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Demonstration of Electro-Osmotic Pulse (EOP) Technology to Mitigate Alkali-Silica Reaction in Concrete Pavement

Final Report on Project F08-AR24

Michael K. McNerney, Orange S. Marshall Jr., P. A. Noyce,
and G. Blohm

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Demonstration of Electro-Osmotic Pulse (EOP) Technology to Mitigate Alkali-Silica Reaction in Concrete Pavement

Final Report on Project F08-AR24

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Final report

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Under Project F08AR24, "Electrokinetic Remediation of Alkali-Silica Reaction (ASR) in
Concrete Pavements at Campbell Army Airfield, Fort Campbell, KY"

Abstract

All Department of Defense (DoD), Army, federal government, and private-sector facilities experience the problem of concrete deteriorating via alkali-silica reaction (ASR). ASR is a form of concrete corrosion that slowly deteriorates concrete from the inside by forming highly expansive gels that cause cracking and swelling of the concrete matrix. This project evaluated Electro-Osmotic Pulse (EOP) technology to mitigate ASR in an area of the visitor's ramp at Campbell Army Airfield. An EOP system was designed, installed, and monitored in a concrete pavement section affected by ASR. In addition to installing EOP technology, concrete moisture monitoring probes were installed at selected locations. The performance of the EOP system was evaluated by recording temperature and moisture levels inside the concrete for a period of nine months.

The ability of the EOP system to mitigate ASR is inconclusive. Although there are indications that moisture is being removed from the concrete pavement, it is not clear that the concrete's internal relative humidity has been reduced below 80%, the moisture reduction value that ensures ASR will not occur. The calculated return on investment (ROI) for the project was 5.68. However, a long-term approach for performance monitoring must be completed before the technology can be recommended.

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Preface

This demonstration was performed for the Office of the Secretary of Defense (OSD) under Department of Defense (DoD) Corrosion Control and Prevention Project Fo8AR24, “Electrokinetic Remediation of Alkali-Silica Reaction (ASR) in Concrete Pavements at Campbell Army Airfield, Fort Campbell, KY.” The proponents were the U.S. Army Office of the Assistant Chief of Staff for Installation Management (ACSIM) and the U.S. Army Installation Management Command (IMCOM). The technical monitors were Robert A. Herron (OUSD(AT&L) Corrosion), Ismael Melendez (IMPW-E), and Valerie D. Hines (DAIM-ODF).

The work was performed by the Materials and Structures Branch of the Facilities Division (CEERD-CFM), U. S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL). Significant portions of this work were performed by Electro Tech CP, Accord, NY. At the time this report was prepared, Vicki L. Van Blaricum was Chief, CEERD-CFM; Donald K. Hicks was Chief, CEERD-CF; and Michael K. McInerney was the ERDC CPC Program Coordinator. The Deputy Director of ERDC-CERL was Dr. Kirankumar Topudurti, and the Director was Dr. Lance D. Hansen.

The following personnel supported this effort and are gratefully acknowledged for their assistance:

- Terry Ennis, Airfield Manager Campbell Army Airfield
- Audie Hardin, Fort Campbell Public Works Business Center (PWBC)

The Commander of ERDC was COL Ivan P. Beckman, and the Director was Dr. David W. Pittman.

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	$(F-32)/1.8$	degrees Celsius
Feet	0.3048	meters
inches	0.0254	meters
square feet	0.09290304	square meters

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1 Introduction

1.1 Problem statement

All Department of Defense (DoD) concrete structures are subject to the destructive effects of alkali-silica reaction (ASR). This form of concrete corrosion slowly deteriorates concrete from the inside by forming highly expansive gels that cause swelling and cracking of the concrete matrix. ASR is a heterogeneous chemical reaction that takes place between aggregate particles (e.g., chert, quartzite, opal, strained quartz crystals) and the alkaline pore solution of the cement paste. All Portland cements contain alkalis, and many are highly alkaline. The alkali content of concrete is also likely to increase with the use of additives and admixtures. The infusion of chlorides in the form of seawater or pavement de-icing salts may also increase alkalinity. Water in the pore fluid is imbibed into the reaction sites and eventually, alkali-calcium silica gel is formed. When this substance absorbs water, it expands in volume and imposes internal stresses on the concrete matrix. Studies have shown that ASR typically develops and continues in concrete when internal relative humidity exceeds 80%–85% (e.g., Thomas et al. November 2013).

The following three conditions must be satisfied to initiate ASR: (1) sufficient alkali content, (2) sufficient reactive silica within the aggregate, and (3) sufficient moisture to sustain the reaction. Therefore, to prevent or control ASR, it is necessary either to reduce the levels of each factor to below the reaction threshold or to introduce materials that can inhibit the reaction.

Several remedial options are available to prevent water from reaching the concrete surface or limiting water's penetration into the concrete. The most well-known remedial actions are the following:

- Improve drainage and enhance maintenance, but this action is not effective when the source of moisture is below the pavement or behind bridge wing wall.
- Apply a penetrating sealer (silane) to reduce internal relative humidity, but this option doesn't work well if the affected concrete isn't accessible or is in direct contact with water or saturated soil.

- Apply cladding to certain concrete bridge elements that are not saturated from contact with a concealed water source.
- Apply lithium compounds, which can be effective for certain bridge elements and pavements, but have not yet been rigorously field tested.
- Fill cracks to reduce the ingress of water and chloride ions.

A report published by the U.S. Army Corps of Engineers (USACE) Transportation Systems Center (USACE TSC 2006) provides several indicators of how costly and hazardous ASR damage is to DoD infrastructure. Army airfields are known to have ASR-degraded pavements, but specific repair-cost estimates weren't available to the report's authors. However, an Air Force survey of all its facilities identified ASR-damaged airfield pavements at 20 bases and estimated that it would cost \$87 million to repair only five of those 20 airfields (Air Force Civil Engineer Support Center [AFCEC] 2006). That report estimated that one individual base, Seymour-Johnson Air Force Base (AFB), NC, could reach ASR rehabilitation project costs of \$28 million. The report also found Navy airfields to have significant ASR problems but without dedicated ASR-mitigation resources, the Navy (at the time of the report) was merely documenting ASR as part of its airfield pavement condition assessment program.

An alternative remedial method—electro-osmotic pulse (EOP) technology—has previously been shown to effectively reduce moisture ingress to concrete structures (McInerney et al. 2002). Data obtained during EOP demonstrations for moisture reduction have shown that EOP is able to dry concrete to below 55% relative humidity and keep it dry (Marshall 2009; Morefield, et. al. 2003). By making moisture unavailable to support formation of the ASR gel, EOP could be capable of greatly reducing the rate of concrete deterioration caused by ASR in DoD infrastructure. To investigate the feasibility and cost effectiveness of protecting military installation pavements from ASR damage, the DoD's Corrosion Prevention and Control (CPC) Program funded a demonstration/validation project to install and evaluate an EOP system at Fort Campbell, KY.

1.2 Objective

The objective of this project was to demonstrate EOP technology in a portion of a concrete visitor's ramp at Campbell Army Airfield and evaluate its effectiveness in preventing ASR-driven concrete degradation.

1.3 Approach

The project team designed, developed, and installed an EOP system in a section of concrete pavement affected by ASR. In addition to installing EOP in the demonstration section, concrete moisture monitoring probes were installed at selected locations. The performance of the EOP system was evaluated by recording the temperature and moisture levels inside the concrete for a period of six months.

The electrical specifications for the EOP ASR mitigation system are (1) anode current density not to exceed 10 mA per square foot of anode surface and (2) EOP applied voltage not to exceed 30V between anode and earth. These specifications conform to national electrical codes to provide system safety (NFPA 2008).

1.4 Metrics

The core metric for this project was to decrease the relative humidity in the concrete to reduce or eliminate alkali-silica reactions in the demonstration structure. The principal criterion for success was to maintain internal concrete relative humidity below 80%. This metric ensures that insufficient moisture is available to support ASR.

In order to quantify this metric, the EOP system was monitored at 32 locations within the concrete test area by using hybrid probes with humidity cells embedded at depths of 2 in., 5 in., and 8 in.

2 Technical Investigation

2.1 Project overview

The demonstration was conducted at Fort Campbell Army Air Field, Kentucky. A previous inspection and associated testing indicated the concrete runway was suffering from ASR deterioration of concrete (USACE TSC 2006). Therefore, an EOP system was designed for the visitor's ramp of Campbell Army Airfield to stop the ASR in the concrete pavement and thereby prevent further expansion of the concrete due to ASR. Concrete temperature and moisture monitoring probes were installed at selected locations. The performance of the EOP system was evaluated by recording the temperature and moisture levels inside the concrete for a period of six months.

2.2 Technology overview

EOP technology offers an effective method to control moisture and prevent water ingress in concrete. In 1809, F.F. Reuss originally described electroosmosis in an experiment that showed that water could be forced to flow through a clay-water system when an external electric field was applied to the soil (Reuss 1809). The basic physics and chemistry of electroosmosis can be found in several textbooks and treatises (e.g. Glasstone 1946 and Tikhomolova 1993).

Research since then has shown that the electric field is initiated by the movement of cations (positively charged ions) in water, presenting in the pore fluid of clay or in similar porous media such as concrete; as the water moves, the cations move with it. The reverse is also possible; the application of an external electric field will cause the water molecules to move via electro-osmosis. Electro-osmosis has been used in civil engineering to de-water dredged and other high water-content waste solids, consolidate clays, strengthen soft sensitive clays, and increase the capacity of pile foundations.

A system has been developed to use EOP technology to reduce moisture within concrete structures by applying a pulsating electric field combined with an off-period. The theory of electro-osmosis and its application to water control in concrete structures is described in McNerney et al. (2002).

The pulsating electro-osmotic sequence consists of a pulse of positive voltage (as seen from the dry side of the concrete), a pulse of negative voltage, and a period of rest when no voltage is applied.¹ The pulse of positive voltage has the greatest duration. The amplitude is typically 20–30 V of direct current (DC).

The electrical pulse causes cations (e.g., Ca^{++}) and associated water molecules to move from the dry side towards the wet side and against the direction of flow induced by the hydraulic gradient, thus preventing water penetration through the concrete structure.² The schematic arrangement of a typical EOP system installed in a basement wall is shown in Figure 1.

Figure 1. Schematic arrangement of a typical EOP system.

The components of an EOP system include anodes, cathodes, power supplies, and monitoring sensors. The EOP system components' individual functions are further defined below:

¹ U.S. Patent 7,135,102 Morefield, Weiss, Malone, Hock, and McInerney, "Method and System for De-watering Particulate Materials," November 14, 2006.

² U.S. Patent 7,935,236 Marshall, Morefield, McInerney, Hock, and Femmer, "Electro-osmotic pulse (EOP) treatment method," May 3, 2011. U.S. Patent 7,135,102.

Anodes are inert, catalytically activated electrodes that are embedded in the dry side of the concrete structure. The anodes provide a positively charged side for the water movement circuit. The anode system is carefully designed to provide an even distribution of charge. Anodes may be in the form of probes (nominally cylindrical in shape), ribbons, or surface-applied meshes. The selected anode type and arrangement is dictated by various engineering aspects including rebar density, concrete type, reinforcement cover, and practical limitations such as the presence of water barriers and obstacles to the system's installation.

Cathodes are copper-based electrodes that are distributed on the wet side of the structure. They may be installed either in the concrete or outside the concrete structure. The cathodes form the negative circuit of the EOP system. Cathodes provide the water collection side of the circuit, and their placement is critical in EOP design.

Power supply is responsible for applying a safe, pulsed, low-voltage, DC electric field between the anodes and cathodes. The power supply's controller utilizes a special waveform that optimizes water transport in the concrete while protecting the embedded rebar from corrosion.

Monitoring sensors are placed within the structure to continuously monitor and regulate the effectiveness of the EOP system. They are used to monitor various parameters such as moisture level, temperature, voltage, current, and corrosion potential.

2.3 Field work

The EOP system was demonstrated in a 100 x 200 ft section of the visitor's ramp at Campbell Army Airfield (shown in Figure 2's outlined area, with close-up of same area shown in Figure 3). There were two individual areas—Area 1 measured 60 x 95 ft, and Area 2 measured 80 x 95 ft, providing a total area of 13,300 sq ft.

Figure 2. Location of EOP trial at Fort Campbell.

Figure 3. Close-up of visitor's ramp area showing locations for EOP trial.

2.3.1 System design

The EOP system's objective was to reduce moisture levels in the concrete to reduce the ASR. Water enters the concrete pavement in two locations—from the surface and from below the surface. Thus, two cathode systems were designed, a surface one (Case 1 in Appendix A) and a soil one (Case 2 in Appendix A).

The probe anodes were installed in the middle of the slab to be capable of providing an electric potential between the anode and the pavement surface, and between the anode and the soil.

As-built drawings of the design and installation are presented in Appendix B. The surface cathodes were installed in parallel with two separate circuits of odd and even runs, as detailed in Figure B16 and Figure B19. The soil cathodes were also installed in parallel by interconnecting seven strings of cathodes, as detailed in Figure B14 and Figure B18.

All probe anodes were connected in parallel with two separate circuits of odd and even runs, as detailed in Figure B17 and Figure B20.

All metallic items within the soil and embedded reinforcement in the concrete were tested for stray current effects and were bonded to the system if found to be affected by stray current. Pipelines or other services were tested. The reinforcement within the EOP zone was bonded. Dowel bars or ancillary steel items were tested for continuity and if necessary, they were bonded.

The trial area of concrete was formerly used for aircraft refueling. As such, the selected slab contained antistatic tie-down points for aircraft grounding. The aircraft antistatic tie-down points consisted of an individual earth rod driven into the soil beneath the slab. The tie-downs were originally isolated from the reinforcement; therefore, they were electrically bonded to the reinforcing steel within the slab which then provided protection via the EOP reinforcing steel connection.

Each sensor of the pavement monitoring system measures two parameters—humidity and temperature. The monitoring system was designed such that performance data collected from each of the installed temperature and humidity sensors is stored for data analysis within the main control unit (MCU).

The MCU is capable of measuring input voltages from the sensors. The analog voltages are converted to digitally calibrated unit values in either degrees Fahrenheit for temperature or as a percentage for humidity.

The MCU also provides overall management by collecting and storing data from the EOP power supplies and the temperature and humidity probes. In the event of an interruption in this communication, there is an onboard microprocessor within each power supply that operates the EOP system within the same parameters set within the MCU.

The unit performs the following functions through onboard programmed protocols:

- Data logging interval (selectable)
- Date and time stamp of logged data
- Graphs of all monitoring sensors

2.3.2 Installation of the EOP technology

Installation of the EOP system required two crews— one crew for drilling, coring, and cutting chases, and one crew installing the EOP components. In addition, an electrical engineer was required to test and commission the system.

The work area was not located on an active runway and was away from the main ramps and refueling area, so no special precautions were needed during the system's installation.

2.3.2.1 Pre-installation preparation

Before installing any system components, it was vital to identify and locate any reinforcing steel in the slab. During this work, the contractor identified dowel bars that were discontinuous from the reinforcing steel and established that the edge slabs were the only slabs that contained a reinforcing steel mat. In addition, there were small reinforcing steel cages around the tie-down's antistatic points.

After locating the reinforcing steel, workers marked chalk lines on the concrete's surface for cutting anode and cathode installation chases. Utilizing the design concepts, the following locations were additionally marked on the concrete's surface:

- Temperature and humidity probe locations
- Cable chases in addition to anode and cathode lines
- Core holes for cathode ground rods

The laid-out EOP field is shown in Figure 4.

Figure 4. Chalk lines on concrete to show EOP field layout.

2.3.2.2 EOP system installation

Slots were cut into the pavement surface for the top-surface mixed metal oxide (MMO) ribbon cathode system and for the connecting wires to the anodes and the below-pavement copper cathodes (Figure 5). All slots were vacuum cleaned of any dust and were also pre-wetted prior to grouting to prevent hydraulic shock to the repair grout.

In Figure 5, cut #1 (under boot) is for the probe anodes' connecting wire, cut #2 (with connection to hole) is for the copper cathode's connecting wire, and cut #3 is for the MMO ribbon (which all go to the east end [top of photo] for connection to the MCU). The hole drilled through the pavement for the below-pavement copper cathodes (foreground of Figure 5) is shown in a close-up in Figure 6.

Figure 5. Pavement cuts for components of EOP system.

Figure 6. Close-up of hole drilled in concrete for copper cathode.

Many more slots were cut into the concrete surface for placement of the MMO ribbons for the top-surface cathode system (Figure 7). All ribbons were spot welded to titanium conductor bars that acted as the primary feeds. A minimum of three welds were made per ribbon/conductor bar connection.

Figure 7. Worker makes many chase cuts for top-surface cathode system (top of photograph is east).

After electrical connection of the MMO ribbons and prior to grouting, the electrical resistance between the anode, copper cathode system, MMO ribbon system, and steel was tested to ensure that all circuits were electrically discontinuous.

The cathodes were grouted in position such that the grouted slot was level and flat with the concrete area's surface (Figure 8). During grouting, the potential difference between the MMO ribbon, probe anode, and steel was constantly monitored for any electrical shorting.

Figure 8. Close-up of grouted MMO ribbon for top-surface cathode system.

The anodes were installed at the center of the concrete slab. The discrete anodes were installed in 1/2 in. diameter holes at the approximate locations shown on the drawings. Prior to drilling the anode holes, the surface of the concrete was tested with a cover meter to ensure that the anodes were placed no closer than 1 in. to any steel reinforcement.

The discrete anodes are made from MMO activated titanium ribbon mesh coiled to form a tube 3/8 in. wide x 5.9 in. long. The anodes were interconnected using AWG (American wire gauge) 17 titanium wire. The conductor bar slots were 1 1/2 in. deep x 3/8 in. wide. The anodes and conductor bars were grouted in position with a free-flowing non-shrink cementitious grout. All slots were cleared of dust and pre-wetted prior to grouting.

Prior to grouting, the electrical resistance between the anode, copper cathode system, MMO ribbon system, and reinforcing steel was tested to ensure there were no short circuits.

The below slab copper cathodes were installed through 4 in. core holes. The standard copper earth rod was driven into the soil and the electrical connection was made using a clamp. The clamp was sealed for moisture ingress and checked for continuity. The cable was brought to the surface and routed within the dedicated slots in the concrete pavement. The core hole within the concrete was then filled with nonconductive epoxy (Figure 9).

Figure 9. Epoxy used to seal hole cut for below-slab cathode.

To prevent stray current corrosion of the reinforcing steel, connections were made to the reinforcing steel located around the edge slab of the trial area. The connecting cable was routed back to the EOP power supply via grooves cut in the concrete pavement.

Dowel bars were found interlinking the sections of the runway together which were discontinuous from the reinforcing steel and were not inter-linked in any way. These were not electrically bonded into the system due to the increased difficulty and cost.

The adjoining and subsurface fuel piping was checked during commissioning for interference and an increase in corrosion potential; no problems were found. No other interference to metallic items were found to be problematic during testing.

2.3.2.3 Monitoring probe installation

A total of 32 temperature and humidity probes were installed. The probes were designed to monitor the temperature and humidity (moisture) at three depths within the concrete slab. This arrangement is detailed in Figure 10. The locations of the probes in the test area are shown in Figure 11 (Area 1) and Figure 12 (Area 2).

Figure 10. Detail of temperature and humidity probes.

Figure 11 shows that probes 1, 4, 6, 7, 9 and 12 were installed outside the EOP zone and within 1 ft. of the boundary (expansion joint), with the exception of probe 7 which was located 20 ft. away from the EOP zone.

Probes 2, 3, 5, 8, 10, 11, 13, 14 and 15 were installed within an EOP zone.

Figure 12 shows that probes 20, 25, 26, 30, and 32 were installed outside the EOP zone and within 1 ft. of the boundary (expansion joint), with the exception that probe 26 was located 20 ft. away from the EOP zone.

Probes 19, 21, 22, 23, 24, 27, 28, 29, and 31 were installed within an EOP zone.

Probes 16, 17, and 18 were installed between both zones and approximately 20 ft. from either EOP zone.

Figure 11. Layout of monitoring probes in Area 1.

Figure 12. Layout of monitoring probes in Area 2.

2.4 Commissioning

2.4.1 Humidity and temperature sensors

System commissioning was carried out from 15 February 2010–14 April 2010. Data from the 32 temperature and humidity probes is presented in Appendix C.

The purpose of the two-month commissioning period was to enable the sensors to attain equilibrium with their surroundings. This period also allowed the team to ascertain if any of the sensors were reporting faulty or sporadic readings. The EOP system was NOT energized during this period.

Table 1 lists the probe sensors commissioning results and shows how many of which type and location of sensor reported faulty or sporadic readings. Table 1 also lists the number of failed sensors as a percentage of the total number of sensors by type and location (32 of each location). The faulty readings could be attributable to moisture ingress into the probes.

Table 1. Summary of faulty probe sensors 15 February–14 April 2010.

	H1	H2	H3	T1
Number of faulty sensors by location	2	7	6	8
Percentage of faulty sensors by location	6%	21%	18%	25%

The data also indicated a general trend of moisture reduction from about 85% to 80% and an increase in concrete temperature from about 35 °F to 80 °F. The increasing atmospheric temperature during this period could explain the rise in temperature inside the concrete slab. See Figure 13 and Figure 14 for examples of humidity and temperature sensor data from two probes—one inside and one outside the EOP zone—during the commissioning period.

Figure 13. Data from probe 4 (outside EOP zone) during commissioning period.

Figure 14. Data from probe 8 (inside EOP zone) during commissioning period.

2.4.2 Pavement crack survey

A pavement survey in the form of photographs is included within this report as Appendix D. The survey was performed in April 2010 prior to energizing the EOP system. Each photograph shows a dimensioned crack from an area of pavement. The intent of surveying the cracks is to encourage re-visiting these same cracks after the EOP system has been in operation for a number of years and to then correlate existing crack patterns with future defects. If the EOP system reduces the moisture within the concrete slab, thereby preventing ASR, then the areas of cracks recorded should not change. Appendix D details the slab section and the exact location and size of the crack when surveyed.

2.5 Performance monitoring/testing

2.5.1 Initial energizing

A complete visual inspection was carried out on the EOP system and all its component parts. It was confirmed that all components and cables were properly installed, labeled, and protected appropriately.

The EOP system was energized on 15 April 2010 after all mortars and grouts had cured for at least 45 days. The following tasks were performed at that time:

- The output voltage and current were recorded for all DC power supplies that were providing current to the EOP system.
- The current supplied to the reinforcing steel was set to ensure no more than 5% of the EOP current was supplied to the steel.
- Data from the temperature and humidity probes were downloaded.

The initial settings of the EOP system are listed in Table 2.

Table 2. Initial settings of EOP system.

	Area 1	Area 2
Mode	Constant current	Constant current
Current	2700 mA	3115 mA
Voltage (maximum)	24 V	24 V
Rebar Current	$R_{CBAA} = 2\%$ (53 mA)	$R_{CBAA} = 1\%$ (30 mA)

2.5.2 Four-month inspection

On 25 August 2010, a complete visual inspection was carried out on the EOP system and all its component parts. It was confirmed that all components and cables were connected and operating properly under the initial power supply settings (Table 2). No changes were made to these settings.

As stated above, data from the power supplies and the temperature and humidity probes were downloaded. Appendix C presents graphs by probe of both sets of data.

The probes were evaluated for functionality. Table 3 presents cumulative details of probe sensor operations through 25 August 2010 and lists the percentage of failures by type and location at that time.

Table 3. Cumulative summary of faulty probe sensors through 25 August 2010.

	H1	H2	H3	T1
Number of faulty sensors by location	2	11	16	12
Percentage of faulty sensors by location	6%	34%	50%	37.5%

2.5.3 Final inspection

The final inspection was conducted 15 January 2011. Data from the power supplies and the temperature and humidity probes were downloaded again. Graphs of both sets of data are presented in Appendix C.

Table 4 presents details of cumulative probe operating results through 15 January 2011 and also lists the percentage of failures by type.

Table 4. Summary of faulty probe sensors through 15 January 2011.

	H1	H2	H3	T1
Number of faulty sensors by location	11	22	24	16
Percentage of faulty sensors by location	24%	39%	75%	50%

3 Discussion

3.1 Results

Nine months of data (15 April 2010–15 January 2011) collected by the monitoring system were analyzed to determine if the system metric was being met. This data includes the internal humidity and temperature sensors and the power supply output voltage and current.

As shown in Table 4, the performance of the internal humidity and temperature sensors was poor. Sensors at location H3 showed a much greater number of faulty sensors than did sensors at locations H1 and H2. It is unclear why there were so many failures. One explanation may be that the probe cavities filled with water, which then damaged the sensors. This explanation also may account for why the lowest-depth sensors had the most failures, and the uppermost had the least.

Data from two probes that were functional throughout the monitoring period—one inside and one outside the EOP zone—are shown in Figure 15 and Figure 16.

Figure 15. Data from probe 1 (inside EOP zone) during the performance period.

Figure 16. Data from probe 23 (outside EOP zone) during the performance period.

The slight reduction in relative humidity corresponds with the increase in temperature during the summer. (If water vapor content stays the same and the temperature rises, relative humidity decreases.) This trend is apparent in both the area inside the EOP zone of influence (Figure 15) and the area outside the EOP zone of influence (Figure 16). Therefore, decreased humidity readings are most likely due to seasonal changes in temperature and not due to the EOP system.

Failure of the humidity probes to show internal concrete moisture reduction is contrasted by the EOP system's power supply data, which suggested the system was effective. Previous studies of EOP system performance have shown that a reduction in recorded power supply current represents a decrease in moisture in the concrete (McInerney et al. 2002).

EOP power supply voltage and current for Areas 1 and 2 are shown in Figure 17 and Figure 18, respectively.

Figure 17. Area 1, EOP power supply voltage and current.

Note: Initial data was missing due to a faulty power supply board. The second set of missing data was due to a power outage.

Figure 18. Area 2, EOP power supply voltage and current.

The power supplies were set in a constant current mode. To maintain a constant current according to Ohm's law,¹ when the resistance of the circuit changes, the voltage must be changed—when the resistance increases, the voltage must be increased; and when the resistance decreases, the voltage must be decreased. Both power supplies showed the voltage increased over the first 6–9 months while the current remained constant. This finding meant the resistance of the circuit (resistivity of the concrete) was increasing. An increase in the concrete's resistivity corresponds to a decrease in its moisture content.

After the power supplies reached their maximum voltage, they could no longer maintain a constant current, so the current decreased as the concrete's moisture content further decreased.

Water in concrete is either (1) chemically bonded (water reacts with cement particles to cause hydration of the cement; or (2) it is physically bonded (water that did not react with cement gives rise to capillary porosity in the concrete). The pores can contain water vapor, water vapor and liquid water, or be fully saturated with water (Quincot et al. 2011).

The EOP system moves liquid water, not water vapor. However, the humidity probes measure water in the vapor state. Therefore, a possible reason for not seeing an EOP effect on humidity in the concrete pore cavities is because the amount of water vapor in the cavity never changed. The basis for the use of humidity probes, however, is that the water vapor in the cavity will equalize with the water vapor in the surrounding concrete. As liquid water is removed, the concrete pores are filled by water vapor from the cavity and vice versa—as the pores fill with liquid water, the water vapor is forced into the cavity. Unfortunately, there are some other processes that may dominate the simple vapor convection process, such as adsorbing of the water vapor to the cement, preventing its movement and the transition of water between its liquid and vapor states.

The reason this method was chosen over other moisture monitoring methods was that measurements could be automated, avoiding the cost and inconvenience of having a technician take measurements and record data.

¹ Ohm's law states that the current moving through a conductor between two points is directly proportional to the voltage across the two points; $V=IR$, where "V" is voltage, "I" is current, and "R" is resistance.

3.2 Lessons learned

There were two lessons learned related to the monitoring system.

3.2.1 Monitoring probes

The multisensor humidity and temperature probes were temperamental and so, they had too many failures. It is also uncertain whether the probes were providing a correct measurement of the concrete's internal relative humidity. Either another method of measuring the internal moisture or some modification of the multisensor probes should be considered.

Quincot et al. (2011) evaluates several methods and gives examples. Electrical resistivity measurements of concrete have also been used to successfully measure moisture content (McInerney et al. 2002).

3.2.2 Probe depth inaccuracies

Probes used in this work were constructed to measure humidity at varying depths, but it appears the lowest-depth humidity sensors were filling with water or condensation and causing faulty readings. Sensor location H3 showed a greater number of faulty readings than locations H1 and H2. Installing independent probes at different depth levels should be considered rather than installing a hybrid probe with varying sensor depths within a single probe as was done in this study. This change in probe type will prevent multicellular failure that was experienced due to sensor failure within a single probe's cavity.

4 Economic Summary

4.1 Costs and assumptions

Total project costs were \$860,000. A rough breakdown of project expenses is presented in Table 5.

Table 5. Breakdown of total project costs.

Description	Amount
Labor	\$123,800
Materials	\$140,000
Contracts	\$536,200
Travel	\$25,000
Reporting	\$25,000
Air Force and Navy participation	\$10,000
Total	\$860,000

A breakdown of the contracts portion (\$536,200) of the total cost for this CPC project is shown in Table 6.

Table 6. Project field demonstration costs.

Item	Description	Amount
1	Labor for project management and execution	\$65,880
2	Travel for project management	\$11,900
3	Cost for equipment and materials	\$109,300
4	Labor and travel costs for installation	\$67,620
5	Cost for monitoring performance	\$281,500
	Total	\$536,200

The EOP system was installed in a total area of 13,300 sq ft of the concrete ramp. The system's installation required a total of 1,935 labor hours, which was split between 5 field laborers, 1 project manager, 1 engineer, and 5 subcontracted skilled laborers. The total cost for contract labor was \$37,268, and travel costs for this crew-were \$30,353. The contractor's costs for materials and equipment totaled \$109,300. The costs for the EOP system's materials and installation is approximately \$13.30 per square foot (before monitoring). The total cost including monitoring was \$458,420 or approximately \$34.47 per square foot.

Using location data from the USACE report on Alkali-Aggregate Problems on Portland Cement Concrete Airfield Pavements (USACE TSC et.al. 2006) of some of the worst DoD alkali-aggregate airfield pavement problems; dimension data from Air AIRNAV.com and Google Earth, and making a conservative estimate on the extent of the problem, the DoD could have at least 26,600,000 sq ft of comprised runway, taxiway, and parking aprons¹.

4.1.1 Alternative 1 (Baseline scenario)

The annual maintenance and rehabilitation (M&R) costs for the trial area's ASR-affected pavement is estimated at \$40K. This cost includes an estimated 2 hr of labor daily to remove foreign objects and debris (FOD) from the runways and taxiways, cut expanded concrete to relieve slabs impacting each other, remove pressed-out joint sealants, remove spall materials that can be caught up in drafts from aircraft engines and rotors, and fill crackss.

In this baseline scenario, a total of 1.0M sq ft of ASR-compromised runway and taxiway is replaced. The estimated total cost to replace the pavement is \$21.70 per square foot, which equals square-foot costs of \$12.39 to remove the old pavement and \$9.31 to install the new. These cost estimates were developed from RSMeans (2007) data. Thus the total cost of replacement in the baseline scenario is calculated to be \$21.7M.

The cost to maintain the new concrete pavement will be \$10K per year (150 hr of labor plus patching materials), with the cost increasing by \$500 per year.

4.1.2 Alternative 2 (Demonstrated technology)

In this scenario, the total cost to install an EOP system in 1.0M sq ft of ASR-compromised runway and taxiway is \$15M or \$15 per square foot. The EOP system will last 20 years. At year 21, the EOP system will require a major overhaul at one-half the cost (\$7.50 per square foot) of a new system.

¹ The 13 Air Force Bases identified in the report were used to determine a lower estimate of total ASR comprised pavement. Total square footage of runways, taxiways and parking aprons was estimated for these bases using data from Air AIRNAV.com and Google Earth. Total area was 266,000,000 ft². A conservative value of 10% of this pavement is estimated to be comprised by ASR.

There is an annual maintenance cost of \$2K for the first 10 years of EOP operation, and \$4K per year for the second 10 years of operation.

The annual cost to maintain the concrete pavement once the EOP system is installed will be the same as maintaining new pavement—\$10K per year (150 hr labor plus patching materials), increasing by \$500 per year.

There is a new system savings of \$40K per year due to avoidance of the annual M&R cost for an ASR-affected pavement.

4.2 Return on investment computation

The return on investment (ROI) for this technology was computed by using methods prescribed by Office of Management and Budget (OMB) Circular No. A-94, *Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs* (OMB 1994). After comparing the costs and benefits of the two alternatives, the 30-year ROI is projected to be about 5.68, as shown in Table 7.

The original ROI estimate from the project management plan [PMP]) was 93.40. The large difference between the initial and final ROI projections is because the original ROI estimate included an impact on readiness cost of \$25.2M whenever the pavement is replaced or repaired. Further research found that airfields have multiple runways and taxiways, so troops will not be displaced during pavement replacement and repair.

Table 7. ROI calculation.

Return on Investment Calculation

Investment Required

860,000Return on Investment Ratio **5.68**Percent **568%**Net Present Value of Costs and Benefits/Savings 16,028,394 20,909,272 **4,880,878**

A Future Year	B Baseline Costs	C Baseline Benefits/Savings	D New System Costs	E New System Benefits/Savings	F Present Value of Costs	G Present Value of Savings	H Total Present Value
1	21,700,000		15,000,000		14,019,000	20,280,820	6,261,820
2	10,000		12,000	40,000	10,481	43,670	33,189
3	10,500		12,500	40,000	10,204	41,223	31,019
4	11,000		13,000	40,000	9,918	38,908	28,990
5	11,500		13,500	40,000	9,626	36,720	27,094
6	12,000		14,000	40,000	9,328	34,648	25,319
7	12,500		14,500	40,000	9,029	32,692	23,663
8	13,000		15,000	40,000	8,730	30,846	22,116
9	13,500		15,500	40,000	8,430	29,099	20,668
10	14,000		16,000	40,000	8,133	27,448	19,315
11	14,500		16,500	40,000	7,839	25,893	18,054
12	15,000		19,000	40,000	8,436	24,420	15,984
13	15,500		19,500	40,000	8,093	23,033	14,940
14	16,000		20,000	40,000	7,756	21,717	13,961
15	16,500		20,500	40,000	7,429	20,476	13,046
16	17,000		21,000	40,000	7,113	19,306	12,193
17	17,500		21,500	40,000	6,807	18,205	11,398
18	18,000		22,000	40,000	6,510	17,162	10,652
19	18,500		22,500	40,000	6,221	16,175	9,954
20	19,000		23,000	40,000	5,943	15,246	9,302
21	19,500		7,519,500	40,000	1,815,959	14,369	-1,801,590
22	20,000		22,000	40,000	4,965	13,542	8,577
23	20,500		22,500	40,000	4,745	12,759	8,014
24	21,000		23,000	40,000	4,533	12,023	7,490
25	21,500		23,500	40,000	4,329	11,328	7,000
26	22,000		24,000	40,000	4,133	10,676	6,544
27	22,500		24,500	40,000	3,942	10,056	6,114
28	23,000		25,000	40,000	3,760	9,475	5,715
29	23,500		25,500	40,000	3,585	8,928	5,343
30	24,000		26,000	40,000	3,416	8,410	4,993

5 Conclusions and Recommendations

5.1 Conclusions

The ability of the EOP system to mitigate alkali-silica reaction (ASR) is inconclusive. Although there are indications that moisture is being removed from the concrete pavement, it is not clear that the internal relative humidity has been reduced below 80%—the value that will ensure that insufficient moisture is available to allow the ASR to occur. Further monitoring is required.

The multisensor humidity and temperature probes were temperamental and had too many failures. It is also uncertain that they were providing a correct measurement of the concrete's internal relative humidity. Either another method of measuring the internal moisture or modification of the multisensor probes must be considered. Quincot et al. (2011) evaluate several methods and provide examples. Electrical resistivity measurements of concrete have also been used to successfully measure moisture content (McInerney et al. 2002).

Due to the volume of concrete and the amount of moisture present, the period of monitoring appears to have been too short to fully evaluate the efficacy of EOP for ASR mitigation. There are many variables that affect the length of time necessary to demonstrate success.

5.2 Recommendations

5.2.1 Applicability

Although this project addressed the application of EOP technology specifically to reduce ASR in airfield pavements, this technology is applicable to any concrete pavement or other concrete structure suffering from ASR. The method of execution will depend on the type of concrete, the type of structure, and the environment.

5.2.2 Implementation

The results of this demonstration are inconclusive in showing that EOP technology can reduce ASR in concrete pavements. Thus, this technology currently is not recommended for widespread implementation. Since the electrokinetic process (the basis of EOP technology) is a slow process, a

long-term approach for performance monitoring must be completed before the technology can be accepted.

Criteria and resource documents that could be updated based on a successful demonstration of this technology in mitigating ASR would be the following:

1. ETL 06-2 Alkali-Aggregate Reaction in Portland-Cement Concrete (PCC) Airfield Pavements: This ETL provides guidance on identification, maintenance, and avoidance of alkali-aggregate reaction problems in Air Force PCC airfield pavements. It provides (1) testing protocols for identifying potentially reactive aggregate, and (2) required mitigation actions if such aggregates are used in PCC for airfields.
2. Resources on ASR from the Federal Highway Administration (FHWA) at www.fhwa.dot.gov/pavement/concrete/asr/resources. One such resource is FHWA-HIF-13-019, *Alkali-Aggregate Reactivity (AAR) Facts Book* (Thomas et al. March 2013). This document provides detailed information on AAR. It fully discusses ASR by covering chemistry, symptoms, test methods, prevention, specifications, diagnosis and prognosis, and mitigation. Alkali-carbonate reaction (ACR) is also addressed.

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Appendix A: Design Calculations

A finite element analysis approximation was conducted using a commercial package for DC Conduction, Tera Analysis Finite Element Analysis.¹ Details of the analysis are shown in Case 1 and Case 2.

Case 1

The EOP system utilizes ribbon anodes in the upper surface of the slab and copper cathode rods in the soil (Figure A1).

Case 2

The EOP system utilizes ribbon cathodes in the upper surface of the slab, anode rods in the center of the slab and copper cathode rods in the soil (Figure A2).

¹ Tera Analysis Ltd, Svendborg, Denmark.

Figure A1. Case 1: The EOP system utilizes ribbon anodes in the upper surface of the slab and copper cathode rods in the soil beneath slab.

Assumptions

1. Concrete resistivity = 500,000 Ohm.cm
(Note: after period of EOP operation)
2. Soil resistivity = 50,000 Ohm.cm
3. Cathode copper rod = 1 inch x 1 ft
4. 30VDC applied between anode and cathode

Conclusion

Operation of EOP system with 3ft spacing on anodes and 3ft spacing of cathodes should result in drying of slab. Area with low current density between anodes would dry as a result of diffusion and equilibrium conditions to balance drying effects in concrete.

Figure A2. Case 2: The EOP system utilizes ribbon cathodes in the upper surface of slab, anode rods in the center of the slab, and copper cathode rods in the soil beneath slab.

Appendix B: As-Built Drawings and Component Specifications

Drawings

This appendix contains a set of engineering drawings and specifications for the EOP system. The drawings are presented to show how the system design of Appendix A was implemented. The drawings and specifications were completed by ELECTROTECHCP UK.

Tables B-1 and B-2 list the drawings included in this appendix. Figures B1 through B13 show the unit layout and wiring for the EOP control and sensor monitoring systems. For the system installed at Fort Campbell there are four units housed in one large enclosure; one main control unit, two EOP control units, and one data acquisition unit.

Figures B14 through B20 detail the cathode, anode, and monitoring probe layouts for EOP trial areas 1 and 2. The drawings also include installation notes and guidelines.

Table B1. Fort Campbell EOP, Project C1538 Drawing register (Electro-Tech CP).

Drawing No.	Drawing Title	REV 00	REV 01
C1538-QC40-S-001-01/L	MAIN CONTROL UNIT GENERAL ASSEMBLY DRAWING	04 SEP 09	26 OCT 09
C1538-QC40-S-002-00/L	MAIN CONTROL UNIT WIRING SCHEMATIC	04 SEP 09	26 OCT 09
C1538-QC40-S-003-00/L	DATA ACQUISITION UNIT (DAQ) GENERAL ARRANGEMENT	04 SEP 09	26 OCT 09
C1538-QC40-S-004-00/L	DAQ WIRING SCHEMATIC: VAC	04 SEP 09	26 OCT 09
C1538-QC40-S-005-00/L	DAQ WIRING SCHEMATIC: DC	04 SEP 09	26 OCT 09
C1538-QC40-S-006-00/L	DAQ WIRING SCHEMATIC: MONITORING	04 SEP 09	26 OCT 09
C1538-QC40-S-007-00/L	DAQ DIN RAIL LAYOUT	04 SEP 09	26 OCT 09
C1538-QC40-S-008-00/L	EOP UNIT GENERAL ARRANGEMENT DRAWING	04 SEP 09	26 OCT 09
C1538-QC40-S-009-00/L	EOP UNIT WIRING SCHEMATIC: AC	14 SEP 09	26 OCT 09
C1538-QC40-S-010-01/L	EOP UNIT WIRING SCHEMATIC: DC	14 SEP 09	26 OCT 09
C1538-QC40-S-011-00/L	EOP UNIT WIRING SCHEMATIC: DC	14 SEP 09	26 OCT 09
C1538-QC40-S-012-00/L	EOP UNIT GENERAL TRAFOLITE FASCIA	14 SEP 09	25 OCT 09
C1538-QC40-S-014-00/L	CABINET LAYOUT DRAWING	08 SEP 09	26 OCT 09

Figure B1. Main control unit, general assembly layout (Electro-Tech CP).

Figure B2. Main control unit, wiring schematic (Electro-Tech CP).

AS BUILT

[illegible]

ERDC/CERL TR-19-18

Figure B4. Data acuisition unit, wiring schematic VAC (Electro-Tech CP).

AS BUILT

01	AS BUILT	LD	PRW	PRW	24 SEP 09
02	FIRST ISSUE	LD	PRW	PRW	24 SEP 09
REV	ISSUED FOR	BY	CHKD	APRD	DATE
ELECTROTECHCP (UK) 5B DUNST WAY DUNST ROAD GRANTHAM LINCOLNSHIRE NG16 7JG UNITED KINGDOM

+44 (0) 1476 563 630 PRODUCTION@ELECTROTECHCP.COM					
DRAWN	LD	CHECKED	PRW	APPROVED	PRW
DATE	04 SEP 09	DATE	04 SEP 09	DATE	04 SEP 09
OWNER	CONSTRUCTION ENGINEERING RESEARCH LABORATORY (CERL)				
PROJECT	FORT CAMPBELL EOP				
CLIENT	ELECTROTECHCP, LLC				
DRAWING	DAQ UNIT WIRING SCHEMATIC VAC				
PROJECT	C1538				
DOCUMENT NO	C11538-0040-S-004-000/L				

Figure B5. Data acquisition unit, wiring schematic DC (Electro-Tech CP).

AS BUILT

01	AS BUILT	LMR	PRTW	PRTW	28 OCT 08
00	FIRST ISSUE	LD	PRTW	PRTW	24 SEP 08
REV	ISSUED FOR	BY	CHKD	APPR	DATE

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PRODUCTION@ELECTROTECHCP.COM

DRAWN	LD	CHECKED	PRTW	APPROVED	PRTW	SCALE
DATE	04 SEP 08	DATE	04 SEP 08	DATE	04 SEP 08	NTS
OWNER	CONSTRUCTION ENGINEERING RESEARCH LABORATORY (CERL)					
PROJECT	FORT CAMPBELL ERP					
CLIENT	ELECTROTECHCP LLC					
DRAWING TITLE	DAQ UNIT WIRING SCHEMATIC: DC					
PROJECT NO.	C1538					
DOCUMENT NO	C11538-01C410-S-005-007/L					

Figure B7. Data acquisition unit, DIN rail layout (Electro-Tech CP).

PROBE 1				PROBE 17			
DI	700-2-1	700-2-0/P14-0V	DI	700-16-1	700-16-0/P17-0V	DI	700-16-0
TEMP-1	P1-11		TEMP-1	P17-11		TEMP-1	P17-11
TEMP-2	P1-12		TEMP-2	P17-12		TEMP-2	P17-12
IDENTITY-1	P1-14		IDENTITY-1	P17-14		IDENTITY-1	P17-14
TEMP-3	P1-13		TEMP-3	P17-13		TEMP-3	P17-13
PROBE 2				PROBE 18			
DI	700-3-1	700-3-0/P24-0V	DI	700-18-1	700-18-0/P18-0V	DI	700-18-0
TEMP-1	P2-11		TEMP-1	P18-11		TEMP-1	P18-11
TEMP-2	P2-12		TEMP-2	P18-12		TEMP-2	P18-12
IDENTITY-1	P2-14		IDENTITY-1	P18-14		IDENTITY-1	P18-14
TEMP-3	P2-13		TEMP-3	P18-13		TEMP-3	P18-13
PROBE 3				PROBE 19			
DI	700-4-1	700-4-0/P34-0V	DI	700-20-1	700-20-0/P19-0V	DI	700-20-0
TEMP-1	P3-11		TEMP-1	P19-11		TEMP-1	P19-11
TEMP-2	P3-12		TEMP-2	P19-12		TEMP-2	P19-12
IDENTITY-1	P3-14		IDENTITY-1	P19-14		IDENTITY-1	P19-14
TEMP-3	P3-13		TEMP-3	P19-13		TEMP-3	P19-13
PROBE 4				PROBE 20			
DI	700-5-1	700-5-0/P44-0V	DI	700-21-1	700-21-0/P20-0V	DI	700-21-0
TEMP-1	P4-11		TEMP-1	P20-11		TEMP-1	P20-11
TEMP-2	P4-12		TEMP-2	P20-12		TEMP-2	P20-12
IDENTITY-1	P4-14		IDENTITY-1	P20-14		IDENTITY-1	P20-14
TEMP-3	P4-13		TEMP-3	P20-13		TEMP-3	P20-13
PROBE 5				PROBE 21			
DI	700-6-1	700-6-0/P54-0V	DI	700-22-1	700-22-0/P21-0V	DI	700-22-0
TEMP-1	P5-11		TEMP-1	P21-11		TEMP-1	P21-11
TEMP-2	P5-12		TEMP-2	P21-12		TEMP-2	P21-12
IDENTITY-1	P5-14		IDENTITY-1	P21-14		IDENTITY-1	P21-14
TEMP-3	P5-13		TEMP-3	P21-13		TEMP-3	P21-13
PROBE 6				PROBE 22			
DI	700-7-1	700-7-0/P64-0V	DI	700-23-1	700-23-0/P22-0V	DI	700-23-0
TEMP-1	P6-11		TEMP-1	P22-11		TEMP-1	P22-11
TEMP-2	P6-12		TEMP-2	P22-12		TEMP-2	P22-12
IDENTITY-1	P6-14		IDENTITY-1	P22-14		IDENTITY-1	P22-14
TEMP-3	P6-13		TEMP-3	P22-13		TEMP-3	P22-13
PROBE 7				PROBE 23			
DI	700-8-1	700-8-0/P74-0V	DI	700-24-1	700-24-0/P23-0V	DI	700-24-0
TEMP-1	P7-11		TEMP-1	P23-11		TEMP-1	P23-11
TEMP-2	P7-12		TEMP-2	P23-12		TEMP-2	P23-12
IDENTITY-1	P7-14		IDENTITY-1	P23-14		IDENTITY-1	P23-14
TEMP-3	P7-13		TEMP-3	P23-13		TEMP-3	P23-13
PROBE 8				PROBE 24			
DI	700-9-1	700-9-0/P84-0V	DI	700-25-1	700-25-0/P24-0V	DI	700-25-0
TEMP-1	P8-11		TEMP-1	P24-11		TEMP-1	P24-11
TEMP-2	P8-12		TEMP-2	P24-12		TEMP-2	P24-12
IDENTITY-1	P8-14		IDENTITY-1	P24-14		IDENTITY-1	P24-14
TEMP-3	P8-13		TEMP-3	P24-13		TEMP-3	P24-13
PROBE 9				PROBE 25			
DI	700-10-1	700-10-0/P94-0V	DI	700-26-1	700-26-0/P25-0V	DI	700-26-0
TEMP-1	P9-11		TEMP-1	P25-11		TEMP-1	P25-11
TEMP-2	P9-12		TEMP-2	P25-12		TEMP-2	P25-12
IDENTITY-1	P9-14		IDENTITY-1	P25-14		IDENTITY-1	P25-14
TEMP-3	P9-13		TEMP-3	P25-13		TEMP-3	P25-13
PROBE 10				PROBE 26			
DI	700-11-1	700-11-0/P104-0V	DI	700-27-1	700-27-0/P26-0V	DI	700-27-0
TEMP-1	P10-11		TEMP-1	P26-11		TEMP-1	P26-11
TEMP-2	P10-12		TEMP-2	P26-12		TEMP-2	P26-12
IDENTITY-1	P10-14		IDENTITY-1	P26-14		IDENTITY-1	P26-14
TEMP-3	P10-13		TEMP-3	P26-13		TEMP-3	P26-13
PROBE 11				PROBE 27			
DI	700-12-1	700-12-0/P114-0V	DI	700-28-1	700-28-0/P27-0V	DI	700-28-0
TEMP-1	P11-11		TEMP-1	P27-11		TEMP-1	P27-11
TEMP-2	P11-12		TEMP-2	P27-12		TEMP-2	P27-12
IDENTITY-1	P11-14		IDENTITY-1	P27-14		IDENTITY-1	P27-14
TEMP-3	P11-13		TEMP-3	P27-13		TEMP-3	P27-13
PROBE 12				PROBE 28			
DI	700-13-1	700-13-0/P124-0V	DI	700-29-1	700-29-0/P28-0V	DI	700-29-0
TEMP-1	P12-11		TEMP-1	P28-11		TEMP-1	P28-11
TEMP-2	P12-12		TEMP-2	P28-12		TEMP-2	P28-12
IDENTITY-1	P12-14		IDENTITY-1	P28-14		IDENTITY-1	P28-14
TEMP-3	P12-13		TEMP-3	P28-13		TEMP-3	P28-13
PROBE 13				PROBE 29			
DI	700-14-1	700-14-0/P134-0V	DI	700-30-1	700-30-0/P29-0V	DI	700-30-0
TEMP-1	P13-11		TEMP-1	P29-11		TEMP-1	P29-11
TEMP-2	P13-12		TEMP-2	P29-12		TEMP-2	P29-12
IDENTITY-1	P13-14		IDENTITY-1	P29-14		IDENTITY-1	P29-14
TEMP-3	P13-13		TEMP-3	P29-13		TEMP-3	P29-13
PROBE 14				PROBE 30			
DI	700-15-1	700-15-0/P144-0V	DI	700-31-1	700-31-0/P30-0V	DI	700-31-0
TEMP-1	P14-11		TEMP-1	P30-11		TEMP-1	P30-11
TEMP-2	P14-12		TEMP-2	P30-12		TEMP-2	P30-12
IDENTITY-1	P14-14		IDENTITY-1	P30-14		IDENTITY-1	P30-14
TEMP-3	P14-13		TEMP-3	P30-13		TEMP-3	P30-13
PROBE 15				PROBE 31			
DI	700-16-1	700-16-0/P154-0V	DI	700-32-1	700-32-0/P31-0V	DI	700-32-0
TEMP-1	P15-11		TEMP-1	P31-11		TEMP-1	P31-11
TEMP-2	P15-12		TEMP-2	P31-12		TEMP-2	P31-12
IDENTITY-1	P15-14		IDENTITY-1	P31-14		IDENTITY-1	P31-14
TEMP-3	P15-13		TEMP-3	P31-13		TEMP-3	P31-13
PROBE 16				PROBE 32			
DI	700-17-1	700-17-0/P164-0V	DI	700-33-1	700-33-0/P32-0V	DI	700-33-0
TEMP-1	P16-11		TEMP-1	P32-11		TEMP-1	P32-11
TEMP-2	P16-12		TEMP-2	P32-12		TEMP-2	P32-12
IDENTITY-1	P16-14		IDENTITY-1	P32-14		IDENTITY-1	P32-14
TEMP-3	P16-13		TEMP-3	P32-13		TEMP-3	P32-13
COMMS				COMMS			
DI	EL-20A		DI	EL-20B		DI	EL-20B
TEMP-1	EL-20A		TEMP-1	EL-20A		TEMP-1	EL-20A
TEMP-2	EL-20A		TEMP-2	EL-20A		TEMP-2	EL-20A
IDENTITY-1	EL-20A		IDENTITY-1	EL-20A		IDENTITY-1	EL-20A
TEMP-3	EL-20A		TEMP-3	EL-20A		TEMP-3	EL-20A

Figure B8. EOP unit, general arrangement layout (Electro-Tech CP).

AS BUILT

01	AS BUILT	LD	PRIN	PRIN	04 SEP 06
02	FIRST ISSUE	LD	PRIN	PRIN	04 SEP 06
REV	ISSUED FOR	BY	CHKD	APPD	DATE
ELECTROTECHCP (UK) 36 DOWNS WAY CHESANT ROAD GROUNTHAM LINCOLNSHIRE NG31 7EL UNITED KINGDOM					
+44 (0) 1478 563 630 PRODUCTION@ELECTROTECHCP.COM					
DRAWN	LD	CHECKED	PRIN	APPROVED	SCALE
DATE	04 SEP 06	DATE	04 SEP 06	DATE	04 SEP 06
CHKD	NTS	DATE	04 SEP 06	DATE	04 SEP 06
OWNER CONSTRUCTION ENGINEERING RESEARCH LABORATORY (CERL)					
PROJECT FORT CAMPBELL EOP					
CLIENT ELECTROTECHCP LLC					
DESIGN EOP UNIT GENERAL ARRANGEMENT DRAWING					
PROJECT 01538					
DOCUMENT NO.					
C11538-0C40-S-008-00/L					

B9. EOP unit, wiring schematic AC (Electro-Tech CP).

AS BUILT

D1	AS BUILT	LMD	PRTW	PRTW	14 SEP 09
D2	FIRST ISSUE	LMS	PRTW	PRTW	14 SEP 09
REV	ISSUED FOR	BY	CHKD	APPD	DATE
ELECTROTECHCP (UK)					
38 DYSART WAY					
FRANTHAM					
LINCOLNSHIRE					
NG31 7EL					
UNITED KINGDOM					
+44 (0) 1476 593 630					
PRODUCTION@ELECTROTECHCP.COM					
DRAWN	LMS	CHECKED	PRTW	APPROVED	PRTW
DATE	14 SEP 09	DATE	14 SEP 09	DATE	14 SEP 09
OWNER: ODINSTRUCTION ENGINEERING RESEARCH LABORATORY (ODRL)					
PROJECT: FORT CAMPBELL EOP					
CLIENT: ELECTROTECHCP LLC					
DRAWING: EOP UNIT WIRING SCHEMATIC AC					
PROJECT NO: C11538					
DOCUMENT NO					
C11538-01C410-S-0109-0107/L					

Figure B10. EOP unit, wiring schematic DC (Electro-Tech CP).

AS BUILT

01	AS BUILT	LMB	PRTW	PRTW	26 SEP 08
02	FIRST ISSUE	LMB	PRTW	PRTW	14 SEP 09
REV	ISSUED FOR	BY	CHKD	APPRD	DATE

electro tech CP

444 03 1476 925 830
PRODUCTION@ELECTROTECH-CP.COM

DRAWN	LMB	CHECKED	PRTW	APPROVED	PRTW	SCALE
DATE	14 SEP 09	DATE	14 SEP 09	DATE	14 SEP 09	NTS

OWNER: CONSTRUCTION ENGINEERING RESEARCH LABORATORY (CERL)

PROJECT: FORT CAMPBELL EOP

CLIENT: ELECTROTECH CP, LLC

DRAWN: EOP UNIT WIRING SCHEMATIC DC

PROJECT NO: C11538

DOCUMENT NO

C11538-QC40-S-0110-011/L

ERDC/CERL TR-19-18

B12. EOP unit, general trafolite fascia (Electro-Tech CP).

B13. EOP units, cabinet layout drawing (Electro-Tech CP).

AS BUILT

01	AS BUILT	DATE	DATE	DATE	DATE	DATE	DATE	DATE	DATE
02	DESIGN	DATE	DATE	DATE	DATE	DATE	DATE	DATE	DATE
03	ISSUED FOR	DATE	DATE	DATE	DATE	DATE	DATE	DATE	DATE
ELECTROTECHCP (UK)									
30 CHURCH WAY									
STANTON ROAD									
BROOKHURST									
ENCLOSURE									
N53 7E									
UNIT 10 KINCORP									
+44 (0) 1475 855 830									
PRODUCTS@ELECTROTECHCP.COM									
DESIGN	DATE	CHECKED	DATE	APPROVED	DATE	SCALE			
DATE	OR REP. ON	DATE	OR REP. ON	DATE	OR REP. ON	DATE			
OWNER: CONSTRUCTION ENGINEERING RESEARCH LABORATORY (CERL)									
PROJECT: TOTT CAMPBELL EOP									
CLIENT: ELECTROTECHCP LTD									
DRAWING: CABINET LAYOUT DRAWING									
PROJECT NO: C1538									
DOCUMENT NO									
C1538 Q C 4 0 S 0 1 4 0 0 1									

Table B2. Fort Campbell EOP, Project C42666 Drawing register (Electro-Tech CP).

FORT CAMPBELL EOP TRIAL [C42666]			
DRAWING NUMBER	DRAWING TITLE	REV A	REV Z (AS BUILT)
C42666-000	DRAWING REGISTER	8/4/2010	8/4/2010
C42666-001	TRIAL AREA 1 - COPPER CATHODE LAYOUT	8/4/2010	8/4/2010
C42666-002	TRIAL AREA 1 - MMO CATHODE LAYOUT	8/4/2010	8/4/2010
C42666-003	TRIAL AREA 1 - ANODE LAYOUT	8/4/2010	8/4/2010
C42666-004	TEMPERTURE AND HUMIDITY PROBE LAYOUT	8/4/2010	8/4/2010
C42666-005	TRIAL AREA 2 - COPPER CATHODE LAYOUT	8/4/2010	8/4/2010
C42666-005	TRIAL AREA 2 - MMO CATHODE LAYOUT	8/4/2010	8/4/2010
C42666-007	TRIAL AREA 2 - ANODE LAYOUT	8/4/2010	8/4/2010

Figure B14. Trial Area 1, copper cathode layout (Electro-TECH CP).

ERDC/CERL TR-19-18

WIRING DETAILS

DETAIL A

NOTES:

- 1 Wiring details to be carried out in Slabs 14EH, 14EI, 14EJ, 18EH, 18EI & 18EJ
- 2 Cables to be **HMWPE BLACK 14AWG**
- 3 2 # Cables to be routed back to EOP Power Supply Unit
- 4 Detail A is to consist of Heatshrink Crimp and adhesive lined heatshrink
- 5 Insulation Resistance checks at 500V to be carried out to all connections
- 6 All cables are to be routed in dedicated cable chases.
- 7 All cables are to be separated within chase by a minimum of $\frac{1}{2}$ "
- 8 Cables are to be securely fastened to concrete deck with non metallic fixing

[illegible]

Figure B16. Trial Area 1, anode layout (Electro-TECH CP).

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ERDC/CERL TR-19-18

ERDC/CERL TR-19-18

WIRING DETAILS

DETAIL A

NOTES:

- 1 Wiring details to be carried out in Slabs 14EH, 14EI, 14EJ, 18EH, 18EI & 18EJ
- 2 Cables to be HMWPE BLACK 14AWG
- 3 2 # Cables to be routed back to EOP Power Supply Unit
- 4 Detail A is to consist of Heatshrink Crimp and adhesive lined heatshrink
- 5 Insulation Resistance checks at 500V to be carried out to all connections
- 6 All cables are to be routed in dedicated cable chases.
- 7 All cables are to be separated within chase by a minimum of $\frac{1}{2}$ "
- 8 Cables are to be securely fastened to concrete deck with non metallic fixing

[illegible]

ERDC/CERL TR-19-18

The design specifications used for the EOP system and materials are listed below.

Design life

The design life of the trial system is dictated by the service life of the individual components, as listed below:

- Anode system—20 years
- Cathode system—20 years
- Monitoring system & electrical installation—20 years
- Humidity and temperature monitoring sensors—5 years

MMO top surface cathode system

The MMO cathode system was installed in slots in the concrete surface using MMO Activated Grade 1 Titanium. The MMO cathode selected was Elgard Type 100 Anode ribbon with a theoretical life in excess of 20 years. The cathodes were grouted in position with BASF 928 material such that the grouted slot was level and flat with the runway surface.

Copper ground cathode system

The Copper cathode system uses 5/8 in. diameter copper grounding rods that are 1-ft in length. Each copper cathode was fitted to a titanium cable conductor that was used to link the copper cathodes. The titanium cable to copper cathode connection was sealed and insulated with epoxy resin prior to installation. The minimum cable size was 17 AWG.

EOP anode system

The anode system has a minimum design working life of 20 years and is made of an MMO-activated Grade 1 titanium, suitable for direct embedment in concrete.

The anode system was installed with using 6 in. long x 3/8 to 1/2 in. diameter tubular anodes or MMO ribbon anode formed into tubes 6 in. long x 3/8 to 1/2 in.

The anodes were installed at the midpoint of the concrete slab and grouted in using BASF 928 non-polymer modified cementitious grout. The cable for linking the anodes was a minimum of AWG 17 Grade 1 titanium.

Titanium conductor bar

A titanium conductor bar was used to link with the top-surface cathode system. The conductor bar is 1/2 in. wide x 0.035 in. long and the ribbon is Grade 1 titanium. The design life of the titanium conductor bar is in excess of 20-years.

Insulated titanium wire

Type 1 insulated titanium wire 17 AWG was used to connect the discrete probe anodes in a ring circuit.

Monitoring sensors

The trial had 32 humidity and temperature monitoring probes that measured the interior concrete temperature and relative humidity at 2 in., 5 in., and 8 in. depths. The probes were custom-made for the project, as detailed in Figure 10, and have a design life of approximately 5-years.

DC cables

All single-core field cables used for the cathodes, reinforcing steel, and anodes were #14 AWG stranded copper with high molecular weight polyethylene (HMWPE) insulation.

Power Supply Unit (PSU)

The EOP power supplies were housed within two separate cabinets. The cabinets were connected to the main control cabinet for communications and control. Each power supply cabinet controls a separate trial area and has a maximum output of 12A at 30V. The electrical schematic for each power supply is shown in drawing C1538-QC40-S-009-00/L (Figure B9).

Miscellaneous electrical equipment

The subcontractor provided specifications for all wiring, cabling, electrical conduit fittings, and junction boxes that were used for the EOP and monitoring systems.

All buried wiring used for the anode, cathode and reinforcing steel connections was coated with HMWPE insulation.

The electrical cable for each monitoring probe was a multi-core integral cable long enough to reach the data acquisition unit without being spliced.

Appendix C: Slab Monitoring Probes, EOP Power Supplies, and Weather Data

This appendix presents the data for the in-slab monitoring probes. The records are divided into two periods, commissioning and performance. Commissioning was carried out from 15 February 2010—14 April 2010. During this period the EOP system was NOT energized. The performance period directly followed the commissioning period and lasted for nine months (15 April 2010—15 January 2011). During the performance period the EOP system was energized.

The purpose of the two-month commissioning period was to enable the sensors to attain equilibrium with their surroundings. This period also allowed the team to ascertain if any of the sensors were reporting faulty or sporadic readings.

A total of 32 temperature and humidity probes were installed. The probes were designed to monitor the temperature and humidity (moisture) at three depths within the concrete slab. This arrangement is detailed in Figure 10. The locations of the probes in the test areas are shown in Figure 11.

The EOP influenced zones are bounded by the bold lines and include slab sections 14EH – 18EH, 14EI – 18EI, and 14EJ – 18EJ for Trial Area 1 and 14EM – 18EM, 14EN – 18EN, 14EO – 18EO, 14EPM – 18EP for Trial Area 2.

Trial Area 1 measured 60 x 95 ft (5,700 sq ft). There are 15 monitoring probes within Area 1. Probes 1, 4, 6, 7, 9, and 12 were installed outside the EOP influenced zone and within 1 ft of an expansion joint, with the exception of Probe 7 which was installed 20 ft away from the expansion joint.

Probes 2, 3, 5, 8, 10, 11, 13, 14, and 15 were installed within the EOP influenced zone.

Trial Area 2 measured 80 x 95 ft (7,600 sq ft). There are 14 monitoring probes within Area 2. Probes 20, 25, 26, 30, and 32 were installed outside the EOP influenced zone within 1 ft of an expansion joint, with the exception that Probe 26 which was located 20 ft away from the expansion joint.

Probes 19, 21, 22, 23, 24, 27, 28, 29, and 31 were installed within the EOP influenced zone.

Probes 16, 17, and 18 were installed between both zones and approximately 20 ft from either EOP influenced zone.

Table C1 summarizes the status of the probe sensors at the end of commissioning and the humidity and temperature data for each probe is shown in Figures C1 through C32. The three humidity sensors and single temperature sensor are plotted for each probe. In the figures time is the horizontal axis, humidity in units of % relative humidity is the left vertical axis and temperature in degrees Fahrenheit is the right vertical axis.

Table C2 summarizes the status of the probe sensors through August 25, 2010, the four month operational inspection.

Table C3 summarizes the status of the probe sensors at the end of the performance and the humidity and temperature data for each probe is shown in Figures C33 through C64. Plot format for these figures is the same as for Figures C1 through C32.

Figures C65 and C66 show the EOP power supply voltage and current for Areas 1 and 2, respectively. Time is the horizontal axis, voltage in units of volts is the left vertical axis and current in amperes is the right vertical axis. Rainfall (extracted from the weather data shown in Figure C67) is superimposed on these plots. The rainfall is shown for ease of visualization and the amount is not quantified on these plots. A positive correlation between rainfall and EOP power supply current is often an indication of the EOP system effectiveness in preventing water intrusion.

Commissioning results

Table C1. Summary of probe operation through April 15, 2010
(O = Outside EOP influenced area; I = Inside EOP influenced area).

Probe	Comment
1 - O	OK
2 - I	OK
3 - I	OK
4 - O	OK
5 - I	H1 reading is at maximum of >96% Humidity
6 - O	H2 reading erratic at start up but stabilized
7 - O	H3 reading erratic at start up but stabilized
8 - I	OK
9 - O	T1 reading very unstable
10 - I	H1 had a number of erratic readings but stabilized
11 - I	OK
12 - O	H1 occasionally reading the maximum value but stabilized
13 - I	H2, H3 & T1 became erratic 48 hours prior to placing in service
14 - I	H2 & T1 readings unstable
15 - I	H3 had erratic readings 14 days prior to placing in service
16 - O	OK
17 - O	H1, H2, H3 & T1 were erratic for 1 month but stabilized
18 - O	OK
19 - I	H2, H3, & T1 were originally stable but became erratic
20 - O	H2 is constantly reporting 30% humidity and is suspected to be faulty
21 - I	OK
22 - I	OK
23 - I	OK
24 - I	T1 reading is faulty
25 - O	T1 reading is erratic
26 - O	OK
27 - I	H2 was originally stable but became erratic
28 - I	OK
29 - I	OK
30 - O	H1, H2, H3 & T1 are erratic
31 - I	OK
32 - O	H1, H2, H3 & T1 are erratic

Figure C1. Probe 1 commissioning period.

Figure C2. Probe 2 commissioning period.

Figure C3. Probe 3 commissioning period.

Figure C4. Probe 4 commissioning period.

Figure C5. Probe 5 commissioning period.

Figure C6. Probe 6 commissioning period.

Figure C7. Probe 7 commissioning period.

Figure C8. Probe 8 commissioning period.

Figure C9. Probe 9 commissioning period.

Figure C10. Probe 10 commissioning period.

Figure C11. Probe 11 commissioning period.

Figure C12. Probe 12 commissioning period.

Figure C13. Probe 13 commissioning period.

Figure C14. Probe 14 commissioning period.

Figure C15. Probe 15 commissioning period.

Figure C16. Probe 16 commissioning period.

Figure C17. Probe 17 commissioning period.

Figure C18. Probe 18 commissioning period.

Figure C19. Probe 19 commissioning period.

Figure C20. Probe 20 commissioning period.

Figure C21. Probe 21 commissioning period.

Figure C22. Probe 22 commissioning period.

Figure C23. Probe 23 commissioning period.

Figure C24. Probe 24 commissioning period.

Figure C25. Probe 25 commissioning period.

Figure C26. Probe 26 commissioning period.

Figure C27. Probe 27 commissioning period.

Figure C28. Probe 28 commissioning period.

Figure C29. Probe 29 commissioning period.

Figure C30. Probe 30 commissioning period.

Figure C31. Probe 31 commissioning period.

Figure C32. Probe 32 commissioning period.

Service / performance monitoring results

Table C2. Summary of probe operation through August 25, 2010 (O = Outside EOP influenced area; I = Inside EOP influenced area).

Probe	Comment
1 - O	OK
2 - I	OK
3 - I	OK
4 - O	H3 is reporting 5% humidity which is expected to be faulty
5 - I	H1 Reading is at maximum Measurement of >96% Humidity
6 - O	OK
7 - O	H2 & H3 is reporting 5% humidity which is expected to be faulty. T1 reading has been faulty since June 16
8 - I	H3 has become unstable since May 31
9 - O	H3 has become erratic since May 21. T1 Very unstable since April 29.
10 - I	H2, H3 & T1 have become erratic since June 26
11 - I	OK
12 - O	H1 At times the maximum value has been reached but all readings are stable
13 - I	H2, H3 & T1 have become erratic since placing in service
14 - I	H2 & T1 unstable since June 16
15 - I	H3 Erratic readings since placing in service
16 - O	OK
17 - O	H3 & T1 have been unstable since July 02
18 - O	H3 Erratic readings since June 21
19 - I	H2, H3 & T1 have become erratic since placing in service
20 - O	H2, H3 & T1 have become erratic since placing in service
21 - I	H2 & H3 have become erratic since May 15
22 - I	H2 & H3 have become erratic since June 16
23 - I	OK
24 - I	T1 Reading has been faulty
25 - O	H3 & T1 Reading is erratic
26 - O	OK
27 - I	H2 Originally has become erratic
28 - I	OK
29 - I	OK
30 - O	H1, H2, H3 & T1 were erratic from energizing on 15 th February

Probe	Comment
31 - I	OK
32 - O	H1,H2,H3 & T1 were erratic from energizing on 15 th February

Table C3. Summary of probe operation through January 15, 2011 (O = Outside EOP influenced area; I = Inside EOP influenced area).

Probe	Comment
1 - O	OK
2 - I	H1 became erratic
3 - I	OK
4 - O	H3 faulty
5 - I	H1 faulty
6 - O	H3 faulty
7 - O	H1, H2, H3, and T1 all faulty
8 - I	H2, H3, and T1 all faulty
9 - O	H2, H3, and T1 all faulty
10 - I	H1, H2, H3, and T1 all faulty
11 - I	H3 faulty
12 - O	H1, H2, H3, and T1 all faulty
13 - I	H2, H3, and T1 faulty
14 - I	H2, H3, and T1 faulty
15 - I	H2 and H3 faulty
16 - O	OK
17 - O	H2, H3, and T1 faulty
18 - O	H3 faulty
19 - I	H1, H2, H3, and T1 all faulty
20 - O	H1, H2, H3, and T1 all faulty
21 - I	H2 and H3 faulty
22 - I	H2 and H3 faulty
23 - I	OK
24 - I	H1, H2, H3, and T1 all faulty
25 - O	H2, H3, and T1 faulty
26 - O	H2, H3, and T1 faulty
27 - I	H2 faulty
28 - I	H2 faulty

Probe	Comment
29 - I	H1 and H3 faulty
30 - O	H1, H2, H3, and T1 all faulty
31 - I	H2, H3, and T1 faulty
32 - O	H1, H2, H3, and T1 all faulty

Figure C33. Probe 1 performance period.

Figure C34. Probe 2 performance period.

Figure C35. Probe 3 performance period.

Figure C36. Probe 4 performance period.

Figure C37. Probe 5 performance period.

Figure C38. Probe 6 performance period.

Figure C39. Probe 7 performance period.

Figure C40. Probe 8 performance period.

Figure C41. Probe 9 performance period.

Figure C42. Probe 10 performance period.

Figure C43. Probe 11 performance period.

Figure C44. Probe 12 performance period.

Figure C45. Probe 13 performance period.

Figure C46. Probe 14 performance period.

Figure C47. Probe 15 performance period.

Figure C48. Probe 16 performance period.

Figure C49. Probe 17 performance period.

Figure C50. Probe 18 performance period.

Figure C51. Probe 19 performance period.

Figure C52. Probe 20 performance period.

Figure C53. Probe 21 performance period.

Figure C54. Probe 22 performance period.

Figure C55. Probe 23 performance period.

Figure C56. Probe 24 performance period.

Figure C57. Probe 25 performance period.

Figure C58. Probe 26 performance period.

Figure C59. Probe 27 performance period.

Figure C60. Probe 28 performance period.

Figure C61. Probe 29 performance period.

Figure C62. Probe 30 performance period.

Figure C63. Probe 31 performance period.

Figure C64. Probe 32 performance period.

Figure C65. Area 1 EOP power supply voltage and current.

Note: The Initial data that was missing (18 April 18 - 30 April 2010) was due to a faulty power supply board; the second set of data missing (10 May-5 June 5 2010) was due to a power outage.

Figure C66. Area 2 EOP power supply voltage and current.

Figure C67. Temperature and precipitation at Campbell Army Airfield. (Data from Weather Underground).

Appendix D: Pavement Survey with Photos of Dimensioned Cracks

This appendix presents the results of the pavement survey in the form of photographs (Figure D1–Figure D33). Each photograph shows a dimensioned crack from an area of the pavement. The survey was performed in April 2010 prior to energizing the EOP system.

The purpose of collecting data on the crack pattern on the concrete surface is to be able to correlate this pattern with future defects. If the EOP system reduces the moisture within the concrete slab, thereby preventing ASR, then the areas of cracks recorded should not change. (ASR causes expansion of the concrete and the cracks would increase in size if ASR is active.) Table D 1 details the slab section and the exact location and size of the current cracks when surveyed.

Table D 1. Locations of pavement surface cracks.

Crack ID No.	Figure	Slab Sections	Location	Size of crack
1-1	D1	Joint between 17EP & 17EQ	On 17EQ located 18 in. from corner west side	6 in. (L) x 1/16 in. to 1/64 in.
1-2	D2 a, b	Joint between 17EP & 17EQ	On 17EQ located 39.5 in. from corner west side	3.5 in.(L) starts w/ pop out 1.5 in. x 0.5 in.
	D2 c, d		and corresponding crack on 17EP	5 in. (L) starts w/ pop out 1 in. x 0.5 in.
1-3	D3	Joint on 17EP & 17EQ	On 17EP located 47 in. from corner west side	4 in. (L) 1/16 in. to 1/64 in. (W)
1-4	D4	Joint on 17EP & 17EQ	On 17EP located 51 in. from corner west side	3 in.(L)
1-5	D5	Joint on 17EP & 17EQ	On 17EQ located 49.5 in. from corner west side	7 in. (L)
2-1	D6	Joint between 14EP & 13EP	On 13EP located 26.5 in. from corner west side	2 in. (L) 1/16 in. to 1/64 in. (W)
2-2	D7	Joint between 14EP & 13EP	On 14EP located 27.5 in. from corner west side	2 in. (L)

Crack ID No.	Figure	Slab Sections	Location	Size of crack
2-3	D8	Joint between 14EP & 13EP	On 14EP located 98 in. from corner west side	8 in. (L)
2-4	D9	Joint between 14EP & 13EP	On 13EP located 126.5 in. from corner west side	4 in. (L)
3-1	D10	Joint between 14EN & 14EO	On 14EN located 65.5 in. from corner west side	18 in. (L) 1/16 in. to 1/64 in. (W)
3-2	D11	Joint between 14EN & 14EO	On 14EN located 85.5 in. from corner	4.5 in. (L)
3-3	D12		and corresponding crack on 14EO at 85.75 in.	3.5 in. (L)
3-4	D13	Joint between 14EN & 14EO	On 14EN located 47 in. from corner west pop-out	1.25 x 3.5 in.
4-1	D14	Joint between 17EM & 17EN	On 17EM located 11.5 in. from corner west side	4.5 in. (L)
4-2	D15	Joint between 17EM & 17EN	On 17EN located 16.5 in. from corner west side	4.5 in. (L)
4-3	D16	Joint between 17EM & 17EN	On 17EM located 105.5 in. from corner west side	4.5 in. (L)
4-4	D17	Joint between 17EM & 17EN	On 17EN located 106.75 in. from corner west side	4 in. (L)
5-1	D18	Joint on 17EK & 17EL	On 17EK located 43.25 in. from corner west side	4 ft (L)
5-2	D19	Joint on 17EK & 17EL	On 17EK located 42.5 in. from corner west side	1.2 in. (L)
5-3	D20	Joint on 17EK & 17EL	On 17EL located 50.375 in. from corner west side	3 in. (L)
5-4	D21	Joint on 17EK & 17EL	On 17EK & 17EL located 19.75 ft from corner west side	3.5 in. (L)
5-5	D22	Joint on 17EK & 17EL	On 17EL located 19.75 ft. from corner west side	16 in. (L)
6-1	D23 a, b	Interior of panel 14EJ	Along a line 48 in. from west side	88 in. to 114 in.

Crack ID No.	Figure	Slab Sections	Location	Size of crack
	D23 c, d			
7-1	D24 a, b	Line N to S from joint between 13EJ & 13 EK	On 13EK located 80 in. from corner west side	50.5 in. (L)
	D24 c, d			
	D24 e			
8-1	D25	Joint between 17EJ & 17EK	Located 6.5 in. from corner west side	4 in. (L)
8-2	D26	Joint between 17EJ & 17EK	Located 12 in. from corner west side	4 in. (L) w pop-out at joint
8-3	D27	Joint between 17EJ & 17EK	Located 34 in. from corner west side	4 in. (L)
8-4	D28	Joint between 17EJ & 17EK	Pop-out at 38 in. to 41 in. from corner	3 in. (L)
9-1	D29	Joint between 14EG & 14EH	Located 17' 3.5 in. from corner west side	3 in. (L)
9-2	D30	Joint between 14EG & 14EH	Located 18' 6 in. from corner west side	3 in. (L)
10-1	D31	Joint between 13EG & 13EH	On 13EG located 4 in. from corner west side	9 in. (L)
10-2	D32	Joint between 13EG & 13EH	On 13EH located 9.5 in. from corner west side	7 in. (L)
10-3	D33	Joint between 13EG & 13EH	On 13EG located 48.5 in. to 50.25 in. from corner west side	1 in. (L) x 3 in.

Figure D1. Pavement crack 1-1.

(a)

(b)

Figure D2. Pavement crack 1-2.

(a)

(b)

(c)

(d)

Figure D3. Pavement crack 1-3.

Figure D4. Pavement crack 1-4.

Figure D5. Pavement crack 1-5.

Figure D6. Pavement crack 2-1.

Figure D7. Pavement crack 2-2.

Figure D8. Pavement crack 2-3.

(a)

(b)

Figure D9. Pavement crack 2-4.

(a)

(b)

Figure D10. Pavement crack 3-1.

(a)

(b)

Figure D11. Pavement crack 3-2.

(a)

(b)

Figure D12. Pavement crack 3-3.

(a)

(b)

Figure D13. Pavement crack 3-4.

(a)

(b)

Figure D14. Pavement crack 4-1.

(a)

(b)

Figure D15. Pavement crack 4-2.

(a)

(b)

Figure D16. Pavement crack 4-3.

(a)

(b)

Figure D17. Pavement crack 4-4.

(a)

(b)

Figure D18. Pavement crack 5-1.

(a)

(b)

Figure D19. Pavement crack 5-2.

(a)

(b)

Figure D20. Pavement crack 5-3.

(a)

(b)

Figure D21. Pavement crack 5-4.

(a)

(b)

Figure D22. Pavement crack 5-5.

(a)

(b)

Figure D23. Pavement crack 6-1.

(c)

(d)

Figure D24. Pavement crack 7-1.

(a)

(b)

(c)

(d)

(e)

Figure D25. Pavement crack 8-1.

(a)

(b)

Figure D26. Pavement crack 8-2.

(a)

(b)

Figure D27. Pavement crack 8-3.

(a)

(b)

Figure D28. Pavement crack 8-4.

Figure D29. Pavement crack 9-1.

(b)

(c)

Figure D30. Pavement crack 9-2.

(a)

(b)

Figure D31. Pavement crack 10-1.

(a)

(b)

(c)

Figure D32. Pavement crack 10-2.

(a)

(b)

Figure D33. Pavement crack 10-3.

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13. SUPPLEMENTARY NOTES					
14. ABSTRACT All Department of Defense (DoD), Army, federal government, and private-sector facilities experience the problem of concrete deteriorating via alkali-silica reaction (ASR). ASR is a form of concrete corrosion that slowly deteriorates concrete from the inside by forming highly expansive gels that cause cracking and swelling of the concrete matrix. This project evaluated Electro-Osmotic Pulse (EOP) technology to mitigate ASR in an area of the visitor's ramp at Campbell Army Airfield. An EOP system was designed, installed, and monitored in a concrete pavement section affected by ASR. In addition to installing EOP technology, concrete moisture monitoring probes were installed at selected locations. The performance of the EOP system was evaluated by recording temperature and moisture levels inside the concrete for a period of nine months. The ability of the EOP system to mitigate ASR is inconclusive. Although there are indications that moisture is being removed from the concrete pavement, it is not clear that the concrete's internal relative humidity has been reduced below 80%, the moisture reduction value that ensures ASR will not occur. The calculated return on investment (ROI) for the project was 5.68. However, a long-term approach for performance monitoring must be completed before the technology can be recommended.					
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