

See discussions, stats, and author profiles for this publication at: <http://www.researchgate.net/publication/261013299>

Corrosion Detection in Steel-Reinforced Concrete Using a Spectroscopic Technique

ARTICLE · JANUARY 2014

DOI: 10.1063/1.4864898

DOWNLOADS

191

VIEWS

115

13 AUTHORS, INCLUDING:



E.J. Garboczi

National Institute of Standards and Technolo...

230 PUBLICATIONS **6,153** CITATIONS

SEE PROFILE



Virgil Provenzano

National Institute of Standards and Technolo...

46 PUBLICATIONS **809** CITATIONS

SEE PROFILE



David F Plusquellic

National Institute of Standards and Technolo...

112 PUBLICATIONS **1,441** CITATIONS

SEE PROFILE



Robert D McMichael

National Institute of Standards and Technolo...

191 PUBLICATIONS **4,303** CITATIONS

SEE PROFILE

Corrosion Detection in Concrete Rebars Using a Spectroscopic Technique

E.J. Garboczi[#], P.E. Stutzman[#], S. Wang[#], N.S. Martys[#], A. Hassan[#], D. Duthinh[#], V. Provenzano[#], S.G. Chou[#], D.F. Plusquellic⁺, J.T. Surek⁺, S. Kim⁺, R.D. McMichael[#], M.D. Stiles[#]
National Institute of Standards and Technology, Boulder⁺, CO and Gaithersburg[#], MD

Abstract: Detecting the early corrosion of steel that is embedded in reinforced concrete is a goal that would greatly facilitate the inspection and measurement of corrosion in the US physical infrastructure. Since 2010, NIST has been working on a large project to develop an electromagnetic (EM) probe that detects the specific corrosion products via spectroscopic means. Several principal iron corrosion products, such as hematite and goethite, are antiferromagnetic at field temperatures. At a given applied EM frequency, which depends on temperature, these compounds undergo a unique absorption resonance that identifies the presence of these particular iron corrosion products. The frequency of the EM waves tend to on the order of 100 GHz or higher, so transmitting them through the cover concrete and back out again at a detectable level has been challenging. NIST has successfully detected these two iron corrosion products, and are developing equipment and methodologies that will be capable of penetrating the typical 50 mm of cover concrete in the field. The novel part of this project is the detection of specific compounds, rather than only geometrical changes in rebar cross-section. This method has the potential of providing an early-corrosion probe for steel in reinforced concrete, and for other applications where steel is covered by various layers and coatings.

INTRODUCTION

The US physical infrastructure relies on steel, which is almost always protected from corrosion in some way. It could be in the form of reinforced concrete, which protects the reinforcing steel from corrosion. Other examples include wire tendons in post-tensioned concrete, protected by cementitious grout or polymeric grease, bridge cables protected by grease and sheaths of various materials, water pipes in power plants, protected by polymeric wrappings and/or insulation, and steel bridge girders and tanks, protected by polymeric coatings. Furthermore, the technique may be well-suited as a NDE method in a growing application area of concern related to bio-corrosion.

According to a 2002 NACE/FHWA report [1], the annual costs of steel corrosion in the US infrastructure and in industry exceed \$200 billion per year. An NRC Corrosion Committee report [2] lists corrosion detection as one of 11 Grand Challenges for U.S. corrosion science. Obviously, this refers to detecting corrosion through the protective layer, whatever that may be. Early corrosion detection is desirable, before corrosion impacts the protective layer via mechanical expansion and damage (cracking).

Technical challenges that make this kind of corrosion detection difficult include the small amounts of corrosion present before exterior effects are noticed, the wide variety of time-dependent corrosion products that are generated depending on the corrosion environment (humidity and salt conditions), the random topology and geometry of corrosion products, the simultaneous presence

of multiple products, and the often- irregular geometry of the surfaces on which they form, such as a rebar in concrete.

NEW TECHNICAL IDEAS

A five-year NIST project that started in October, 2010 is developing a new method of sensing iron corrosion products. Instead of just detecting a geometric change or an image of existing corrosion, the goal of the project is to use spectroscopy to uniquely identify the presence of certain iron corrosion products that are anti-ferromagnetic (AFM). Some common AFM iron corrosion products include hematite, goethite, akaganeite, lepidocrocite, and wustite [3]. In AFM materials, the iron electron spins are ordered but have subsets that are anti-parallel, so there is no macroscopic magnetic moment. Nevertheless, AFM materials can display absorption resonances that approach the terahertz (THz) range. EM waves can couple to a magnon, which is a cooperative motion (wave) among the oriented spins. The frequency of the wave depends on the interaction strength between the two spin sets, analogous to how the wave speed of sound in a rope depends on the tension in the rope. Estimates of these strengths can give estimates of frequencies at which to search. The new idea is then to detect the presence of early corrosion by detecting these AFM resonances (AFMR), which then implies the presence of these specific corrosion products. This idea was conceived by William Egelhoff of NIST, who started this project but sadly passed away after the first year.

The project objectives include the following tasks. First, identify what corrosion products are present in which applications, which means that corrosion products need to be characterized. There must be AFM corrosion products present or the detection process will not work. Second, detect AFM resonances (AFMR) in the laboratory and determine their sensitivities to variables like concrete temperature and saturation (moisture content). Third, to enable corrosion detection in reinforced concrete, the AFMR signals need to be detected through a realistic thickness of concrete, such as actually covers the reinforcing steel in bridge decks. As part of this task, the electromagnetic response of concrete needs to be determined, since the electromagnetic signals must go and return through concrete. Fourth, detect AFMR in a mixture of real, composite corrosion products. Finally, a proof-of-concept prototype should be assembled in order to hand-off the technology to commercial vendors, since part of the mission of NIST is to develop technology to benefit to industry, either through standards or tools (as in this case).

RESULTS TO DATE

Full characterization of a suite of samples, including chemically pure powders, mm-scale crystals, and field samples, has been carried out using X-ray diffraction, optical microscopy, and scanning electron microscopy (SEM). Hematite and goethite have definitely been found in field samples, as well as akaganeite in accelerated corrosion samples of steel reinforcing bars covered with a mortar and subject to an impressed voltage. Akaganeite is similar to goethite but with chlorine atoms incorporated into the molecular structure.

Electromagnetic characterization of relevant concrete samples and components, as well as iron corrosion minerals, has been carried out, using standard techniques [4], measuring attenuation, dielectric permittivity, and magnetic susceptibility as a function of frequency, composition, and

temperature [5,6]. Dr. James Baker-Jarvis of NIST led this part of the project until his sudden death from an accident in 2011. The approximate attenuation is exponential – details are given elsewhere [5]. For 50 mm of concrete, the signal power is estimated to be attenuated by approximately a factor of ≈ 50 dB. Electromagnetic scattering from rebars with a non-uniform surface has been modeled [7] to help with signal deconvolution from AFMR detection in real geometries.

Using an existing terahertz apparatus [8] and a patented signal generation and detection system [9,10], the AFMRs in hematite [11] and goethite [12] have been measured, in fine powders ($1\text{ }\mu\text{m}$ to $3\text{ }\mu\text{m}$ particle size) and in real corrosion products. Figure 1 shows the hematite measurements, along with a theoretical fit based on one-magnon scattering [11]. The uncertainty bars are contained within the data point symbols. One can notice the strong dependence of the AFMR frequency ($1\text{ cm}^{-1} = 30\text{ GHz}$) on the temperature. At the Neel temperature of 948 K (not shown in Figure 1), the AFM order vanishes and the absorption frequency is zero. This temperature from the literature has been confirmed by SQUID (superconducting quantum interference device) measurements made at NIST. However, the AFMR frequency dip below this temperature, at around 250 K , is due to the Morin transition [3], where the net AFM spin orientation changes alignment within the crystal without destroying the AFM order. In goethite, the AFMR transition is at substantially higher frequency, on order $\approx 500\text{ GHz}$ at room temperature. Therefore goethite is not a good candidate for corrosion detection through concrete. However, for steel corrosion under a polymeric protective layer of some kind, like a coating or a wrap, goethite can easily be detected by the NIST terahertz apparatus. In this area, one infrastructure application could be a painted steel bridge.

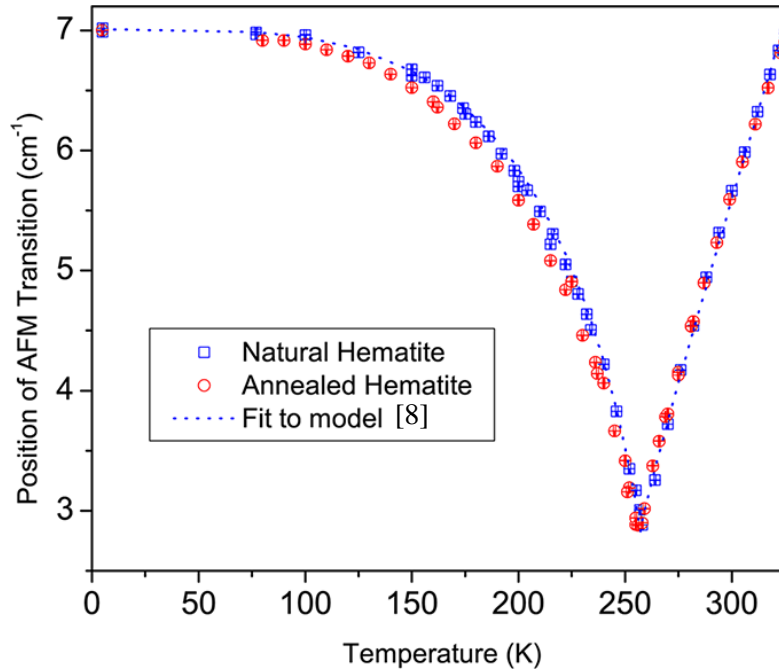


FIGURE 1: The AFMR frequency for hematite as a function of temperature. Note that $1\text{ cm}^{-1} = 30\text{ GHz}$.

An accelerated corrosion testing apparatus with galvanic control of the acceleration has also been developed. A rebar specimen, either bare or coated with a mortar, is wired to a bundle of graphite rods and all are immersed in simulated concrete pore solution. The mortar is made at a high water:cement mass ratio for good flowability into the narrow forms around the rebar. Increasing the number of graphite rods also increases the corrosion current roughly linearly in the surface area of the graphite rod bundle. The oxygen content is controlled by either bubbling lab air constantly through the solution or bubbling nitrogen to reduce the oxygen content of the pore solution. This set-up will be used to study the abundance of various corrosion products as a function of oxygen content in the surrounding solution. A micro-Raman instrument is being used to study the topology and geometry of corrosion products on a real rebar. Samples from the accelerated corrosion experiments will be used for this purpose.

FUTURE WORK DURING THE LAST YEAR OF THE PROJECT

The five-year project will end in September, 2014. During this last year, the project will be focused on improving the understanding of the topology, geometry, and mineralogy of corrosion products formed in realistic environments and how this might affect the AFMR response of the material. These tests will be accomplished by using the project's accelerated corrosion apparatus to produce samples under varying environmental conditions, characterize them with micro-Raman, and then detect AFMRs using the NIST terahertz apparatus. The plan is to demonstrate that AFMR for hematite in real corrosion products can be detected through up to 50 mm-thick layers of concrete and other materials. The power and sensitivity of the detection apparatus is being improved to make this possible. A successful prototype has been developed and talks are being planned with commercial vendors about further improvement of this technology. The electromagnetic modeling of waves passing through a random medium, reflecting from a non-smooth iron surface, and then passing back through the random medium, will be further developed.

Magnetite is also a common iron corrosion product but it is ferromagnetic, not AFM. Based on the project's spectroscopic measurements of the frequency dependence of various parameters in magnetite, a low-frequency (i.e. below 10 GHz) induction method to detect its presence is being developed.

CONCLUSIONS

Positive progress has been made in developing an iron corrosion detection process using resonances in anti-ferromagnetic iron corrosion products. This method has been successful – the only question that remains is how it can be made into a reliable and practical method for detecting early corrosion in protected steel in the US physical infrastructure. This method being developed by NIST could be the answer to this national need.

REFERENCES

1. G.H. Koch, M.P.H. Brongers, N.G. Thompson, Y.P. Virmani, and J.H. Payer, Corrosion costs and preventative strategies in the United States, Publication No. FHWA-RD-01-1562002 (2002), www.nace.org/uploadedFiles/Publications/ccsupp.pdf.

2. National Research Council Committee on Research Opportunities in Corrosion Science and Engineering, *Research Opportunities in Corrosion Science and Engineering*, 2011, http://www.nap.edu/catalog.php?record_id=13032.
3. R.M. Cornell and U. Schwertmann, *The Iron Oxides: Structure, Properties, Reactions, Occurrences, and Uses*, 2nd ed., Wiley-VCH GmbH and Co. KGaA (2000). Wiley On-line library.
4. J. Baker-Jarvis, M.D. Janezic, B.F. Riddle, R.T. Johnk, P. Kabos, C.L. Holloway, R.G. Geyer, and C.A. Grosvenor, *Measuring the Permittivity and Permeability of Lossy Materials: Solids, Liquids, Metals, Building Materials, and Negative-Index Materials*, NIST Technical Note 1536, NIST (2005).
http://whites.sdsmt.edu/classes/ee692gwmm/additional/NIST_Tech%20Note_1536.pdf
5. Sung Kim, Jack Surek, and James Baker-Jarvis, *Electromagnetic Metrology on Concrete and Corrosion*, *Journal of Research of the National Institute of Standards and Technology* 116, 655-669 (2011).
6. James Baker-Jarvis, Sung Kim, Jack Surek, Dat Duthinh, Paul Stutzman, and Edward Garboczi, *Electromagnetic Variations of Concrete*, in preparation (2013).
7. Ahmed Hassan, Nicos Martys, Edward Garboczi, Robert McMichael, Mark Stiles, David Plusquellic, Paul Stutzman, Shuangzhen Wang, and Virgil Provenzano, Jack Surek, David Novotny, Jason Coder, Mike Janezic, and Sung Kim, *Measurement and simulation of millimeter wave scattering cross-sections from steel-reinforced concrete*, *QNDE* 2013.
8. D. F. Plusquellic, K. Siegrist, E. Heilweil, and O. Esenturk, *Applications of THz Spectroscopy in Biosystem*, *Chem Phys Chem* 8(17), 2412 (2007).
9. E. Gerecht, K.O. Douglass, and D.F. Plusquellic, *Chirped-pulse Terahertz Spectroscopy for Broadband Trace Gas Sensing*, *Optics Express* 19(9), 8973-8984 (2011).
10. Kevin O. Douglass, Eyal Gerecht, and David F. Plusquellic, *Chirped-Pulse Fourier Transform Spectroscopy at Millimeter and THz Frequencies*, US Patent, June 20, 2011.
11. S. G. Chou, P. E. Stutzman, S. Wang, E. J. Garboczi, W. F. Engelhoff, David F. Plusquellic, *High Resolution THz Optical Absorption Study of Antiferromagnetic Transitions in Hematite (α -Fe₂O₃)*, *Journal of Physical Chemistry C* 116, 16161-16166 (2012). DOI: 10.1021/jp3036567.
12. S.G. Chou, P.E. Stutzman, V. Provenzano, R.D. McMichael, E.J. Garboczi, and D.F. Plusquellic, *Variable temperature THz optical absorption study of antiferromagnetic magnons in goethite*, in preparation (2013).