Abridgment

Innovations Deserving Exploratory Analysis: Research on Structures

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Strategic Highway Research Program projects are described that have been carried out under the Innovations Deserving Exploratory Analysis (IDEA) program and that relate to structures research. These projects included the following examples of technology: laser-induced ultrasonic wave measurements, ac impedance spectroscopy, conducting polymer anode beds, and electroacoustic wave technology.

The Strategic Highway Research Program (SHRP) is a $150 million, 5-year effort to accelerate the development of new technology in specific areas of highway research. The structures area research, amounting to approximately $10 million, is concerned with evaluation and repair of reinforced concrete structures suffering from corrosion.

The contracts in this part of the program have been discussed elsewhere (*1*,*2*), and are described in this publication. The Innovations Deserving Exploratory Analysis (IDEA) program uses 2 percent of the budget to explore research related to the overall aims of SHRP but outside the scope of the main contracts. IDEA contracts are usually of 1-year duration and are funded in the $50,000 to $100,000 range. Because SHRP research is supported by the state highway agencies (SHAs), it must address state highway problems and produce useful products that SHAs can use. Projects are selected on the basis of their innovation, their potential for producing useable products, and anticipated benefits to the highway industry if the project is successful.

The projects discussed were all selected for their applicability to the problem of corrosion of steel in concrete. Some have been completed and reported on, some are still underway, and others have been approved for additional SHRP IDEA funding to advance the work from the research laboratory to the field testing of a prototype. This paper will address individual projects and their expected results.

LASER-INDUCED ULTRASONICS FOR NONDESTRUCTIVE TESTING (ID002)

This contract was based on a proposal submitted by the National Nondestructive Test Centre, Harwell, United Kingdom. The work was started in September 1988 and was completed about 1 year later. The final report has been submitted (*3*), and will be published soon.

The goal was to develop a laser-induced ultrasonic wave measuring system for rapid, noncontact inspection of concrete and asphalt (including pavements) for detection of flaws in the structures.

The technique used for the laser ultrasonic testing is shown schematically in Figure 1. The system has a laser (Nd–YAG), which produces a 20-nsec pulse, at a power density of 2×10^{11} W/m^2. This power vaporizes a tiny amount of the surface, generating a broadband, ultrasonic pulse. The pulse is detected by a low-power laser interferometer. The interferometer compares a beam of light reflected from the oscillating surface with a reference beam. The output of the interferometer is proportional to the phase change and can therefore be used to determine the movement of the surface.

All stimulation of the concrete and detection of pulses is by lasers. Therefore none of the signal generation or detection equipment is in physical contact with the specimen, i.e., this is a noncontact technique. In principle, it can rapidly scan bridge decks or substructures.

A complete description of the apparatus and results of the work can be found in the final report when available. Figure 2 shows a typical spectrum. The residual R wave is the surface wave between the point of creation of the pulse and the point of detection. The 2P wave is the compression wave reflected from the delamination, the 2S wave is the shear wave from the same delamination, and finally there is a 2P wave from the base of this all-asphalt specimen. Results indicated that the system could detect the bottom surface of a concrete block, and a delimination created in the block. The system also detected delaminations and debonding in aged asphalt. The main problem was difficulty in finding the peak representing a defect in the other noise in the spectrum.

The Harwell research project concluded that the system works in principle. Higher-powered lasers will be needed both for the interferometer and the laser that stimulates the signal. The work carried out for SHRP was conducted with available test equipment on a stable optical bench, which thereby differed from a vehicle-mounted system traveling along a roadway. The system may have more promise as a noncontact substructure nondestructive test (NDT) method. It could be mounted on a stable platform, and the laser fired at concrete surfaces to detect delaminations.

AN ELECTROCHEMICAL TECHNIQUE (ID005)

Cortest of Columbus, Ohio, proposed and carried out this research using ac impedance spectroscopy to detect whether a cathodic protection system was effective in protecting all above-ground elements of a reinforced concrete structure suffering from chloride-induced corrosion. Figure 3 shows the

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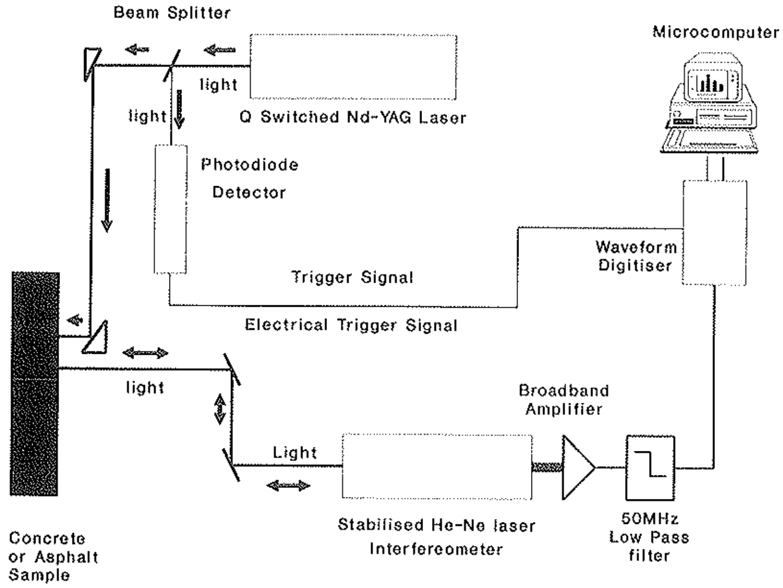

FIGURE 1 Schematic layout of laser system for noncontact inspection of pavement.

experimental set up. The corrosion cell can be represented by an equivalent electric circuit, and ac circuit theory can be applied. The response of the circuit can be represented by Nyquist plots in the complex plane. The shape of the plot should change as the equivalent electrical circuit switches from one representing a corroding cell to one representing a cathodically protected system.

Although there were definite differences between corroding and cathodically protected small specimens, these differences were not apparent on large specimens containing adjacent corroding and noncorroding areas, because macrocell or averaging effects severely reduced the differences. Further work may be funded to overcome the macrocell problem. Because the results of this work have implications for other SHRP projects, a workshop was held (*3*) to share the results of this research with others working in the field and with SHRP's researchers on Projects ID008 and C-101.

ULTRALOW-FREQUENCY AC IMPEDANCE SPECTROSCOPY (ULFACIS) (ID008)

A proposal from SRI International was approved for funding. The objective was to explore the low-frequency end of the ac

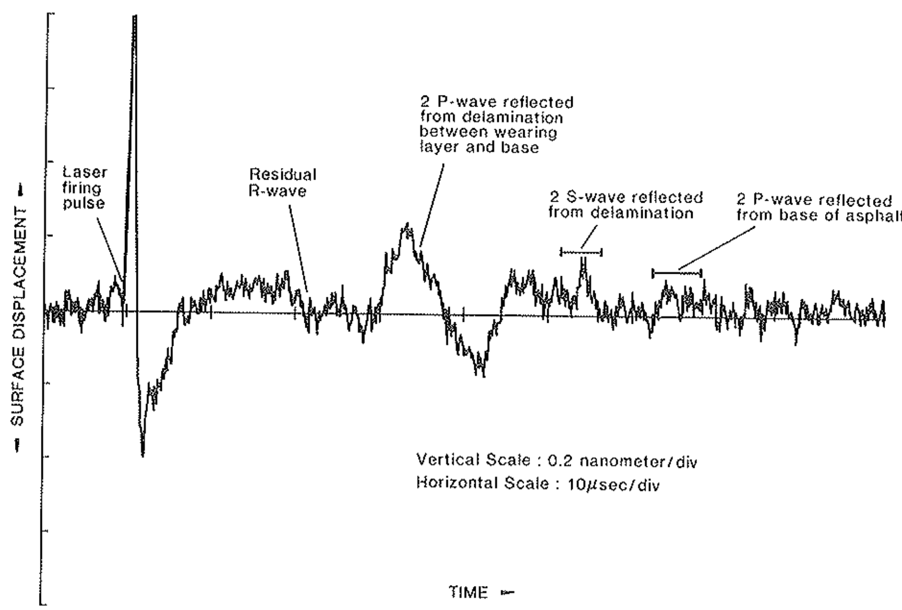

FIGURE 2 Laser-induced ultrasonic waveform from aged asphalt. (Compression wave velocity = 3.0 mm/µsec; separation between lasers = 40 mm; position of lasers near visible delamination.)

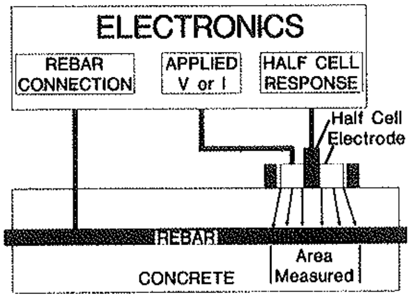

FIGURE 3 Schematic experimental setup for ac impedance measurement.

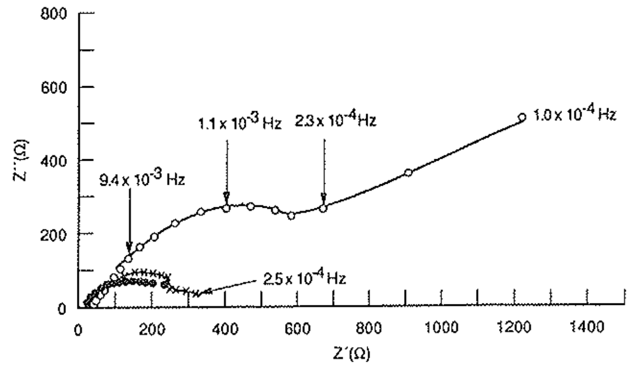

FIGURE 4 Nyquist plots of noncorroding (open circles) and corroding (solid circles and crosses) (SRI).

impedance spectrum to determine how accurately corrosion can be measured and located, given the slow response time of the reinforced-concrete system. The speed of response of the system determines the ac frequency range used, the time taken for a single measurement, and its susceptibility to error caused by rapid changes in local conditions (*3*).

The system of a corroding piece of reinforcing steel in moist concrete can be represented by an electrical circuit consisting of resistances, capacitances, and other electronic impedances that (unlike a simple resistance), change their values with the frequency of the alternating current, creating a phase lag in the circuit. This effect can be displayed as a spectrum of frequency shift and wave amplitude as the applied ac frequency varies. From these plots, usually complex plane plots of the impedances, the resistance of the electrolyte (the concrete) and the interfacial resistance at the steel-concrete interface can be determined. The latter is inversely proportional to the corrosion current, and therefore the corrosion rate can be calculated from Faraday's law. This law relates electrical charge passed with the amount of a metal consumed or deposited at an electrode.

Figure 4 shows examples of the spectra generated, with the frequencies at several points. Figure 5 shows how the spectra are generated. The corroding system can be regarded as an electrical circuit. Because of the presence of the capactance and the Warburg impedance (which represents diffusion control of the corrosion reaction), the circuit resistance appears to change with the ac frequency applied. The phase of the ac is also changed by the circuit. In ac circuit theory, this effect is often represented in a Nyquist plot of the real versus the complex (phase-related) resistance or impedance (*Z* in the figure). Figure 5 shows two possible equivalent circuits and their corresponding Nyquist plots.

During the research, software for processing ac impedance spectra, locating corrosion, and determining corrosion rates was developed. A second stage of work is now underway, with Caltrans sharing the cost by providing manpower and sites. SRI International is developing prototype hardware for the system, and will be doing field tests on real structures.

CONDUCTING POLYMER ANODE BEDS (ID014)

SHRP's research on electrochemical injection of inhibitors (*4*) showed that large, positively charged molecules can be diffused into concrete under the influence of an electric field. This IDEA project proposed by SRI is investigating the de-

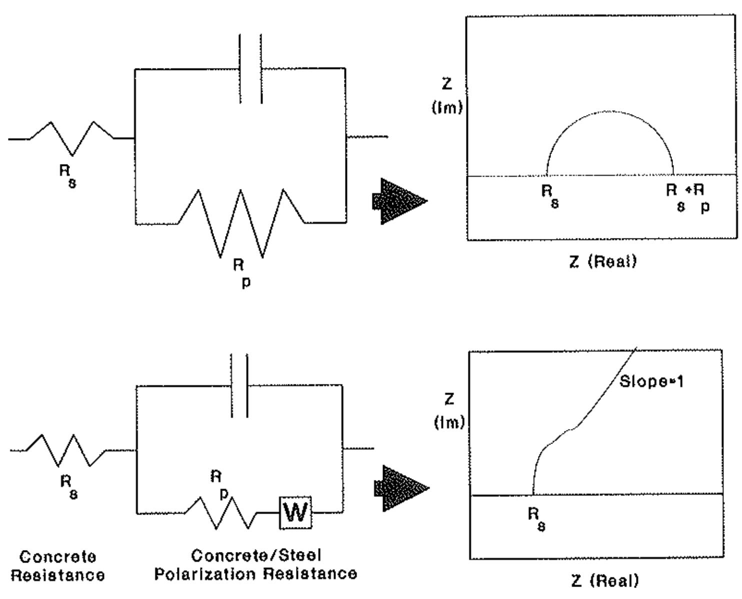

FIGURE 5 Equivalent circuits and their ac impedances.

velopment of an anode for cathodic protection, created by electrical injection of a charged monomer that is polymerized in situ to form a conductive layer in the concrete. It is important that a positively charged molecule is used, as the chloride ion is negatively charged, and would be attracted to the rebar by the field, thus risking accelerating corrosion.

This contract is still underway. Results so far have shown that the monomer can be injected electrically on small specimens. Work is underway to optimize the injection procedure, determine the conductivity of the finished product and to ensure that the injection can be controlled to avoid short circuits between the anode and the rebar. More realistic specimens will be used in the ongoing test program.

ELECTROACOUSTIC TECHNOLOGY (ID019)

Combining an electric field with acoustic vibration has been found to move water around in slurries. Battelle Laboratories, Columbus, Ohio, proposed investigating the efficacy of this process not only in hardened but also in plastic concrete for controlling the water-cement ratio in the wet mix, and for dewatering and corrosion control of aging structures.

Results so far have indicted that the combination of acoustic vibration with an electric field is more effective than either alone in removing chloride ions. Results also suggest that the electroacoustic combination also will accelerate polymer impregnation and inorganic inhibitor injection. Further work will be undertaken to optimize the technology and to apply it to larger, more realistic concrete specimens.

CONCLUSIONS

New technologies being investigated under the SHRP IDEA program may provide the bridge rehabilitation engineer with new tools for attacking the corrosion problems caused by salt ingress on bridge decks and substructures.

The technologies are innovative, and none are yet ready for field use. However, field tests will be conducted on the most promising techniques, and some products will be available by the completion of the program in 1993.

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