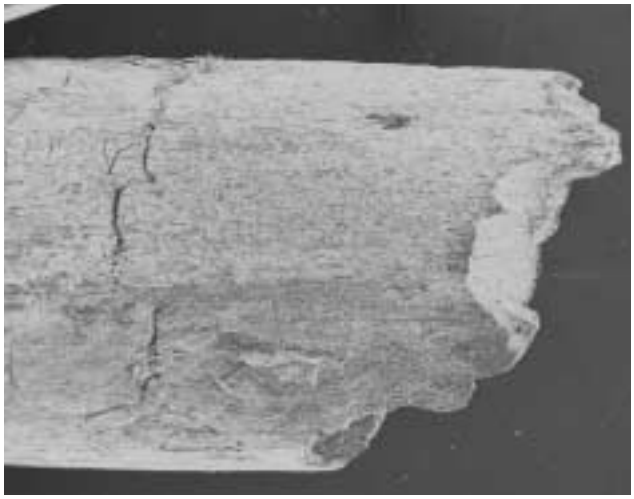


FIG. 1 (a) and (b) Fractured wires from tendon.

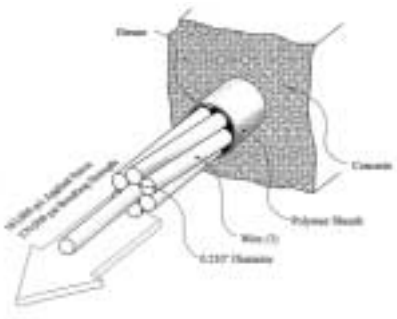


FIG. 2. (a, left photo) Tendon detail; (b, right photo) Sheathed tendons after inoculation.

Methods and Materials

Inoculation—Tendons in this study were removed from the building during a routine stairwell cut. Each tendon consisted of a seven-wire cable in a polyvinyl chloride sheath (Fig. 2a). Each of the seven wires had a diameter of 0.53 cm. Six wires were wrapped around a central core wire. The steel was cold drawn to an approximately 260,000 psi ultimate tensile strength. The resulting cable was coated with a hydrocarbon–based lubricant before insertion into the sheath. Six 16.5 cm long sections of sheathed tendon were used for the testing. Ends of the six sections were sealed with a piece of rubber

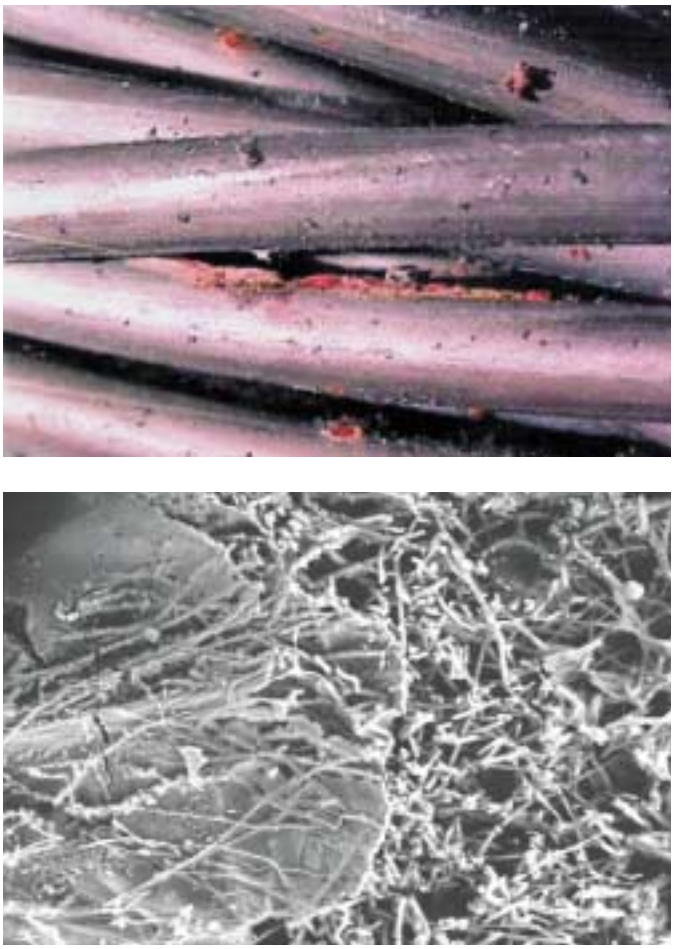


FIG. 3. (a, top photo) Fungi and corrosion products on inoculated tendon; (b, bottom photo) Fungi and corrosion products on inoculated tendon.

secured with a clamp (Fig. 2b). Sections were refrigerated at 4° C from time of collection until inoculation. *Fusarium* sp., *Penicillium* sp., and *Hormoconis* sp. were maintained on potato dextrose agar (PDA).

Tendons were removed from the refrigerator and allowed to come to room temperature before inoculation. One of the rubber end caps on each section was displaced slightly to insert an airgun tip. Three sections were used as controls; *i.e.*, not inoculated, but treated with 0.06 ml atomized sterile distilled water. Spores collected from *Fusarium* sp., *Penicillium* sp., and *Hormoconis* sp. were used to inoculate three sections of sheathed tendons in accordance with ASTM standard G21-90[4] with approximately 10^4-10^5 spores in an aerosol of 0.06 ml water. After inoculation, rubber seals were replaced and the tendons allowed to stand undisturbed at 23° C for approximately five months. No attempt was made to introduce or control the oxygen concentration in the sheathed tendons and no additional grease was added.

At the end of a 5-month incubation, sheathed tendons were opened with a sterile scalpel. Wire sections and sheath interiors were photographed with a digital camera immediately after opening. Contact Petri plates containing PDA were used to sample grease immediately after opening.

Chemical characterization—A Nicolet model 730 Fourier transform infrared spectrometer (FTIR) was used in conjunction with a Spectra-Tech IR Plan Research infrared microscope to collect and analyze infrared spectra of reference grease, reference fungi, in addition to grease and corrosion products from corroded tendons. Samples were placed on mirrored microscope slides and spectra were obtained in the reflectance-absorption mode. Interferograms were obtained after mathematical manipulation of the Fourier transform with two levels of zero filling. Spectral range was 4000-650 wavenumbers (reciprocal wavelength) in all cases. Spectral manipulation included baseline correction, removal of carbon dioxide absorption bands and subtraction of water vapor interferences.

Microscopic examination—Tendons were examined using an Electroscan Model II environmental scanning electron microscope (ESEM) equipped with a NORAN energy-dispersive x-ray analysis system (EDS). The microscope was operated at 20 keV using the environmental secondary detector and sample images were produced using a Polaroid camera with type 55-positive/negative black/white film set for a 60 sec exposure.

Polarization measurements—The polarization behavior of the steel used for the tendons was investigated in concentrated and 1% concentrated acetic, butyric, citric, glutaric, formic and lactic acids. All are commonly associated with fungal degradation of hydrocarbons. Results were compared with polarization in sulfuric acid at pH 1.5 and pH 3. The polarization was conducted at a scanning rate of 2 mV sec^{-1}. The electrode was the cross-section of a single wire of the tendon (0.53 cm diameter; 0.22 cm^2 surface area). The surface of the electrode was polished to 600 grit after each experiment.

Results

FTIR results are displayed as absorbance (y-axis). Peaks assignments are consistent with Smith[5] and Naumann *et al.*[6] The fingerprint region of the infrared spectrum for a hydrocarbon-based was characterized by bands 1460, 1377, and 722 wavenumbers indicating deformation vibration modes for long chain hydrocarbons. Absorption bands at 1580 and 1560 wavenumbers were related to stretching modes of the carboxylate anion in association with a metal ion such as calcium or lithium. The most notable features of spectra for fungi reference spectra were amide I and II stretching frequencies at 1650 and 1590 wavenumbers. Under the experimental conditions, those absorption bands indicate the presence of proteins and are indicative of fungi.[7]

Localized corrosion was observed for all inoculated tendons. In all cases, shallow craters were located under corrosion products. Cracking in association with the craters was observed on two wires from a single tendon. Photographic and ESEM observations of inoculated tendons documented extensive fungal growth in association with localized corrosion (Fig. 3a & b). Petri dishes inoculated with grease from the corroded areas were positive for *Fusarium* and *Hormoconis*. There were no indications of chloride in EDS spectra of the grease. Four FTIR spectra collected from a single inoculated tendon demonstrated varying degrees of degradation Spectra are arranged in

order of increasing degradation (Fig. 4 a-d). The broad peak at 3300-3200 wavenumbers is indicative of bonded hydroxyl groups, such as those found in hydroxy acids. Peaks immediately below 3000 wavenumbers (2924–2850) are typical of hydrocarbons and are due to methyl and methylene groups. The peak for bonded-OH in carboxylic acids is in the same region. Peaks at 1000 wavenumbers are due to the presence of –C-O-C- bonding, a further indication of oxidation. As the grease is oxidized, the carboxylate contribution (1560 wavenumbers) decreases and the carbonyl contribution (1750 wavenumbers) increases. In Fig. 4a there is a strong carboxylate. In Fig. 4b the carbonyl contribution has increased and the carboxylate decreased. Peaks at 3200 and 1000 wavenumbers have increased. The effect is more pronounced in Fig. 4c. In all cases amide peaks are prominent. In Fig. 4d the spectrum indicates the presence of light oil. The carboxylate is missing and the carbonyl is prominent.

There were no indications of corrosion on two of the three control samples. A single site of localized corrosion was observed on one wire of an uninoculated control. Fungal hyphae were located in the corrosion products overlying shallow craters. There were no indications of chloride in EDS spectra of the grease. FTIR spectra for the degraded grease associated with the corrosion products were similar to those in Fig. 4.

Polarization—Polarization curves demonstrated lack of passivity at all concentrations of all acids (Fig. 5 a-b). With time these curves can be expected to decay; however, time-dependent behaviors were not investigated. In the presence of sulfuric acid, corrosion currents calculated from the cathodic Tafel slope were 3.86 and 0.27 mA cm^{-2} for pH 1.5 and 3.0, respectively. Table I summarizes the corrosion currents calculated in a similar way for the organic acids.

Currents varied among the organic acids. Both formic and lactic acids at 1% concentration produced corrosion at approximately the same rate as sulfuric acid at pH 3.0.

Discussion

Experiments described in this paper were initiated to determine whether or not there was a relationship between the observed SCC in post-tensioned steel tendons and the presence of fungi.

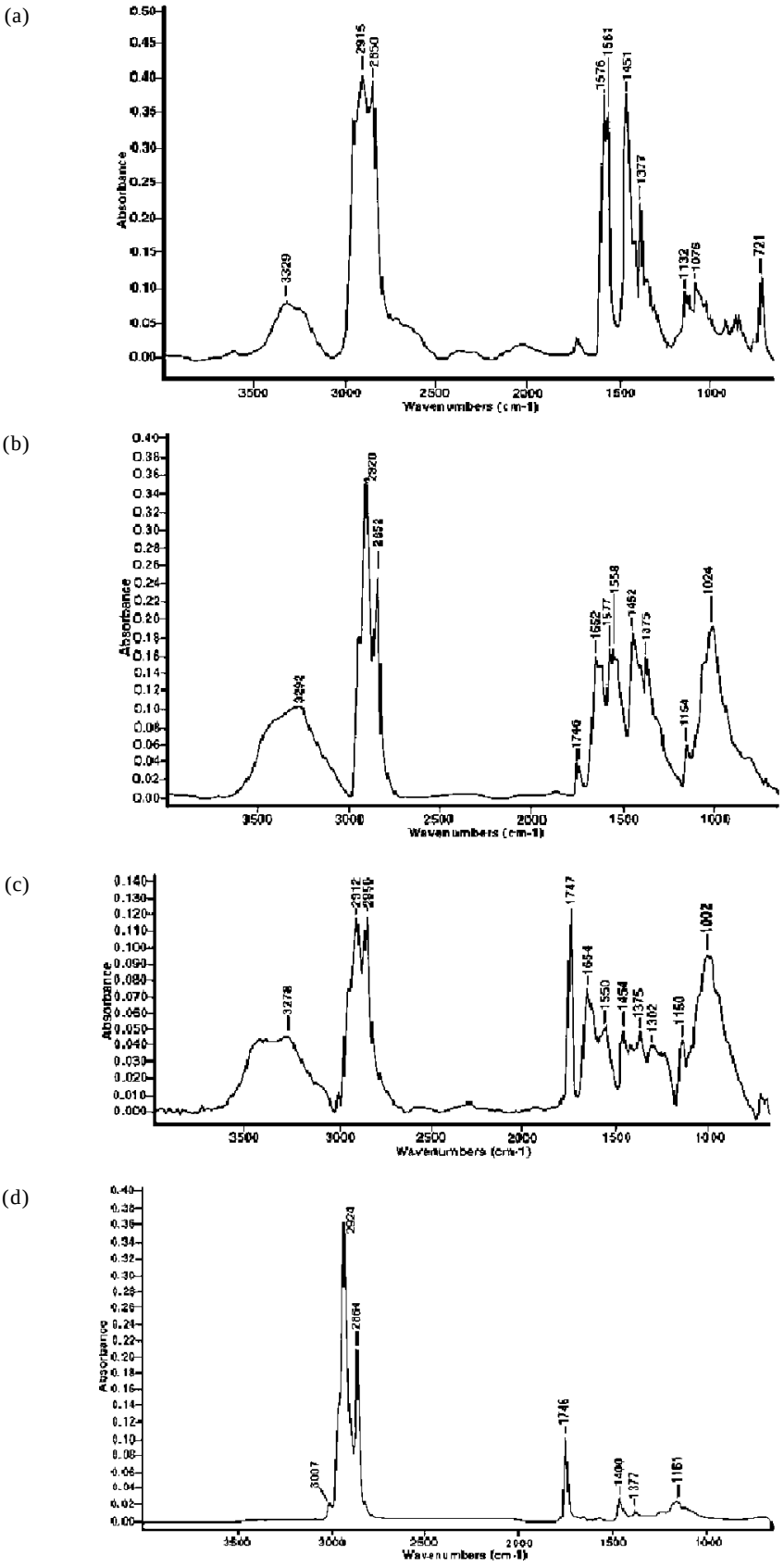


FIG. 4. (a) Grease and corrosion products; (b) Grease and corrosion products; (c) Grease and corrosion products; (d) Oily residue.

Microbiologically influenced corrosion (MIC) has been documented for prestressed tendons in a concrete reactor vessel at Fort St. Vrain Generating Station, Denver, CO.[3,8] After an investigation using metallographic examination, grease analysis, scanning electron microscopy, and biological analysis,

Table I. Corrosion Currents Calculated from Cathodic Tafel Slope mA cm^{-2}.

Acid	Concentrated	1% Concentrated
Acetic	0.18	0.08
Butyric	0.07	0.07
Citric	0.27	0.04
Formic	1.72	0.18
Glutaric	0.02	0.03
Lactic	0.41	0.27

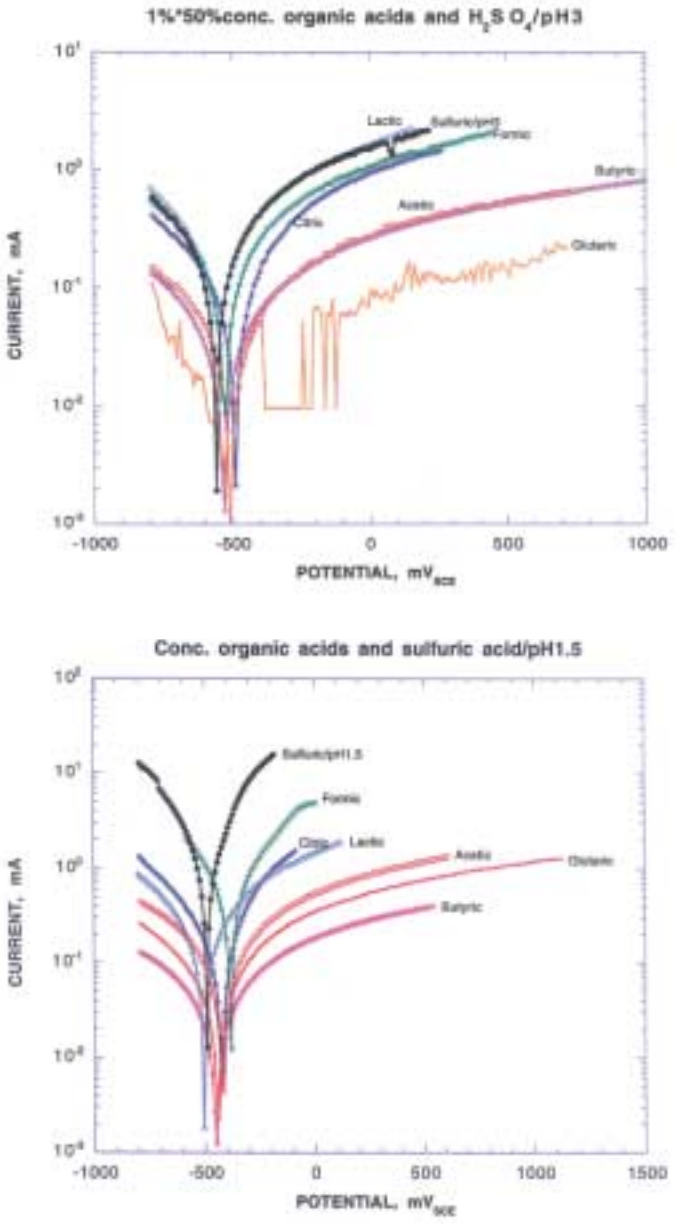


FIG. 5. (a) Polarization curves for 1% concentrated organic acids and sulfuric acid at pH 3.0; (b) Polarization curves for concentrated organic acids and sulfuric acid at pH 1.5.

investigators concluded that microbiological breakdown of organic grease resulted in the formation of formic and acetic acids which combined with moisture and caused corrosion. Corrosion was observed in areas where grease had been consumed or removed during placement of the tendons. Causative organisms were not specifically identified, but experiments conducted with bacteria, including pseudomonads, spore formers and sulfate reducers produced localized corrosion. There was no mention of fungi or their possible role in the observed corrosion.[8]

Similarly bacterial MIC was identified as the cause of breaks in tensioned cables in a silo built of Portland cement in Thayngen, Germany.[9] Cables were single strand (diameter 15 mm) coated with lithium 12-hydrostearate grease in a polyethylene tube (diameter 20 mm, wall thickness > 1 mm). Failures, due to reduction of cable diameter, occurred in areas where cables entered anchor plates and between anchor plates and sheathing. In all cases there was a visible alteration of the condition of the grease in association with corrosion products. Corrosion products were weakly acid to neutral. The watery extract had a vinegary smell and acetic acid was identified in corrosion products. Iron-related and slime bacteria were isolated from the corrosion products.

Most laboratory and field MIC studies have focused on bacterial involvement; however other single-celled organisms, including fungi, can influence corrosion processes. In some environments, including humid atmospheric conditions, fuel water interfaces and soil, fungi may dominate the microflora and influence corrosion. For example, Geesey[10] stressed the potential corrosion problem for metal containers selected for storage of nuclear waste in terrestrial environments.

Liquid water is needed for all forms of life and availability of water influences the distribution and growth of microorganisms. Water availability can be expressed as water activity (a_w) with values ranging from 0 to 1.0. Microbial growth has been documented over a range of water activities from 0.60 to 0.998. Fungi are the most desiccant-resistant microorganisms and can remain active down to a_w = 0.60 whereas few bacteria remain active at a_w values below 0.9. Fungi can grow in small amounts of water and can generate water as a function of hydrocarbon degradation. For example, the fungus *Hormoconis resinae* can grow in 80 mg water per liter of kerosene; and after four weeks incubation, the concentration of water increases more than ten-fold.[11] Fungi can survive as spores in hydrocarbons in the absence of water and germinate when water is available. In addition to water, all organisms require carbon, nitrogen, phosphorus, sulfur, and other trace elements for growth. Microorganisms can use many organic and inorganic materials as sources of nutrients and energy. Many microorganisms can grow on trace nutrients found in laboratory-distilled water.

Most fungi are aerobes and are ubiquitous in atmospheric and aquatic environments. Fungi are nonphotosynthetic organisms, having a vegetative structure known as hyphae, the outgrowth of a single microscopic reproductive cell or spore. A mass of threadlike hyphae makes up a mycelium. Mycelia are capable of almost indefinite growth in the presence of adequate moisture and nutrients so that fungi often reach macroscopic dimensions.

The first step in fungal decomposition of hydrocarbons requires molecular oxygen and the products are alcohols, aldehydes, and aliphatic acids. Formation of hydroxy acids has also been reported.[12] In the experiments presented in this paper, FTIR spectra of grease from inoculated tendons provide evidence for the presence and growth of mycelia in the lubricant, degradation of grease and production of organic acids, including carboxylic and hydroxy acids. Acid production by bacteria and fungi degrading organic materials is a well-documented phenomenon.[13,14] Bacteria showed decreasing capabilities to degrade alkanes with increasing chain length. Filamentous fungi did not exhibit a preference for specific chain lengths.

Acids produced by fungi are damaging to metals, glass, masonry, and other materials.[13-18] The acids most frequently cited as being produced by fungi are formic, citric, and acetic. H_2SO_4 at pH 1.5 exhibits a corrosion current of 3.86 mA cm^{-2} which is a little more than twice that for formic acid. For the 1% organic acid solutions, the corrosion currents for the organic acids ranged from 0.27 to 0.03 mA cm^{-2} and the H_2SO_4 at pH 3.0 exhibits a corrosion current of 0.27 mA cm^{-2}. These are generally lower than for concentrated solutions. The magnitude of the corrosion currents is sufficient to produce significant corrosion in steel. The open circuit potentials for the concentrated solutions are generally higher than for the 1% solutions. This follows from the fact that the slope of the standard hydrogen line is 0.060 mV per pH unit.

Hydrocarbon-based lubricants are routinely used in contact with metal without regard to microbial contamination. Fungal contamination and decomposition of hydrocarbons are well-documented phenomena.[11,12,19] Toropova *et al.*[20] determined that 80% of lubricants used for protecting materials were contaminated with 37 biological agents (21 microscopic fungi and 17 bacteria) during storage and use, independent of climate or relative humidity. They identified the following species most frequently encountered in lubricating oils: *Aspergillus versicolor, Penicillium chrysogen, Penicillium verrucosum, Scopulariopsis brevicaulis, Bacillus subtilis,* and *Bacillus pumilis.* Organisms isolated from one hydrocarbon source could not always grow vigorously on others. Microbial growth in lubricants was accompanied by changes in color, turbidity, acid number, and viscosity. Acid number refers to the acid or base composition of lubricating oils and is also referred to as corrosion number. ■

Conclusion

In situ fungi can degrade hydrocarbon-based lubricants and produce organic acids that cause localized corrosion and SCC of sheathed steel tendons.

Acknowledgments

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About the Authors

Brenda Little *is the Senior Scientist for Marine Molecular Processes for the Naval Research Laboratory, Stennis Space Center, MS. She can be reached at brenda.little@worldnet.att.net.*

Roger W. Staehle *is an adjunct professor in the Department of Chemical Engineering and Material Science at the University of Minnesota. He can be reached at rwstaehle@rwstaehle.com.*