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Fungal influenced corrosion of post-tensioned cables

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Abstract

Laboratory experiments demonstrated that fungal degradation of lubricating grease produced organic acids and localized corrosion of carbon steel cables in polyvinyl chloride sheaths. *Fusarium* sp., *Penicillium* sp. and *Hormoconis* sp. isolated from corroding tendons in a post-tensioned structure were used in the testing. In all cases when fungal spores were intentionally introduced to sheathed tendons, localized corrosion was observed and there was a spatial relationship between fungal hyphae and corrosion. Grease degradation and concomitant acid production were documented with Fourier transform infrared spectroscopy. The association of fungi with corrosion products and the details of the corrosion were documented with scanning electron microscopy.

1. Introduction

Laboratory experiments were designed to assess fungal influenced corrosion of post-tensioned cables using fungal species isolated from a corroding tendon. Bacteria have been implicated in microbiologically influenced corrosion (MIC) of tendons and cables in structures (Ashar et al., 1994; Richner, 1996; NRC Report, 1984), but this is the first paper to investigate the role of fungi in the degradation and corrosion processes of lubricated sheathed carbon steel tendons.

MIC has been documented for prestressed tendons in a concrete reactor vessel at Fort St. Vrain Generating Station, Denver, CO (Ashar et al., 1994; NRC Report, 1984). After an investigation using metallographic examination, grease analysis, scanning electron microscopy, and biological analysis, 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.

Similarly bacterial MIC was identified as the cause of breaks in tensioned cables in a silo built of Portland cement in Thayngen, Germany (Richner, 1996). 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 and slime bacteria were isolated from the corrosion products.

Experiments presented in this paper were undertaken after fungi were isolated and identified from corroding tendons in a structure that had experienced post-tensioned cables failures. Experiments were designed to determine the role of in situ fungi in the corrosion failures.

2. Methods and materials

Six 6.5-in long sections of sheathed tendon were removed from a post-tensioned building during a routine stairwell installation. Each tendon consisted of a seven-wire cable in a polyvinyl chloride sheath (Fig. 1). Each of the seven wires had a diameter of 0.5 cm. Six wires were wrapped around a central core wire. The steel was cold drawn with a 260,000 psi ultimate tensile strength. The resulting cable was coated with a metal soap hydrocarbon grease before

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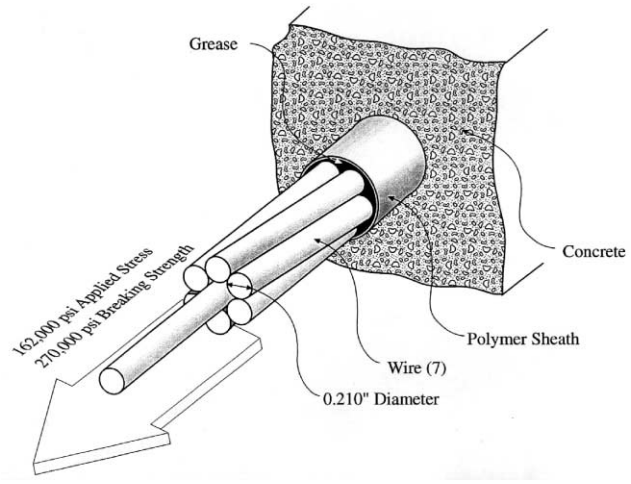

Fig. 1. Tendon detail.

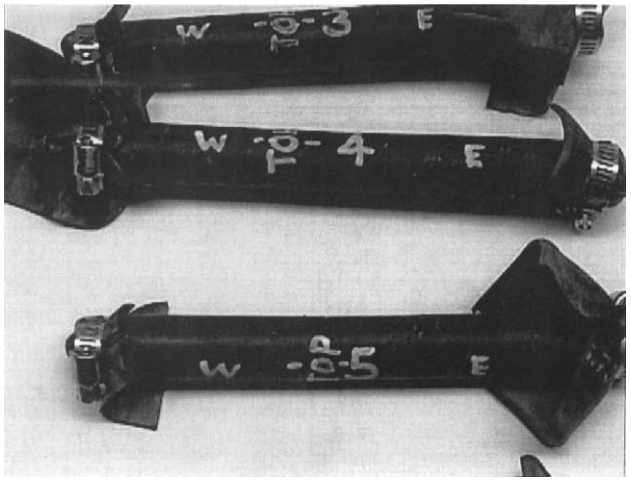

Fig. 2. Sheathed tendons after removal from the building.

insertion into the sheath. Sheaths around the six sections used in the testing were intact and had not been damaged during excavation. Ends of the six sections were sealed with a piece of rubber secured with a clamp (Fig. 2). Sections were refrigerated at 4°C from time of collection until inoculation.

Fusarium sp., *Penicillium* sp., and *Hormoconis* sp. had been isolated from the lubricating grease during a previous corrosion survey of the same building from which the tendons were collected (unpublished data). Isolates 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 allow introduction of the 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 G21-90 standard (1990) 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. The only addition to the tendon sections was 0.06 ml sterile distilled water for each control section and 10^4–10^5 fungal spores in 0.06 ml sterile distilled water for each inoculated section.

At the end of the incubation, sheathed tendons were opened using 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.

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. 512 sample scans were ratioed to 512 background scans at a spectral resolution of eight wavenumbers. 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. FTIR analyses were completed at Davis Chemical Company, Oakbrook, Illinois.

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-s exposure.

3. Results

FTIR results are displayed as absorbance (y-axis). Peaks assignments are consistent with Smith (1999) and Naumann et al. (1996). The fingerprint region of the infrared spectrum for a reference metal soap grease is given in Fig. 3. Bands 1460, 1377 and 722 wavenumbers indicate deformation vibration modes for long chain hydrocarbons. Absorption bands at 1580 and 1560 wavenumbers relate 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 (Fig. 4). Under the experimental conditions,

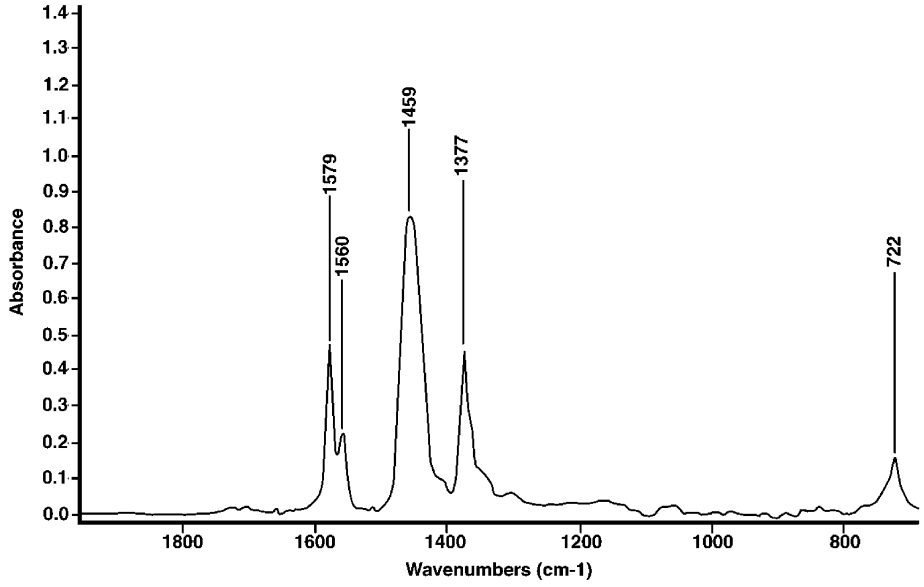

Fig. 3. Reference spectrum for metal soap grease.

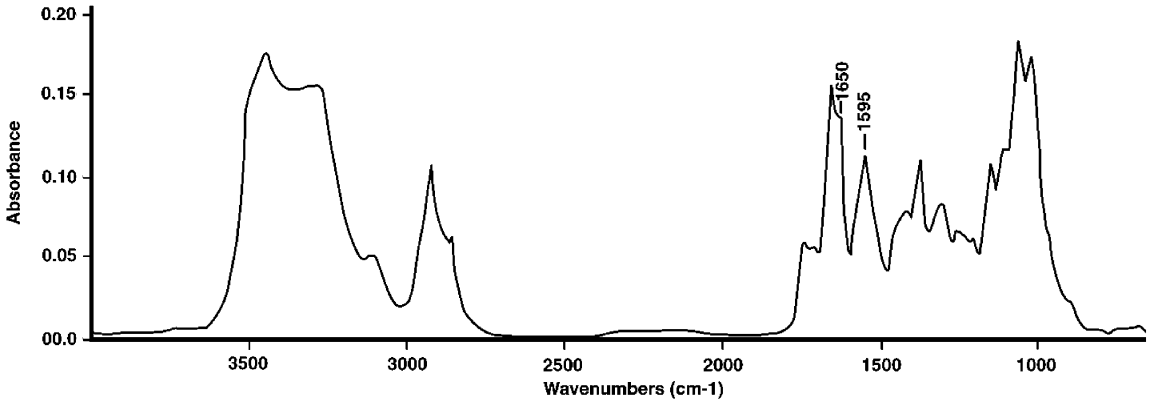

Fig. 4. Reference spectra for *Fusarium.*

these absorption bands indicate the presence of proteins and are indicative of fungi.

Localized corrosion was observed for all inoculated tendons (Figs. 5a and b). 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 corrosion (Figs. 6a and 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 (Figs. 7a–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. 7a there is a strong carboxylate with an absence of carbonyl, in b the carbonyl contribution has increased and the carboxylate decreased. Peaks at 3200 and 1000 wavenumbers have increased. The effect is more pronounced in c. In all cases amide peaks are prominent. In d the spectrum indicates the presence of a light oil. The carboxylate is missing and the carbonyl is prominent.

There were no indications of corrosion on two of the three control samples. Petri plates inoculated with grease from those samples were blank. A single site of localized corrosion was observed on one wire of an uninoculated control

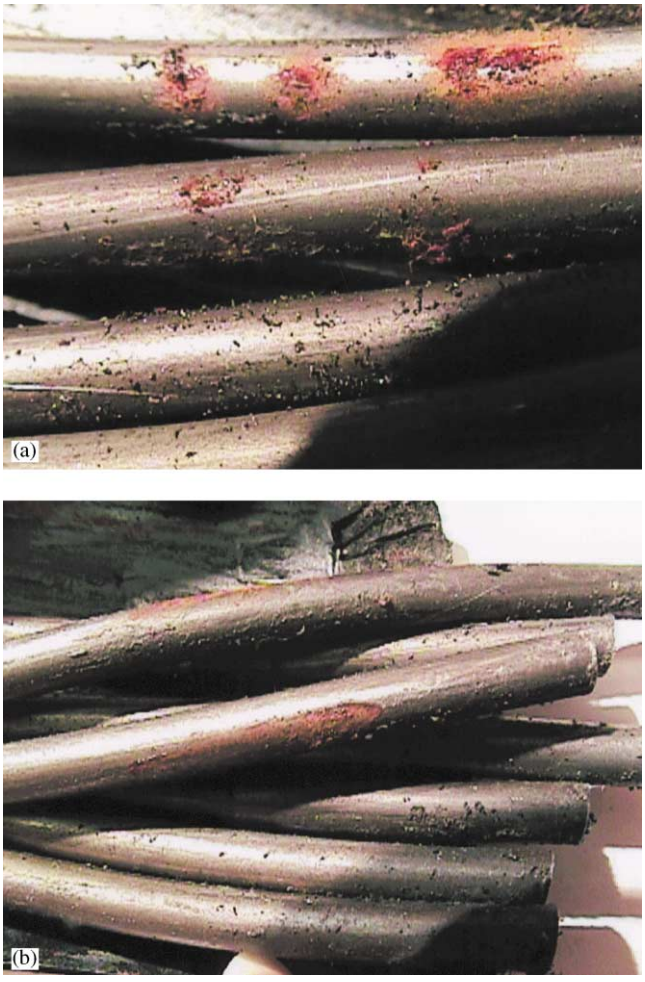

Fig. 5. (a) Fungi and corrosion products on inoculated tendon. (b) Fungi and corrosion products on inoculated tendon.

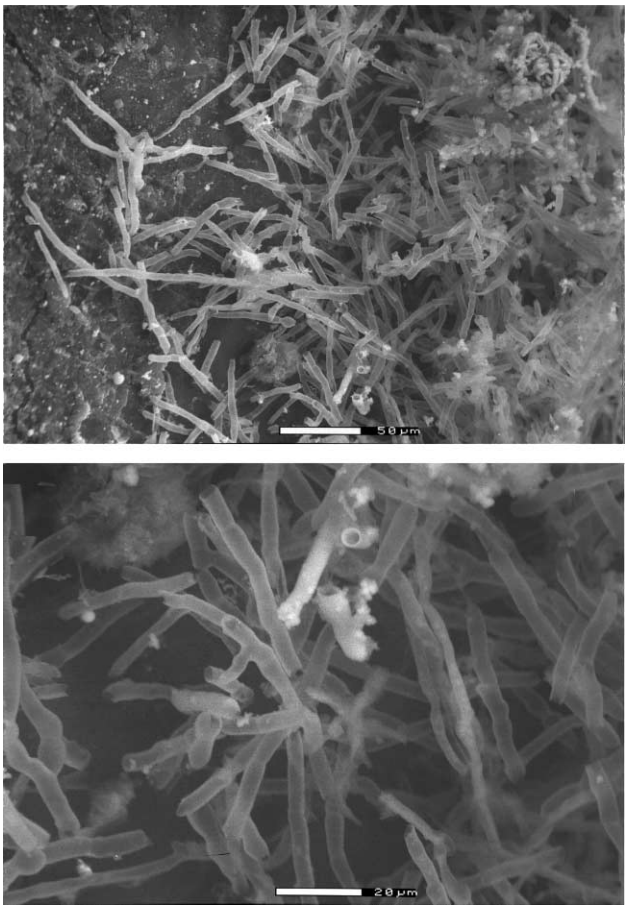

Fig. 6. (a) ESEM micrograph of fungi associated with corrosion of inoculated tendon. (b) ESEM micrograph of fungi associated with corrosion of inoculated tendon.

(Fig. 8). PDA plates were positive for *Fusarium* sp. 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 in associated with the corrosion products were similar to those in Fig. 7.

4. Discussion

Post-tensioned construction has been used in buildings, parking garages, bridges, high-pressure water lines and nuclear power plants (Holley, 1999). Typically, wire, strand, or bar tendons are inserted into preplaced ducts in the structure and are post tensioned from one or both ends after the concrete has achieved sufficient strength. Anchor plates are attached at both ends. Post-tensioned buildings and parking structures have experienced corrosion and deterioration (Vander Vilde, 1999). Embrittlement has been reported in post-tensioning strands in completely enclosed, climate controlled high-rise buildings (Holley, 1999). Uniform surface corrosion or more localized pitting has been reported, but stress corrosion cracking is the predominant mode of cable failure (Vander Vilde, 1999).

In most instances, localized corrosion of post-tensioned cables is attributed to the presence of rainwater in the grease caps (Holley, 1999). Corrosion cannot be due solely to simple ingress of water. The corrosion rate of carbon steel in neutral pH, oxygenated fresh water is approximately $50\,\mu m\ yr^{-1}$ (Metals Handbook, 1988).

The contaminant in grease that is most often cited as causing corrosion is chloride ion (Ashar et al., 1994). Post-tensioned parking structures at or below grade are susceptible to intrusion of chloride ions through slab cracks and buried anchor pockets (Holley, 1999). Greases used on tensioned cables normally contain less than 5 ppm chloride. Possible sources and roles for the chloride ion in cable failures in nuclear power plants and buildings are confusing as indicated in the following quotation from Ashar et al. (1994): "… chloride ion concentration was about 10 ppm. Neither the tendon wires, nor the tendon anchorages showed any adverse effects." There were no indications of chloride contamination of the lubricant used in the tendons in this experiment.

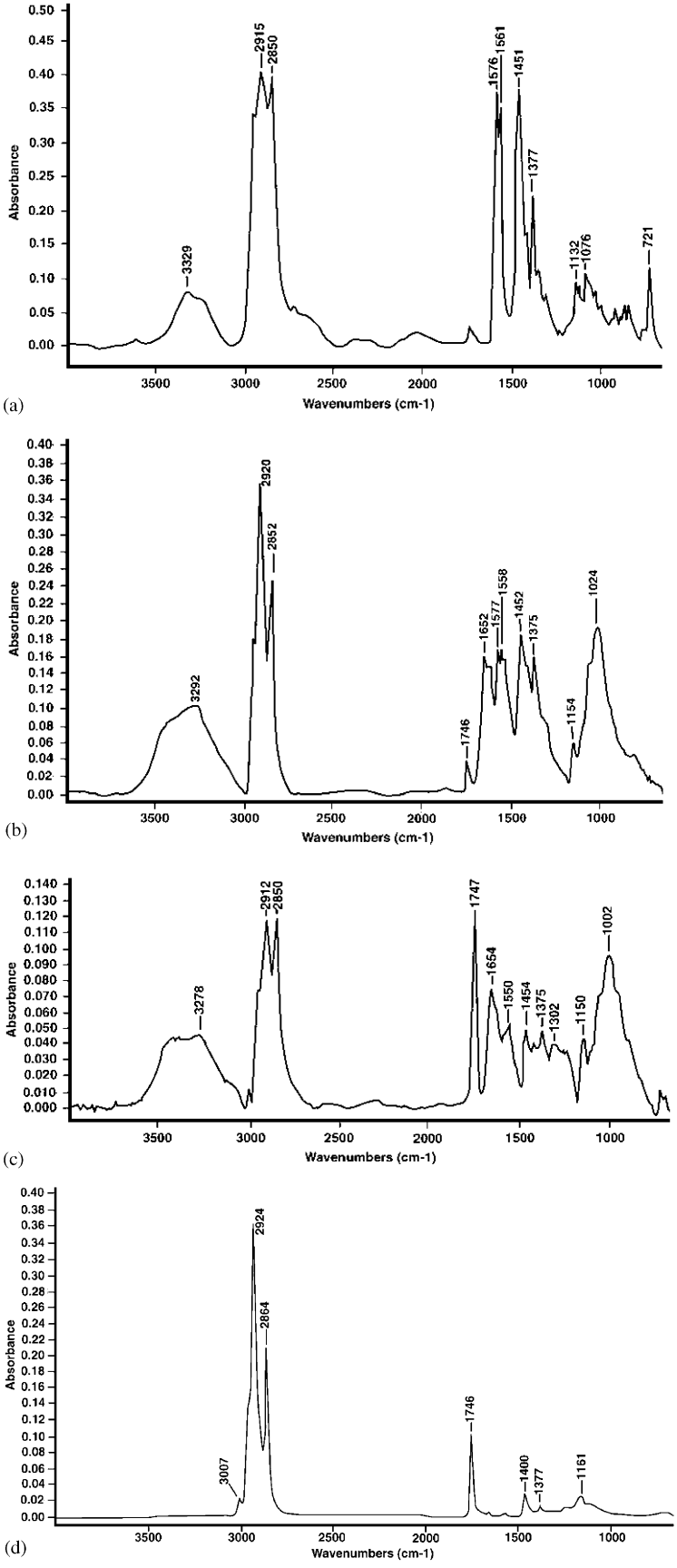

Fig. 7. Spectra collected from a single inoculated tendon. (a)–(c) Grease and corrosion products. (d) Oily residue.

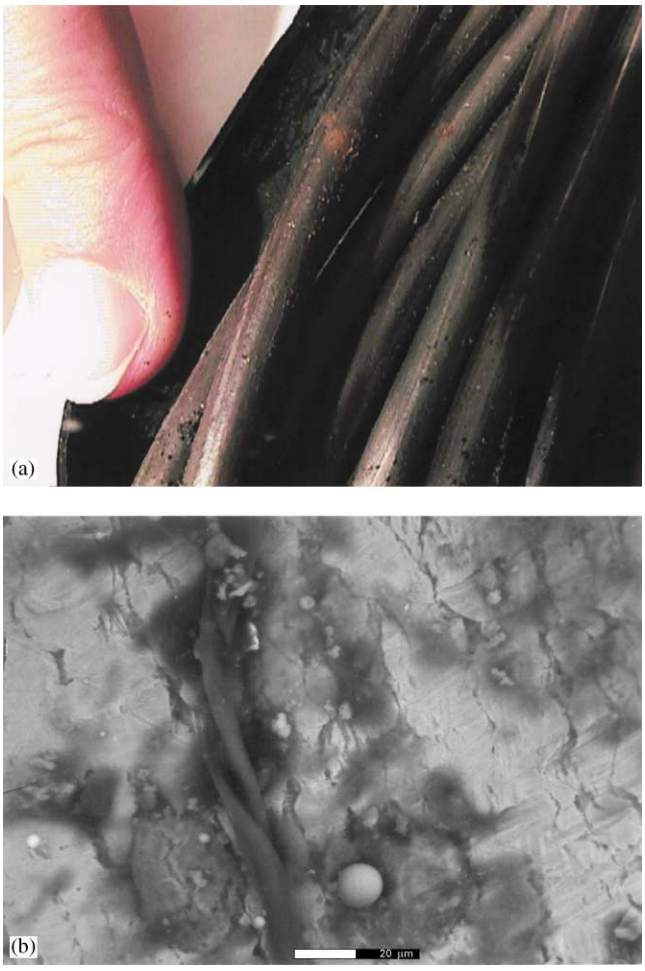

Fig. 8. (a) Corrosion on uninoculated tendon and discoloration of sheath in contact with the tendon. (b)ESEM micrograph of fungi associated with corrosion of uninoculated tendon.

The corrosion rate of carbon steel in fresh waters is independent of pH between 4.5 and 9.5 (Metals Handbook, 1985). This has been confirmed in tap water and distilled water. Over this range of pH values corrosion is controlled by oxygen diffusion. At pH 4.0 or below hydrogen evolution takes place and corrosion increases rapidly. Acid production by bacteria and fungi degrading organic materials is a well-documented phenomenon (Videla, 1986a, b). Acids produced by fungi are damaging metals, glass, masonry and other materials (Videla, 1986a, b; Wilimzig and Bock, 1996; Kaiser et al., 1996; Joza et al., 1996; Weissmann and Drewello, 1996).

Metal soap hydrocarbons are routinely used as lubricants in contact with metal without regard to microbial contamination. Fungal contamination and decomposition of hydrocarbons are well-documented phenomena (Atlas, 1981; Bosecker, 1996; Videla et al., 1993). Toropova et al. (1988) 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 were most frequently encountered in lubricating oils: *Aspergillus versicolor, Penicillium chrysogen, Penicillium verrucosum, Scopulariopsis brevicaulis, Bacillus subtilis* and *Bacillus pumilis*. Organisms isolated from one particular 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. The ability to degrade hydrocarbons is widely distributed among diverse microbial populations (Atlas, 1981). Most work with microbial hydrocarbon degradation has been dealt with remediation of hydrocarbon-contaminated water or soils. Walker et al. (1975) compared degradation of hydrocarbons by bacteria and fungi. Bacteria showed decreasing abilities to degrade alkanes with increasing chain length. Filamentous fungi did not exhibit a preference for specific chain lengths.

Fungal contamination of the lubricant applied to the tendons used in this investigation had been documented in a previous corrosion survey (unpublished data). 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 survive as spores in hydrocarbons in the absence of water and germinate when water is available. *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 (Bosecker, 1996).

The first step in microbial decomposition of hydrocarbons is an aerobic process that requires molecular oxygen. Anaerobic degradation of hydrocarbons by microorganisms proceeds at negligible rates (Atlas, 1981). The first products of microbial oxidation of hydrocarbons are alcohols, aldehydes and aliphatic acids. Formation of hydroxy acids has also been reported (Atlas, 1981). 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. Infrared spectra of grease from localized corrosion on an uninoculated control showed the same pattern of degradation and acid production. Since all tendons used in the experiments were removed from a post-tensioned building and no attempt was made to sterilize tendon sections, growth of fungi and corrosion in a control section was expected and confirmed the existing problem in the building.

5. Conclusions

With the addition of water fungal contaminants grew, degraded lubricants and produced organic acids that caused localized corrosion and cracking of sheathed carbon steel tendons. FTIR was used to assess biodeterioration of grease and production of organic acids.

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