Touch and Step Voltage Measurements on Field Installed Ground Grid Overlaid with Gravel and Asphalt Beds

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National Electric Energy Testing, Research & Applications Center

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EXECUTIVE SUMMARY

Gravel and asphalt are commonly used in and around substations. Gravel is one of the most commonly used surfacing material for substation yards, while asphalt is sometimes used for driveways and parking areas. These high resistivity materials are very useful in reducing the exposure currents to workers during fault conditions. Both the electrical characteristics of a surfacing material and its moisture condition substantially affect the exposure voltage and resulting current. The electrical resistivities of several gravel and asphalt types are listed in IEEE Std. 80. In addition to measuring the resistivities, this project investigated touch voltage and resulting exposure current characteristics of three different types of gravel material and an asphalt bed in various wet and dry conditions. In 2009, Phase 1 of this project evaluated four different types of concrete beds by performing similar tests. The same ground grid was used for the tests performed in this project.

This project was performed using the 24'x24', 4/0 copper mesh grounding grid. Five substrate test areas were installed for comparison. Three different gravel areas consisting of 1-½" Crusher Run, #57 Washed Gravel, and #34 Washed Gravel were installed over three of the quadrants of the ground grid. Different gravel was used for each quadrant. The fourth quadrant contained the concrete slab retained from the previous phase of the project. An asphalt bed was installed outside and adjacent to one of the ground grid quadrants. This test area was used to investigate the resistivity characteristics of asphalt by using the 4-pin resistivity measurement method.

The voltage gradients in and around the ground grid were developed by injecting approximately 22 A from a 240/480 V isolation transformer. Measured variables included the injected current, Ground Potential Rise (GPR), and voltages between selected surface locations and ground grid with and without connecting a 1000 Ω resistor representing a human body in the circuit. The measurements took place on five different days with varying moisture conditions. A more detailed characterization of gravel and asphalt beds was obtained by determining the Thevenin's equivalent resistance (R_{thev}) in series with the 1000 Ω resistor or worker's feet.

The following general conclusions were obtained in the project:

- The protective characteristics of a surfacing material are highly dependent upon its moisture content. A surfacing material is less effective in protecting a worker when it is wet.
- Crushed stones mixed with their own dust are significantly less effective compared to washed stones even in wet conditions.
- Dusty gravel retains the moisture for a long time increasing the time duration during which it is less effective. In comparison, the washed gravel dries out fast recovering its insulating properties.

- Among the washed gravels, the gravel with larger sized stones performs somewhat better than their smaller sized counterparts.
- Between concrete and asphalt, protective characteristics of asphalt are significantly better in almost any environmental condition.

SECTION 1.0 BACKGROUND INFORMATION FROM LITERATURE

Covering the substation yard surface with a material of high resistivity is very effective in reducing worker exposure currents. The value of such a covering in reducing the currents is not always fully realized. Tests performed by Bodier[1] at a substation in France showed that the river gravel used as a surfacing material when moistened had a resistivity of 5000 Ω-m. A layer 4-6" (0.1-0.15 m) thick decreased the *danger factor* (ratio of body to short-circuit current) by an order of magnitude as compared to the native soil. Tests by Langer[2] in Germany compared body currents when touching a hydrant while standing on wet course gravel of 6000 Ω-m with those while standing on dry sod. The currents in the case of dry sod were 20 times higher compared to those with the gravel. The tests performed by other researchers provide further confirmation of these benefits. [3,4]

The range of resistivity values for the surface material layer depends on several factors as listed below:

- Type and size of stone
- Amount of dust or fines
- Amount and type of moisture content
- Amount of atmospheric contamination

IEEE Standard 80[5] provides typical resistivity values for different types of surfacing materials in different regions of the United States. [4,6,7,8] These values suggest that the water with which the rock is wetted has considerable influence on the measured resistivities. Thus, the surface material subjected to sea spry may have substantially lower resistivity than surface material utilized in arid environment. IEEE Standard 80 resistivity values also indicate that local conditions and type and size of stone may affect the value of resistivity. For this reason, it is important that the resistivity of rock samples typical of the type being used in a given area be measured.

SECTION 2.0 TEST PROCEDURE

<u>Field Installation of Ground Grid and Gravel, Concrete and Asphalt Beds</u>

A symmetrical, 24' x 24', 4/0 copper ground grid with four 12' x 12' meshes was previously installed for Phase 1 of this project near the MTF Building in NEETRAC's High Voltage Facility in Forest Park, Georgia. The grid conductors were buried approximately 18" deep. In Phase 1 of this project, concrete slabs were installed to investigate the electrical characteristics on the concrete in the substation environment. One of the slabs located in the SE corner of the grid was left for comparison purpose during this project. This concrete slab contained no rebar or wire mesh.

Gravel test areas were installed over the three remaining quadrants of the ground grid. The gravel used was 1½" Crusher Run, #57 Washed Gravel and #34 Washed Gravel. One asphalt bed was installed adjacent to the quadrant with the #57 Washed Gravel for the tests. The depths of gravel beds were 4 to 6 inches while the asphalt bed consisted of approximately 9 inches deep.

Figure 2-1 shows the dimensions, locations and specifications of the grounding grid, the gravel test areas and the asphalt slab. Figure 2-2 shows a picture of the test area after installation.

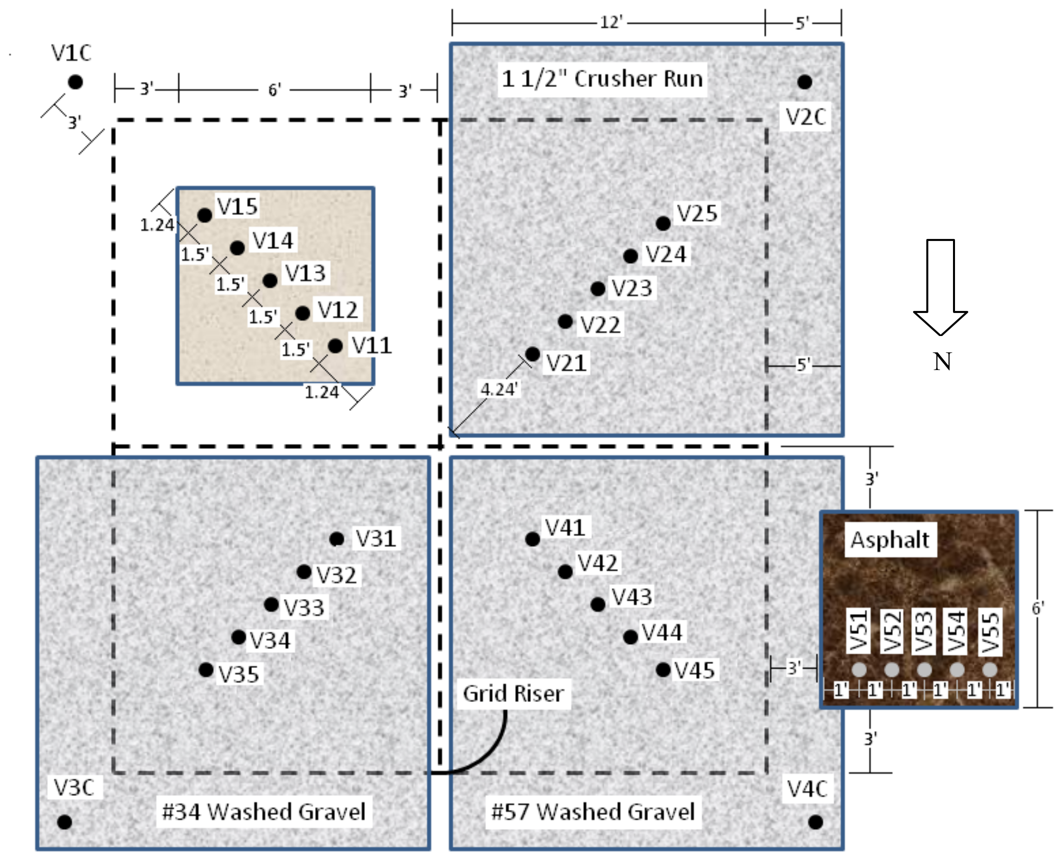

Figure 2-1: Gravel and Asphalt Test Areas

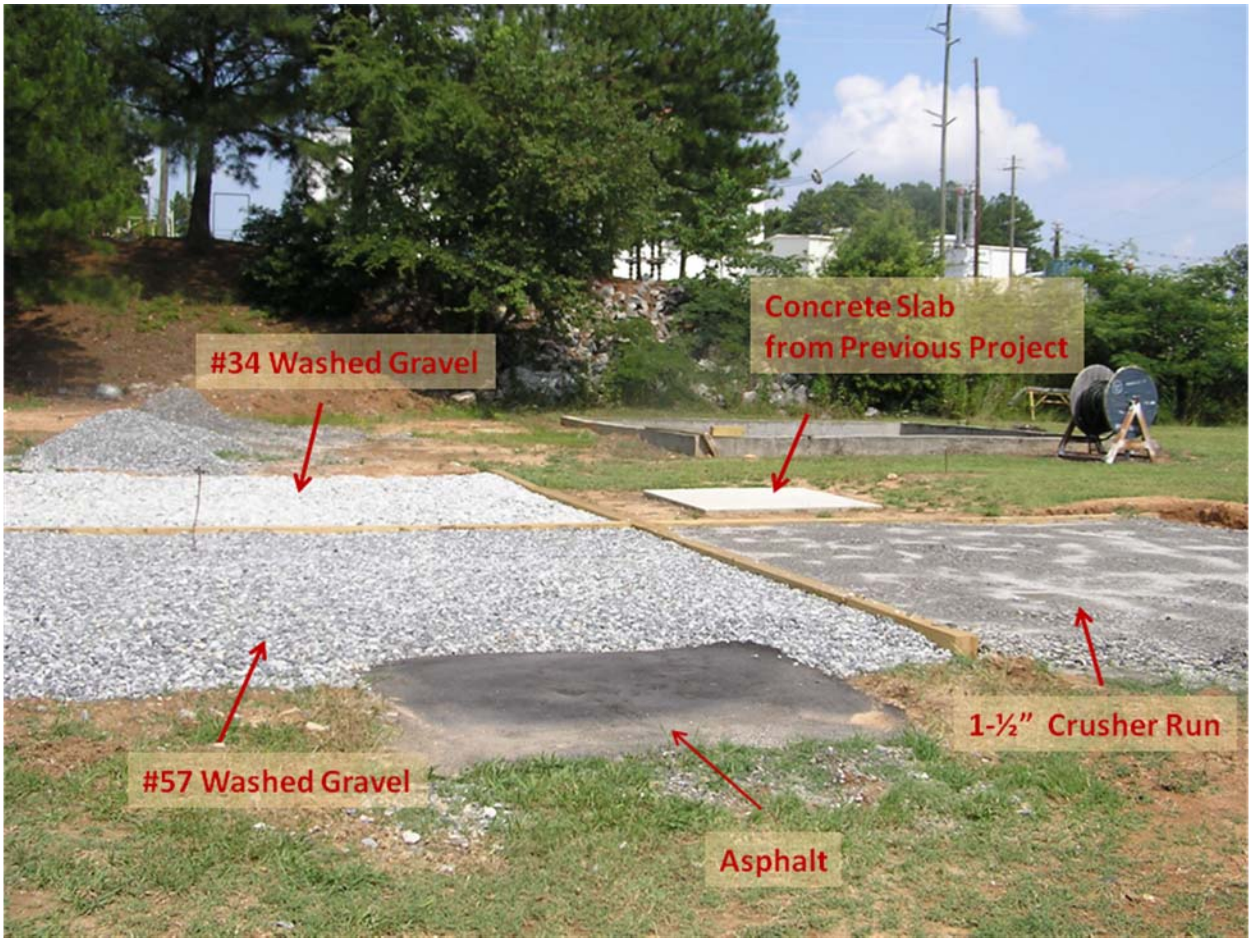

Figure 2–2: Gravel and Asphalt Test Areas after Installation

Timeline

The gravel and asphalt beds were installed in late June 2010. A concrete slab from the previous project was left in place for comparison. The initial tests were performed on July 12, 2010. This allowed a few weeks for the gravel to settle. The weather prior to installation and during these two weeks was predominantly hot and dry, with minimal rain, so the initial tests represented the dry environmental test conditions in this report.

After the dry tests on July 12, 2010, a sprinkler system was set up to run for eight (8) hours overnight. In addition to the sprinkler, the test area also received rain during the night. In all, the rain gauge had nearly four (4") inches of water from the night before. Measurements were taken for the wet environmental test conditions on July 13, 2010.

The testing for the wet environmental conditions was started at 9:00AM. Each test area was wet again for 1-2 minutes prior to taking measurements in that test area. This was done to simulate the environmental conditions immediately following a rain storm in a substation. Also, since taking measurements from all test areas took over an hour, rewetting the individual test area prior to taking measurements prevented significant drying of the test areas between measurements.

This kept the wet environmental test condition consistent for all test areas while taking the measurements. Figure 2-3 shows wetting of one of the test areas prior to taking measurements.

Figure 2-3 – Wetting of Test Area Prior To Testing

After the wet tests were completed, the test areas were allowed to dry for one hour. Another set of readings were taken. This is referred to as the "One Hour after Wet" readings. These measurements were taken in the same order as the previous wet environmental condition tests. This allowed each test area to have a consistent drying time after the wet test condition.

The following day, July 14, no measurements were taken. There was one inch (1") of rain on the evening of July 13, so another day was allowed for drying of the test area. July 15 measurements were taken. These are the "Two Days after Wet" readings. On July 16 another set of readings were taken as the "Three Days after Wet" readings. A final set of Dry Condition readings were taken for comparison with the initial Dry readings. This set of readings was taken on September 2, 2010 after a few days of dry weather.

The following log shows the environmental conditions during the testing.

- 7/9 (Friday) to 7/11 (Sunday) – minimal rain throughout weekend
- 7/12 (Monday) - Soil and Gravel Dry – Initial Dry Condition Readings
- 7/13 (Tuesday) - Previous night - 1" of rain, plus sprinkler; 4" total – Wet Condition Readings
- 7/14 (Wednesday) - 1" of rain the previous night; No Reading Taken
- 7/15 (Thursday) - No rain the previous night; Two Days After Wet Condition Readings
- 7/16 (Friday) - No rain the previous night; Three Days After Wet Condition Readings
- 9/2 (Thursday) - No rain; Repeat Dry Readings

Measurement Details

This project consisted of making several voltage and current measurements on various surfacing materials. A summary of these measurements is provided below. These measurements were taken for each test area in a consecutive manner.

- Injected current (I_g)
- Ground Potential Rise (GPR) with respect to a remote ground rod located approximately 150' from the ground grid
- Open circuit touch voltage measured between the ground grid riser and the metallic shoe soles of the worker. (For this report, the voltage measured without the 1000 Ω resistor in the circuit is defined as an open circuit touch voltage, V_{toc}.)
- Exposure current (I_{exp}) measured as the voltage across a 1000 Ω resistor representing a human body (For this report, the voltage measured across the 1000 Ω resistor is defined as the closed circuit touch voltage, V_{tcc}.)
- Open circuit touch voltage (V_{toc}) measured between the ground grid riser and the pins driven in the gravel (8" pins), concrete (3/4" anchors) and asphalt (3/4" nails). (This measurement was used for comparison with the measurement from the metallic soles representing worker's feet.)
- Resistivity of asphalt using the four-pin method

Some of the variables as identified below were calculated from the measured data:

- Open circuit step voltage (V_{stoc})
- Thevenin's equivalent resistance in series with feet (R_{thev})

Voltage gradients in and around the ground grid were created by injecting approximately 22 amperes into the ground grid. The current was supplied from a pole mounted distribution transformer via a 240/480 V isolation transformer as shown in Figure 2-4.

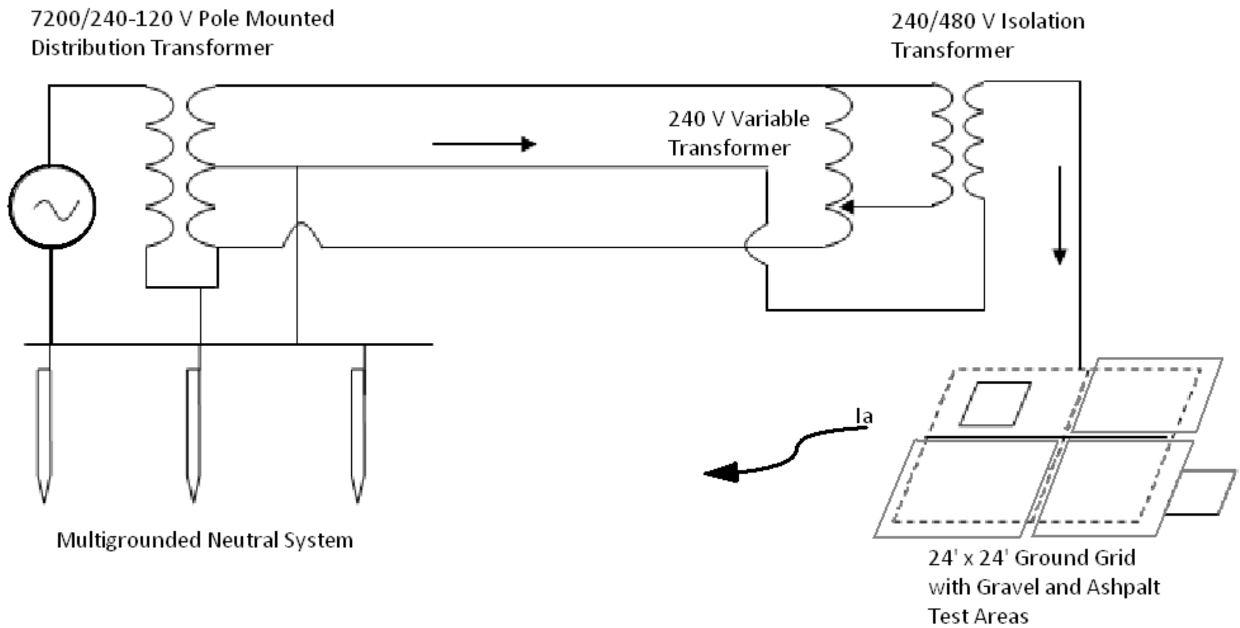

Figure 2-4: Current Injection Circuit

A summary of various measurements including their locations is shown in Figure 2-5. A summary of the measurements taken on the asphalt is shown in Figure 2-6.
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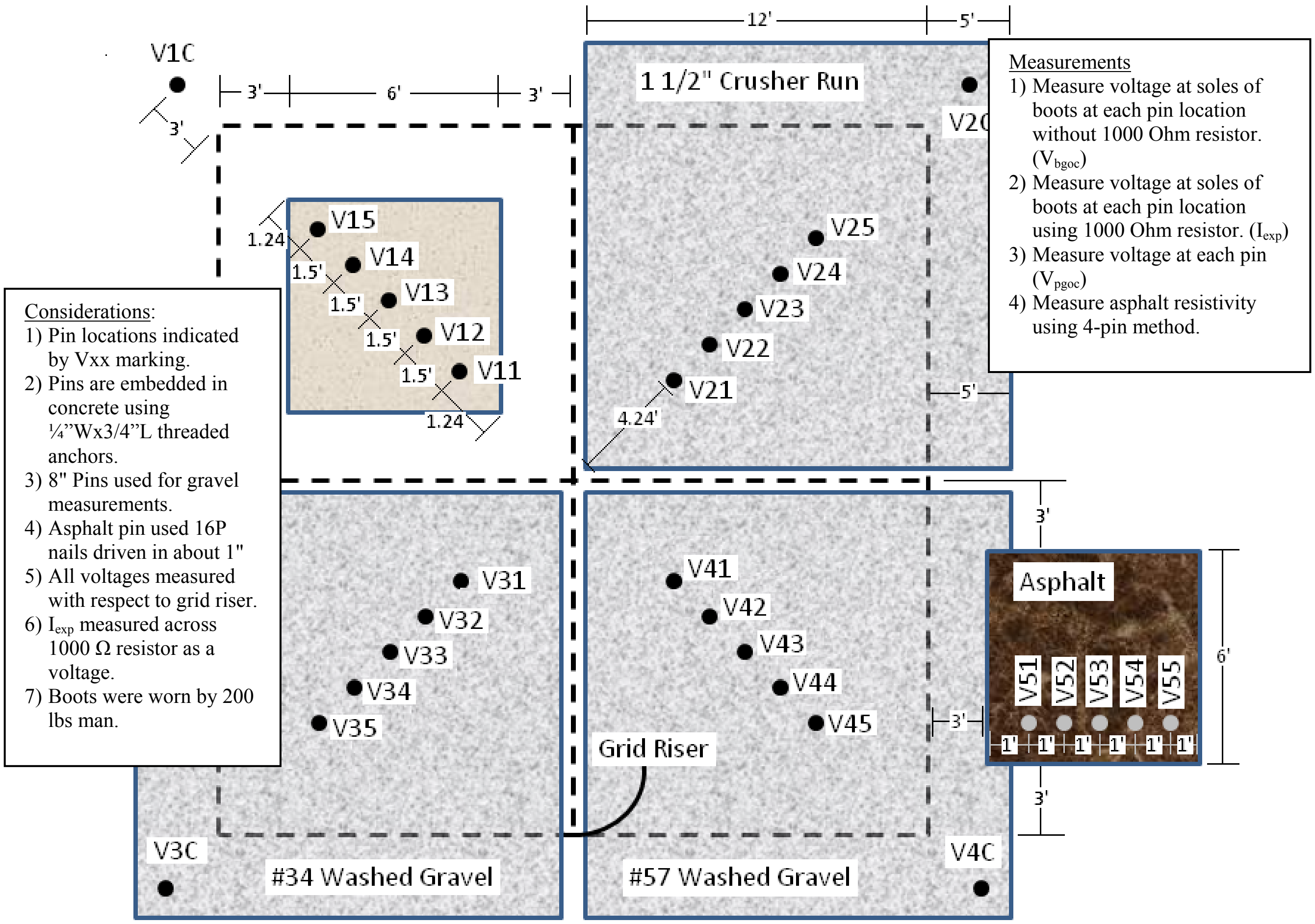


Figure 2-5: Measurement Variables and Locations

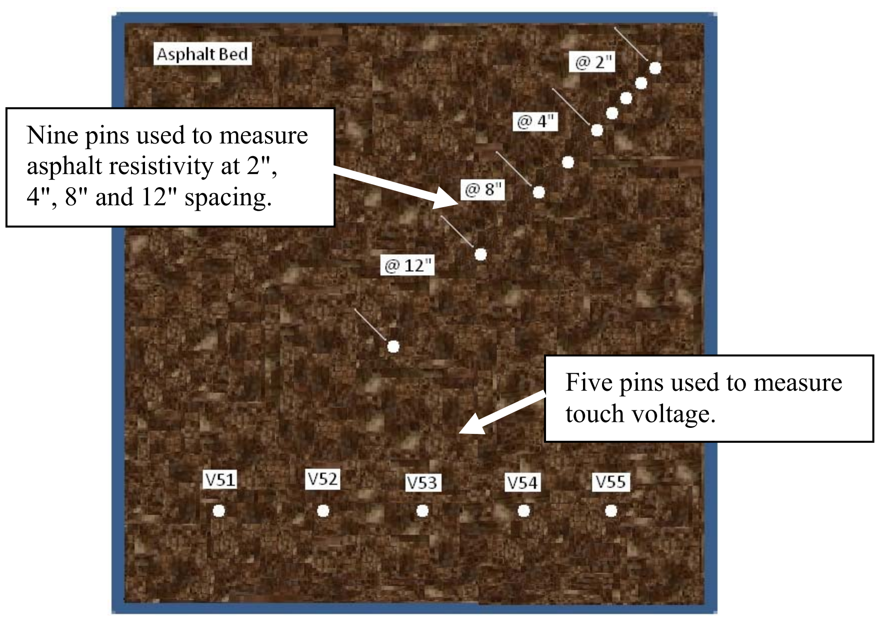


Figure 2-6: Asphalt Bed Resistivity Testing

<u>Apparent Resistivity of Asphalt Using the Four Pin Measurement Method</u>

The four-pin resistivity method was used to determine the electrical resistivity of the asphalt. Figure 2-7 shows the details of how the pins were installed on the asphalt pad. 16P nails were used as the pins in the asphalt. The nails were driven into the asphalt to a depth of one inch. These pins were placed along a diagonal, flush with the surface. The pins were placed in locations to allow for four pin resistivity measurements with spacing of 2, 4, 8, and 12 inches. A 120 V source was used for injecting the current and a digital voltmeter to measure the resulting voltage as shown in the figure.

Figure 2-7: Four-Pin Measurement of Asphalt Resistivity using Nail Electrodes

The resistance values obtained from these measurements were converted to resistivity values by using the formula from IEEE Std. 80 as shown in Equation 2-1.

$$\rho = \frac{4\pi a R}{1 + \frac{2a}{\sqrt{a^2 + 4b^2}} - \frac{a}{\sqrt{a^2 + b^2}}} \quad \text{Ohm-m} \qquad \text{Equation 2-1}$$

Where: "ρ" is the resistivity in ohm-meters,
"a" is the pin spacing either in meters or feet,
"b" is the pin depth with the same units as "a", and
"R" in ohms is the voltage between the inner pins divided by the current through the outer pins.

Resistivity of Gravel Using the Volume or Container Method

The gravel resistivity was measured using the volume method. A cylindrical test device was used with the sample placed between the top and bottom electrodes. Figure 2-8 shows the test device filled with #34 Washed Gravel (left) and 1 ½" Crusher Run (right). To verify good surface contact between each electrode and the gravel, crumpled aluminum balls were used between the gravel and electrode. A 240 V voltage was applied across the electrodes while the current was measured. The first reading was done with dry gravel. The test device was then filled with water for taking the next reading. Finally, the water was drained and a reading was taken.

Figure 2-8: Gravel Resistivity Measurements Using Cylindrical Test Device
(#34 Washed Gravel on the left and 1½" Crusher Run Gravel on the right)

The resistivity of the gravel sample was calculated from the following equation:

$$\rho = \frac{RA}{L} \quad \text{Ohm-m} \qquad \text{Equation 2-2}$$

Where,
ρ = Resistivity, Ohm-m
A = Area of cross-section of cylinder, m^2
L = Cylinder length, m
R = Voltage applied to the electrodes divided by the current through the electrodes, Ohms

Open Circuit Touch and Step Voltages

For the purpose of this report, the open circuit touch voltage (V_{toc}) is defined as the voltage measured between the ground grid conductor and the driven pins or metallic soles of insulated boots. These surface locations may or may not be one meter (approximately three feet) from the ground grid conductor as defined conventionally. Each touch voltage was measured directly using a Fluke 87 digital multimeter. The open circuit step voltages (V_{stoc}) were determined by taking a difference between two touch voltages located approximately three feet apart.

The project also included measuring the open circuit touch voltages by connecting the voltmeter between metallic soles of insulated boots and the ground grid. The soles of insulating boots were covered in wire mesh and aluminum foil. These readings were compared with the open circuit touch voltages measured between the pins and the ground grid.

Refer to Figure 2-5 and 2-6 for identifying various surface locations and the location of the ground grid and ground grid riser.

Exposure Current (I_{exp}) or Closed Circuit Touch Voltage (V_{tcc})

Exposure current is defined as the current flowing through a 1000 Ω resistor with one side connected to the ground grid conductor and the other side connected to a surface location via aluminum foil taped to the soles of two rubber boots. The exposure currents were measured by measuring the voltage across the 1000 Ω resistor. With a 1000 Ω resistor representing a human body, the voltage values read in "volts" directly represent the exposure current values in "mA".

The voltage measured across a resistor representing a human body is defined as a closed circuit touch voltage (V_{tcc}). In actuality, this is the voltage that appears across the body when a contact is made. Since a 1000 Ω resistor represents a human body in this project, it is convenient to define the "exposure current" in mA as the "Closed Circuit Touch Voltage (V_{tcc})" in Volts. Additional details on the significance of this voltage are provided in the following section.

The exposure current was measured at every pin location. Refer to Figure 2-5 for the measurement locations. A 180 pound man wore the rubber boots for the exposure current measurements. Figure 2-9 shows an example of the exposure current measurement on the gravel.

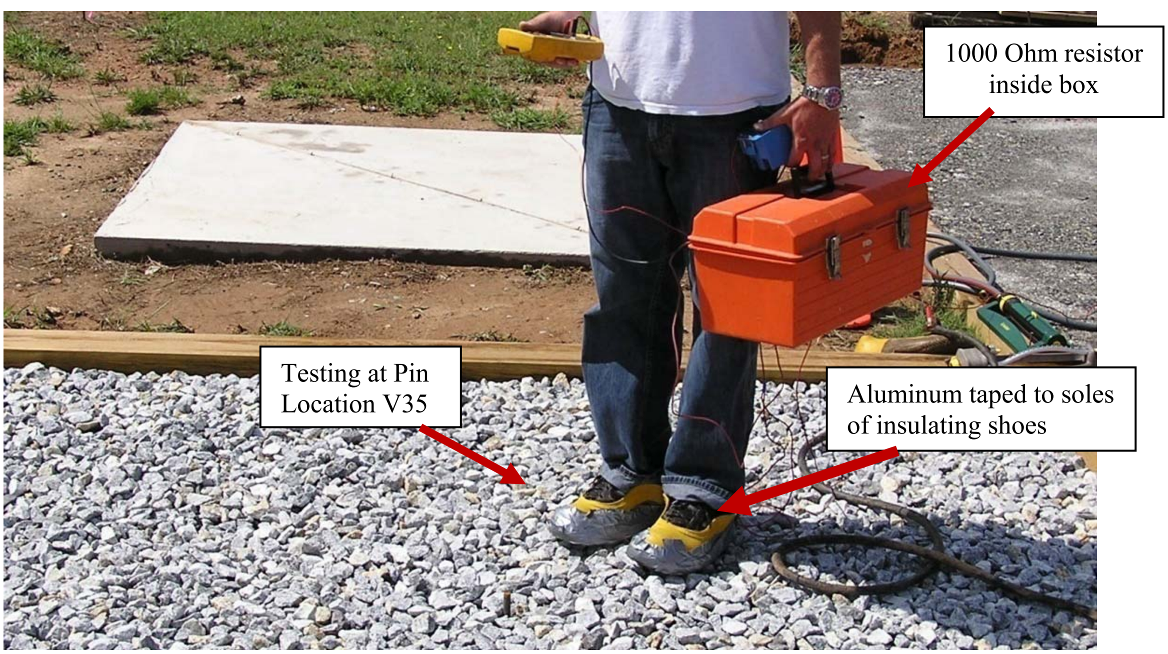


Figure 2-9: Measurement of Exposure Current (I_{exp}) or Closed Circuit Touch Voltage (V_{tcc})

Thevenin's Equivalent Resistance in Series with Feet

To characterize a surfacing material such as asphalt, gravel or soil; it is necessary to determine the Thevenin's Equivalent Resistance (R_{thev}) that is in series with the feet when a contact is made. Since this resistance is in series with the feet, it plays a major role in determining the exposure current in a given environment.

The Thevenin's equivalent resistance can be computed by a number of methods as published in several technical articles [5,10,11]. IEEE Std. 80 provides a conservative but simple relationship for this resistance as shown in Equation 2-3.

$$R_{thev} = 1.5\rho_s \quad \text{Ohms} \qquad \text{Equation 2-3}$$

Where, ρ_s is resistivity of the surfacing material, ohm-meters

The circuit of Figure 2-10 describes the various electrical parameters and their interactions with each other in determining the exposure (body) current. However, this complex network is far from providing a simplified approach to solve for the current. One approach, which provides considerable insight, is to reduce the entire circuit into a two-port network, typically known as Thevenin's equivalent circuit. The circuit looking from the two contact points C_1 and C_2/C_3 is shown in Figure 2-11. Note that a two-port network can be similarly established between contact points C_2 and C_3 to represent a step voltage that may exist between the two feet.

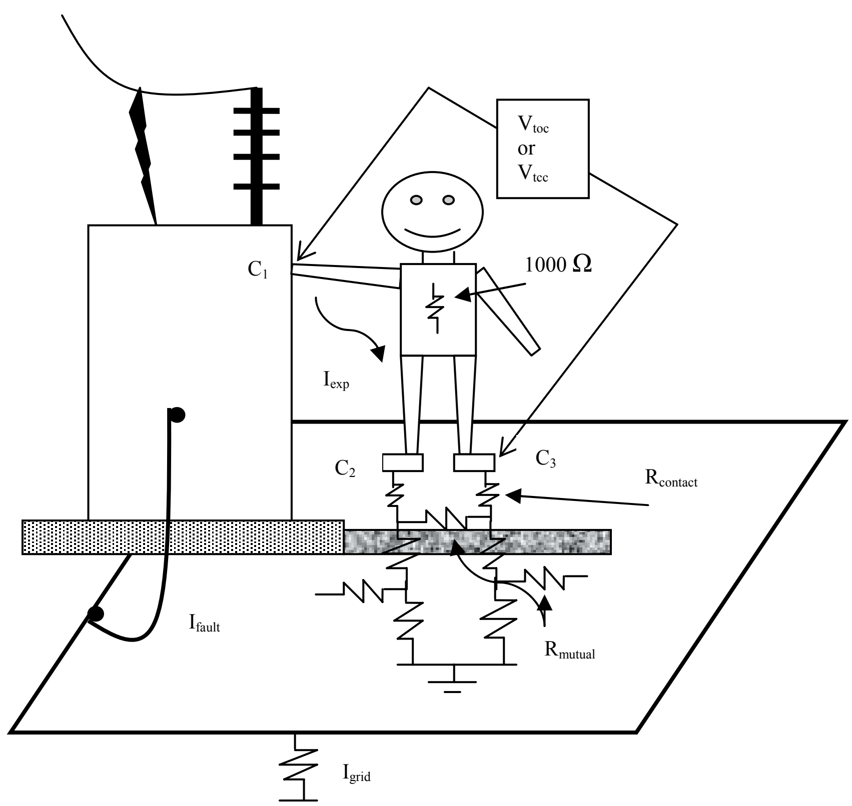


Figure 2-10: Resistance Network in Series with Feet

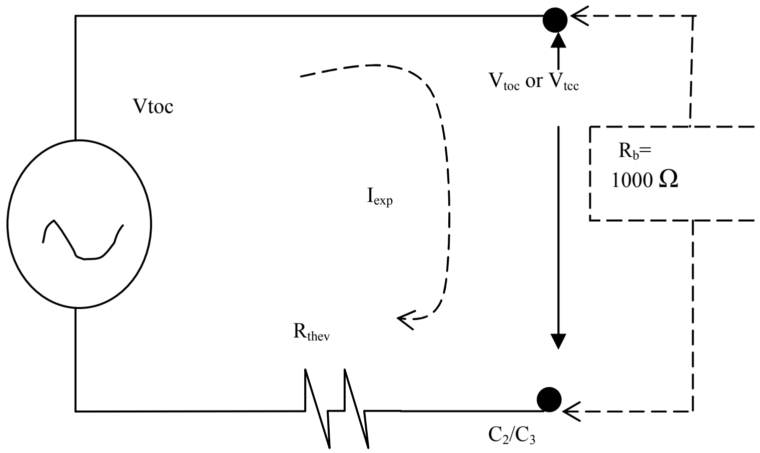


Figure 2-11: Thevenin's Equivalent Circuit to Represent Touch Voltage, Exposure Current and Equivalent Resistance in Series with Worker's Feet

Referring to Figure 2-11, Thevenin's principle replaces the entire circuit of Figure 2-10 by an equivalent circuit consisting of an equivalent voltage source, V_{toc}, in series with an equivalent resistance R_{thev} behind the two points contacted by the person. When these two points are contacted, the current I_{exp} would flow through the body developing the voltage V_{tcc} across the body.

From Figure 2-11, two equations can be easily established:

$$V_{toc} = I_{\exp}\left(R_{thev} + 1000\right) \text{ Volts} \qquad \text{Equation 2-4}$$

$$V_{tcc} = I_{\exp} \times 1000 \text{ Volts} \qquad \text{Equation 2-5}$$

Equation 2-4 and Equation 2-5, an important relationship evolves.

$$R_{thev} = 1000\left(\frac{V_{toc} - V_{tcc}}{V_{tcc}}\right) \text{ Ohms} \qquad \text{Equation 2-6}$$

Equation 2-6 suggests that $V_{toc} \geq V_{tcc}$. It also suggests that the difference in two touch voltages would be greater with higher value of R_{thev}.

SECTION 3.0 TEST RESULTS AND ANALYSIS

General

Appendix A provides a complete set of measured and calculated test data in tabular format.

Open Circuit Touch and Step Voltages

Safety analysis of a ground grid almost always includes computing or measuring open circuit touch and step voltages. The safety goals for the grounding grid are accomplished when these voltages are within the tolerable limits that are typically determined from the characteristics of surfacing materials. Due to numerous applications of concrete in substations, it is important to know its characteristics not only in regard to the voltages on the surface but also its ability to provide an effective resistance in series with the feet when a contact is made. The open circuit touch and step voltage data are presented in this section. The exposure current (closed circuit exposure voltage) and Thevenin's resistance data are presented in the following sections.

Open Circuit Touch Voltage (Vtoc)

Figures 3-1 through 3-5 show the open circuit touch voltages (V_{toc}) measured between the pins and ground grid on concrete, gravel and asphalt beds respectively. Each figure contains six (6) graphs showing the measured data for various environmental conditions of the surfacing materials. All of the measured locations shown in Figures 3-1 through 3-4 are within the ground grid area. Figure 3-5 shows the data for the asphalt bed located three feet from the perimeter of the ground grid. Figure 3-6 shows the similar graphs as above but for four measurement points located three feet outside each ground grid corner.

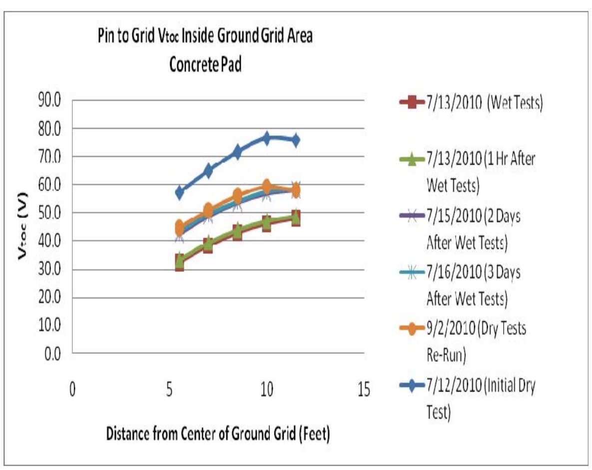


Figure 3-1: Pin to Grid V_{toc} over Concrete Pad

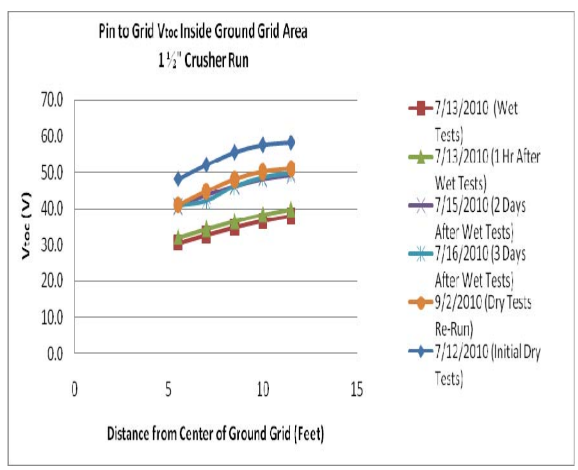


Figure 3-2: Pin to Grid V_{toc} over 1½" Crusher Run Gravel

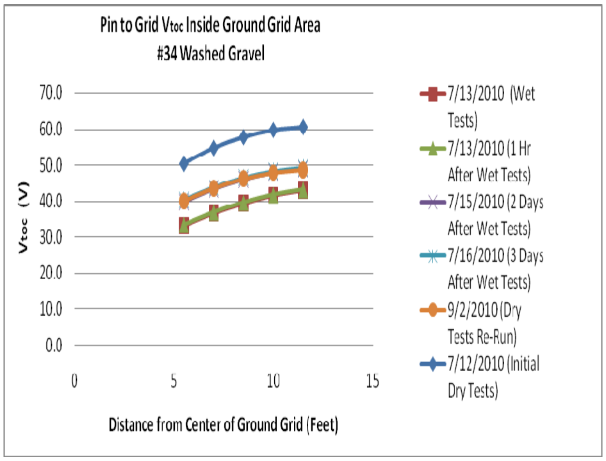


Figure 3-3: Pin to Grid V_{toc} over #34 Gravel

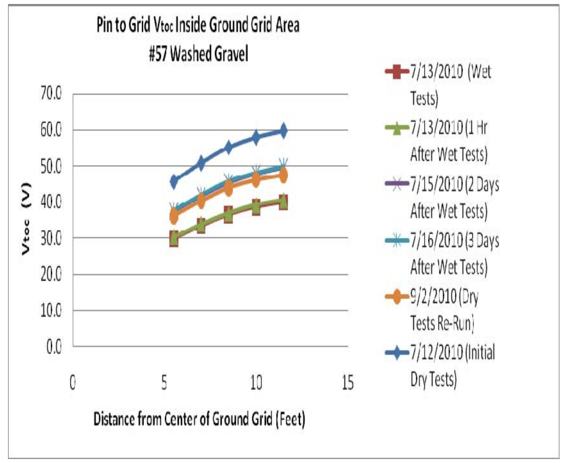


Figure 3-4: Pin to Grid V_{toc} over #57 Gravel

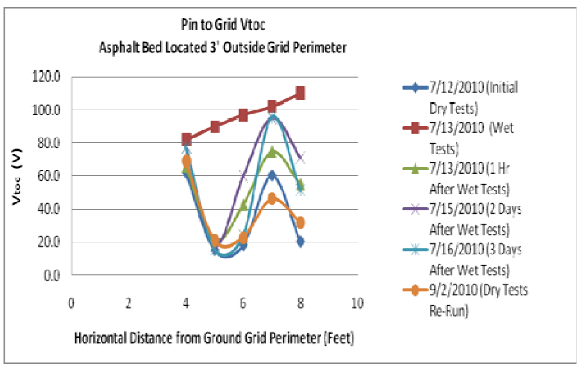


Figure 3-5: Pin to Grid V_{toc} over Asphalt Bed

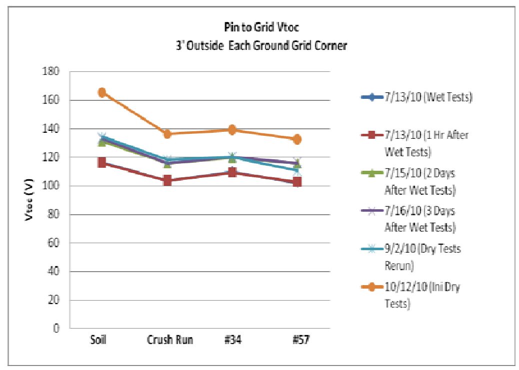
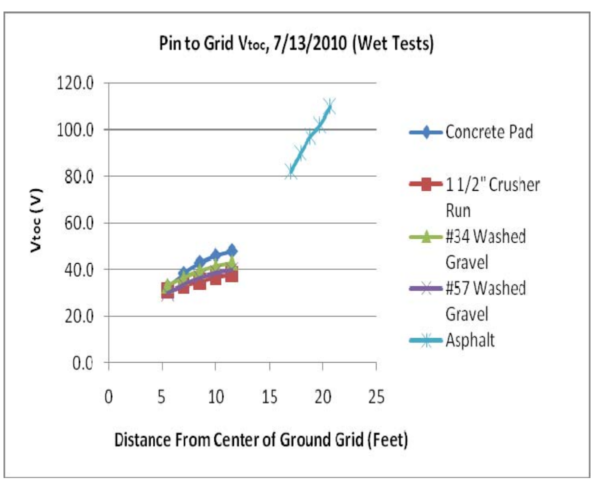


Figure 3-6: Pin to Grid V_{toc} 3' Outside Each Ground Grid Corner

Figures 3-7 through 3-12 show the same open circuit touch voltages but with a different representation. Each of these figures shows a comparison of touch voltages between various surfacing materials for a given environmental condition.



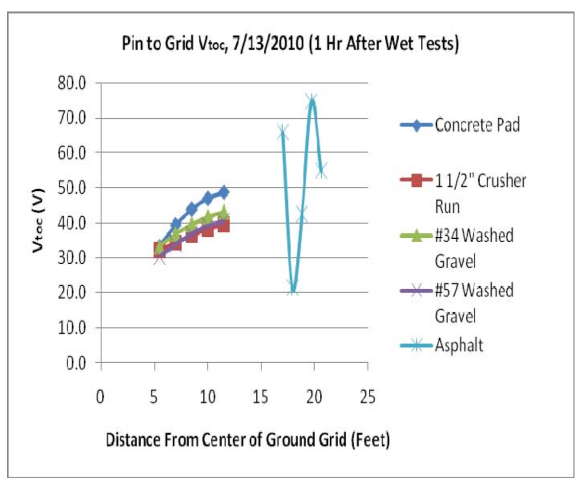
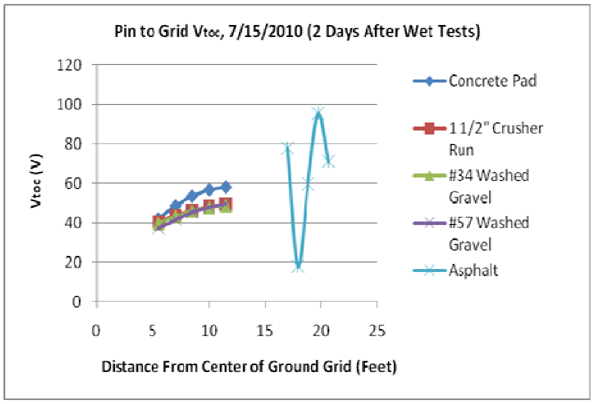


Figure 3-7: Pin to Grid V_{toc} , 7/13/2010 (Wet Tests) Figure 3-8: Pin to Grid V_{toc} (1 Hr After Wet Tests)



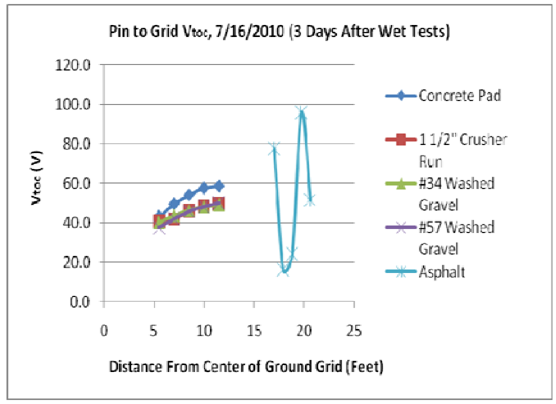
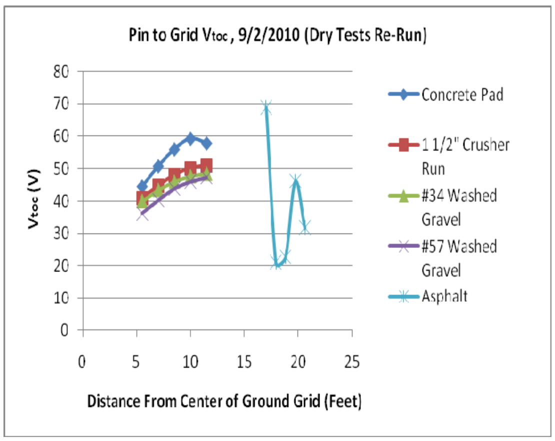


Figure 3-9: Pin to Grid V_{toc} (2 Days After Wet Tests)

Figure 3-10: Pin to Grid V_{toc} (2 Days After Wet Tests)



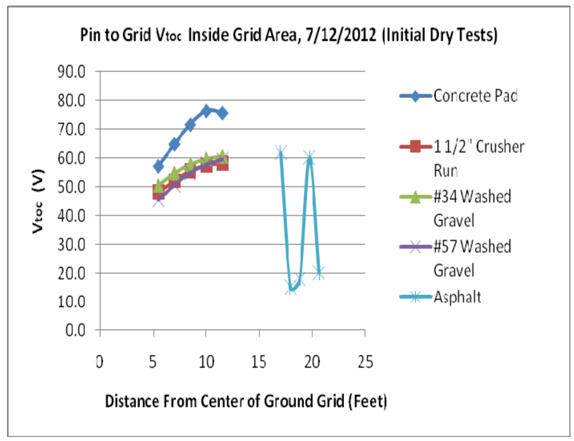


Figure 3-11: Pin to Grid V_{toc}, 9/2/2010 (Dry Tests Rerun)

Figure 3-12: Pin to Grid V_{toc}, 7/12/2010 (Ini Dry Tests)

This project implemented two methods of measuring the open circuit touch voltages. The method shown above consists of driving a pin in the surfacing material and measuring the voltage from the pin to the ground grid. The second method consists of measuring the voltage between the metallic soles of worker’s boots and the ground grid. Between the two methods, the touch voltage measured by the second method includes the influence of the surfacing material and truly represents the voltage contacted by a worker. The method involving pins, however, is more convient to apply and is usually practiced in the industry.

Figure 3-13 through 3-18 show the same measurement scenarios as Figures 3-1 through 3-6, except that these figures represent the open circuit touch voltages measured between the metallic soles of the worker's boots and the ground grid.

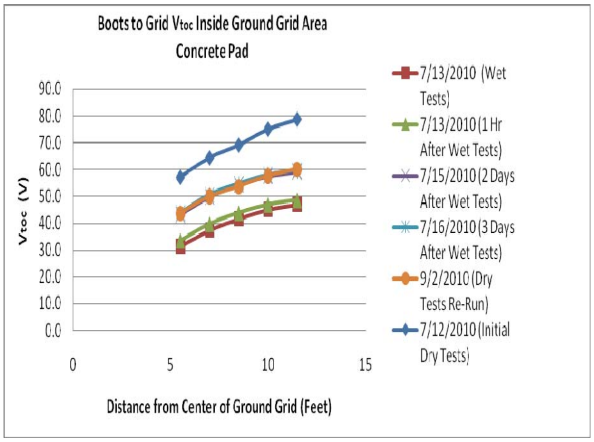


Figure 3-13: Boots to Grid V_{toc} over Concrete Pad

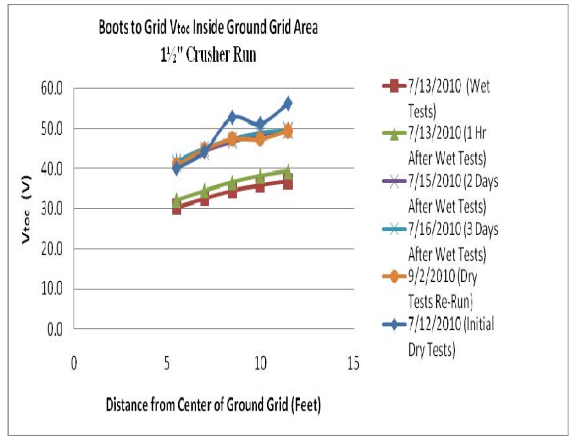


Figure 3-14: Boots to Grid V_{toc} over 1½" Crusher Run

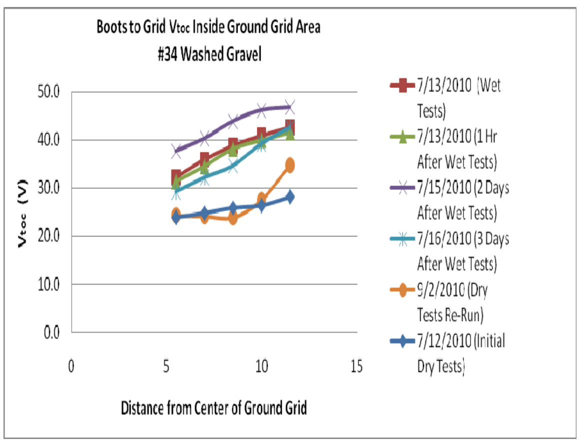


Figure 3-15: Boots to Grid V_{toc} over #34 Gravel

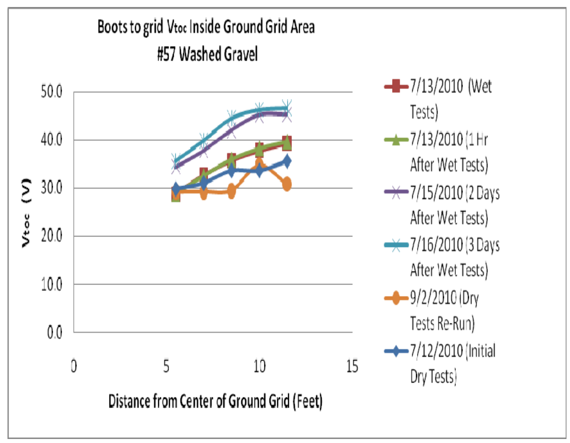


Figure 3-16: Boots to Grid V_{toc} over #57 Gravel

Figure 3-17: Pin to Grid V_{toc} over Asphalt Bed

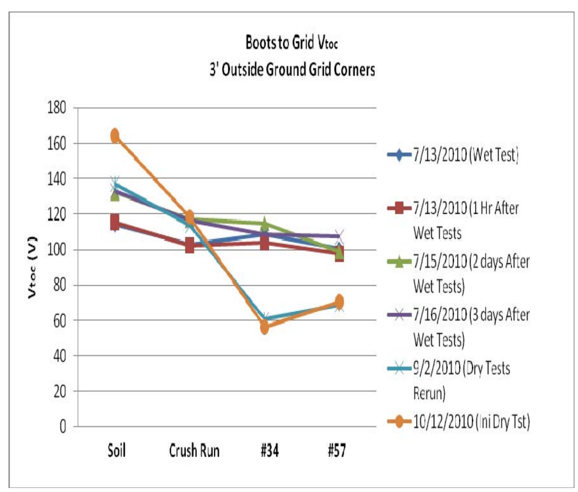


Figure 3-18: Pin to Grid V_{toc} 3' Outside Each Corner

The following are some notable characterisitics of the gravel, concrete and asphalt in regard to open circuit touch voltages:

- No significant difference was noted between the voltages measured from the pin to ground grid and those measured from the soles of a worker's boots to ground grid.
- The maximum touch voltages were measured at three feet outside the ground grid corners.
- At a given location, the touch voltage increased as the drying of the surfacing material and soil progressed.
- In the case of asphalt, the open circuit voltages could not be measured accurately using the Fluke 87 meter particularly for the dry surface conditions. This was due to difficulty in achieving a low resistance contact between the nails and the surrounding asphalt. The measured voltages, as a result, were lower than what they should have been (Figure 3-5). A similar trend was observed in the case of dry #34 and #57 gravel due to high sole to surface contact resistances (Figures 3-15 and 3-16).

<u>Open Circuit Step Voltage</u> (V_{stoc})

Step voltages were calculated by taking a difference between the two pin to pin touch voltages each three feet apart. Similar to touch voltage characteristics, the characteristics of open circuit step voltages over one concrete and three gravel areas are shown in Figures 3-19 through 3-22 respectively. The step voltages over asphalt bed are not presented due to inaccurate data, particularly for the dry conditions.

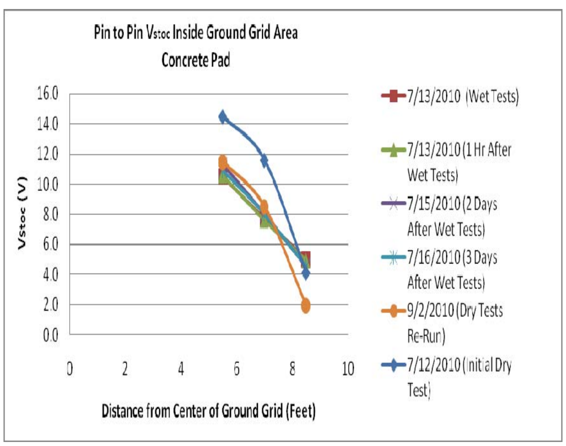


Figure 3-19: Pin to Pin V_{stoc} over Concrete Pad

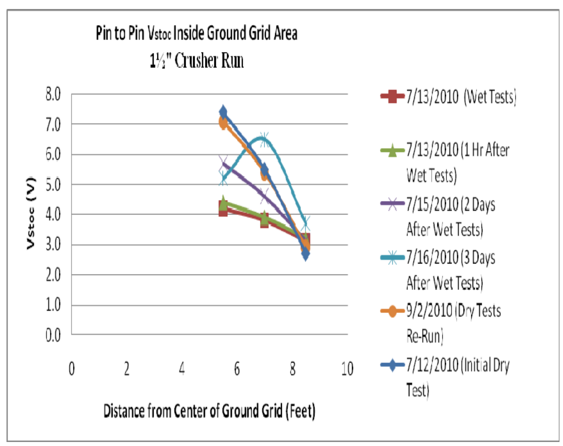


Figure 3-20: Pin to Pin V_{stoc} over 1½" Crusher Run Gravel

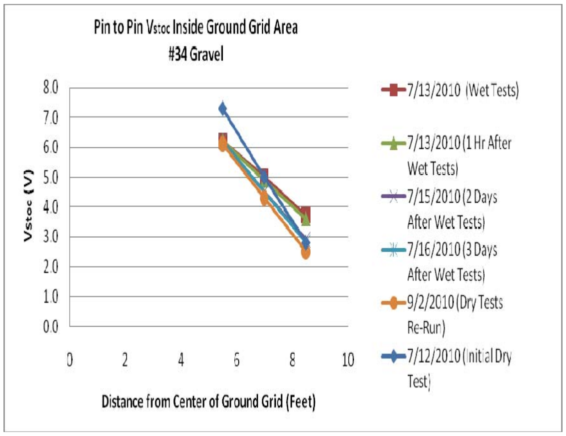


Figure 3-21: Pin to Pin V_{stoc} over #34 Gravel

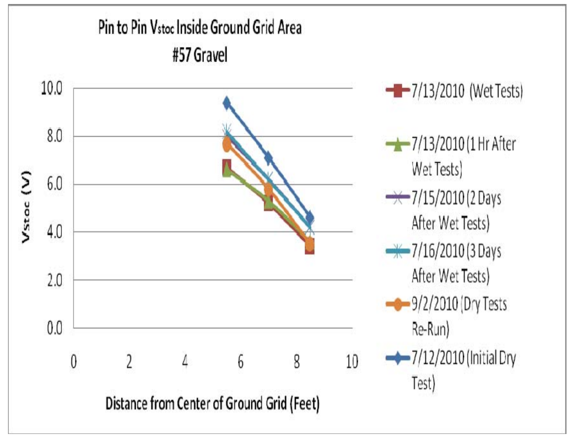


Figure 3-22: Pin to Pin V_{stoc} over #57 Gravel

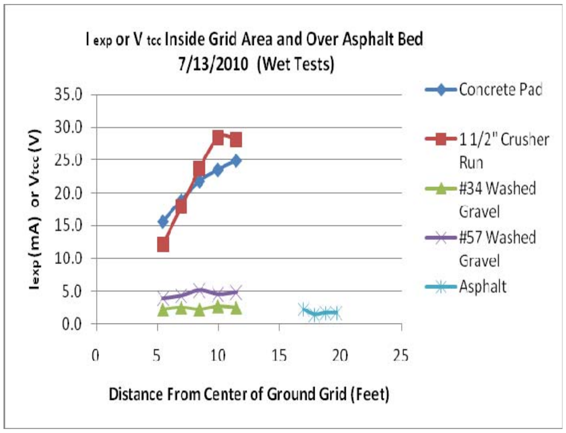
A summary of step voltage characteristics for gravel and concrete beds is provided below.

- The step voltages at all measured locations are lower than corresponding touch voltages.
- Similar to touch voltages, the step voltages increase as the gravel and concrete beds continue to dry.
- Unlike touch voltages, the step voltages are higher near the center of the ground grid.

Exposure Currents or Closed Circuit Touch Voltages

Since the voltage value measured across the 1000 Ω resistor (Volts) can represent the exposure current (I_{exp}) in mA, it is convenient to assign two titles to the same value. Each exposure current value presented in this section could also be titled "Closed Circuit Touch Voltage, V_{tcc}". The significance of a closed circuit touch voltage in determining the Thevenin's equivalent resistance has been explained in a previous section,

Figures 3-23 through 3-27 show the exposure currents over gravel, concrete and asphalt beds at various distances from the center of the ground grid. Each figure shows the exposure current for different environmental condition. Figure 3-28 shows the exposure currents at four corner points located three feet outside the ground grid. This graph shows the comparison between the native soil and the three gravel beds.



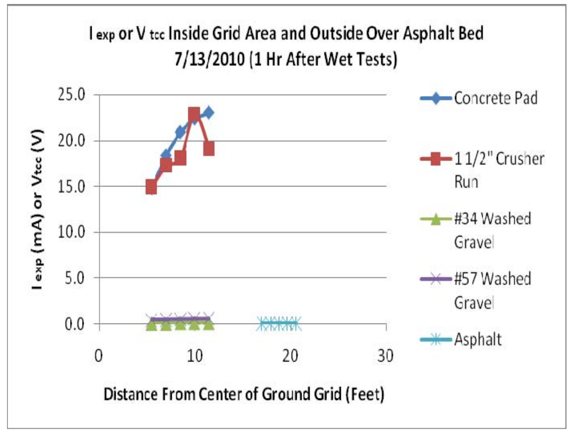
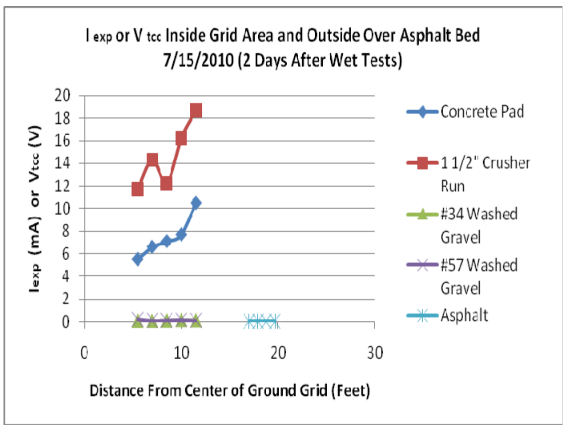


Figure 3-23: I_{exp} or V_{tcc} , 7/13/2010 (Wet Tests)

Figure 3-24: I_{exp} or V_{tcc} (1 Hr After Wet Tests)



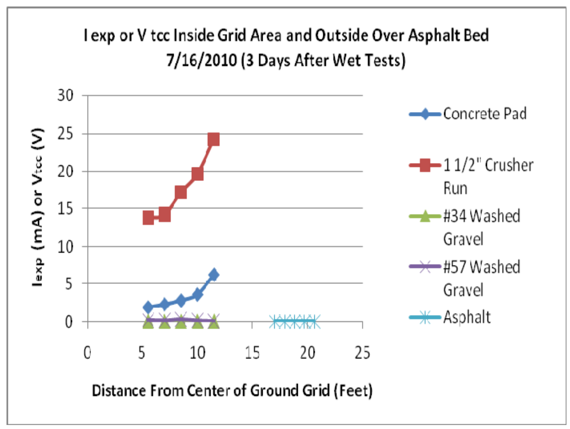
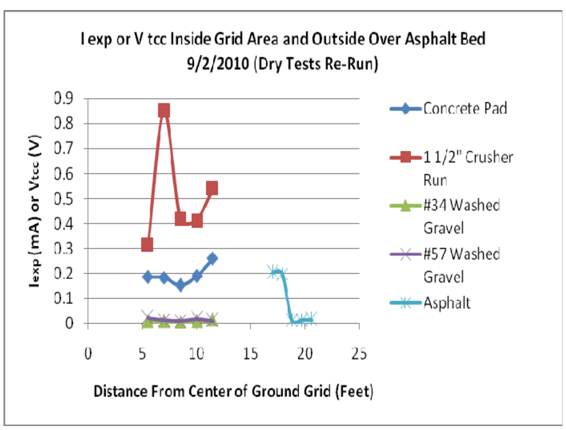


Figure 3-25: I_{exp} or V_{tcc} , (2 Days After Wet Tests)

Figure 3-26: I_{exp} or V_{tcc} (3 Days After Wet Tests)



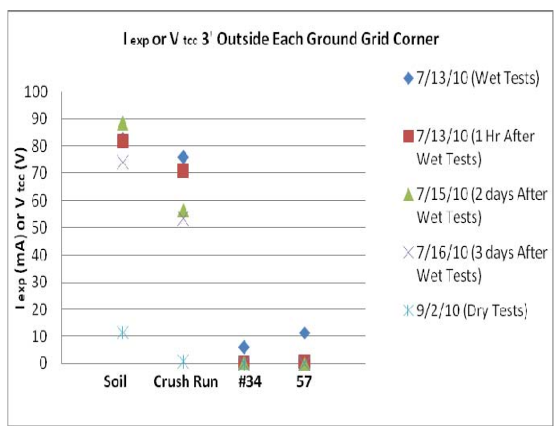


Figure 3-27: I_{exp} or V_{tcc} , (Dry Tests Re-run)

Figure 3-28: I_{exp} or V_{tcc} (Corner Points, All Weather)

The following observations are made from the exposure current data:

- Between wet and dry conditions, the wet condition causes the maximum exposure current for each type of surfacing material including the native soil.
- In wet conditions, the exposure currents are significantly higher for concrete and 1 ½" crusher run compared to washed gravels (#34 and #57) and asphalt.
- In wet conditions, the performance of 1½" crusher run and concrete is almost the same as the native soil.
- Between #34 and #57 washed gravel, the perfrormance of #34 gravel is slightly better due to larger sized rocks.
- The exposure currents on washed gravel (#34 and #57) and asphalt beds reduce dramatically within an hour from wetting. In comparison, 1 ½" crusher run took three days of drying to reduce the exposure current to the same level.
- As expected, the highest exposure currents were measured three feet outside the ground grid corners.
- In the case of washed gravel and asphalt, the change in exposure currents are much more dramatic (several orders of magnitudes) compared to the change in the open circuit touch voltage.

Thevenin's Equivalent Resistance

One way to characterize a surfacing material and its resistive parameters is to determine the Thevenin's equivalent resistance in series with worker's feet by measuring open and closed circuit touch voltages. Figures 3-29 through 3-34 show the Thevenin's equivalent resistance of gravel, concrete and asphalt beds at several different test locations around the ground grid. Each figure shows the resistances for a particular environmental condition. Figure 3-34 shows the equivalent resistances for asphalt bed in various wet and dry conditions.

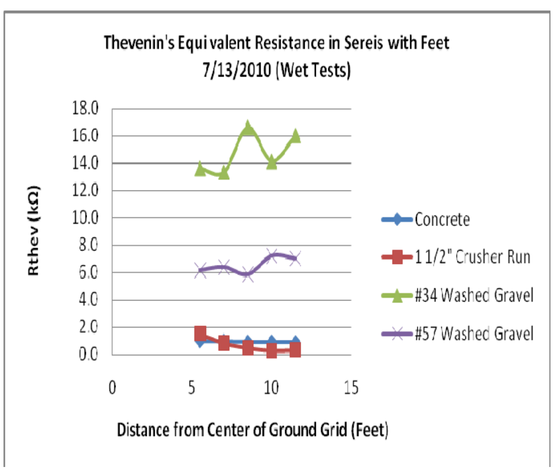


Figure 3-29: R_{thev} , (7/13/2010, Wet Tests)

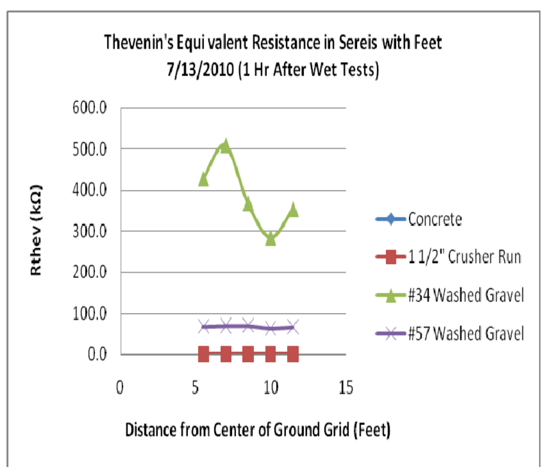


Figure 3-30: R_{thev} (1 Hr After Wet Tests)

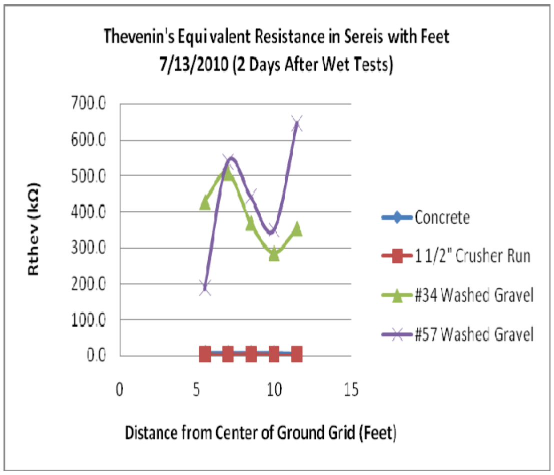


Figure 3-31: R_{thev} , (2 days After Wet Tests)

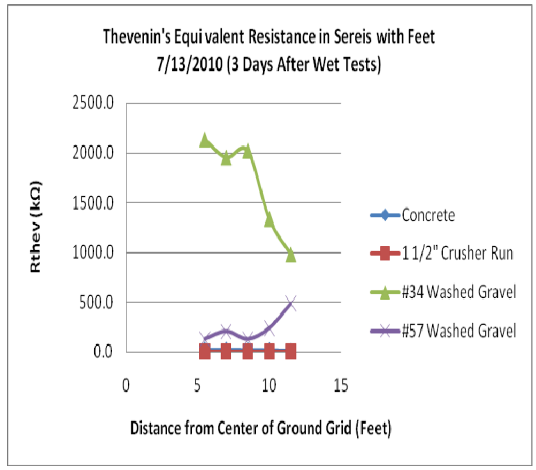


Figure 3-32: R_{thev} (3 Days After Wet Tests)

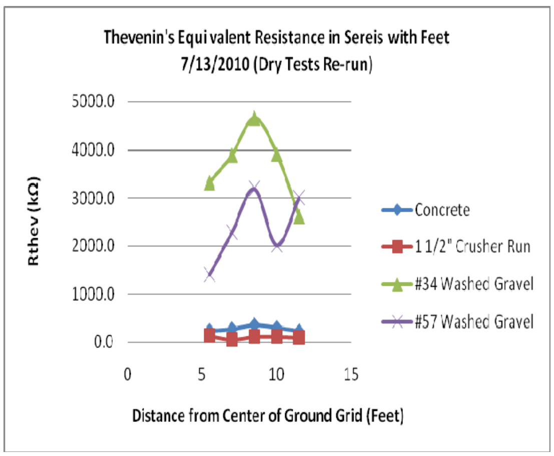


Figure 3-33: R_{thev} , (Dry Tests Re-run)

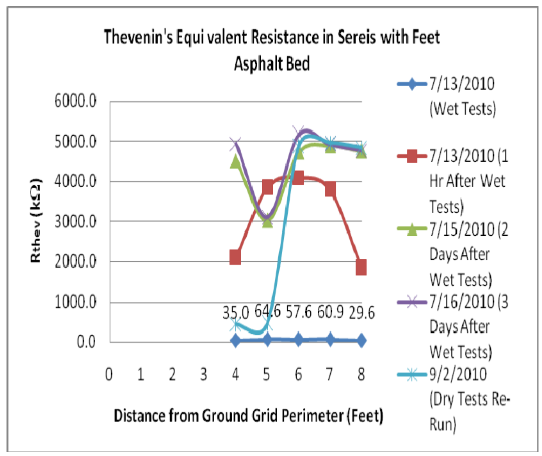


Figure 3-34: R_{thev} (Asphalt, Wet to Dry Conditions)

The following observations are made from Thevenin's equivalent resistance data presented in Figures 3-29 through Figures 3-34:

- The contact resistance at the feet and overall resistivity of the surfacing material have significant influence on Thevenin's equivalent resistance protecting a worker. Both of these variables in turn are highly dependent on the moisture content of the surfacing material.
- In the case of each surfacing material, the lowest Thevenin resistances were calculated for the wet surface conditions.
- In the case of asphalt and washed gravel, the Thevenin's equivalent resistances dramatically increased (several orders of magnitudes) as the surfaces became dry.
- For most surface covering materials and for relatively wetter environmental conditions (wet and one hour after wet tests), the Thevenin resistances were consistent at all test locations. As the surfaces became dry, the resistances between the locations changed significantly, particularly in the case of washed gravel and asphalt beds.

Apparent Resistivity of Asphalt by Four-pin Method

Asphalt resistivity was measured using the four-pin method as described in the previous sections. The resistivities calculated from the measured voltages and currents are shown in Figure 3-35

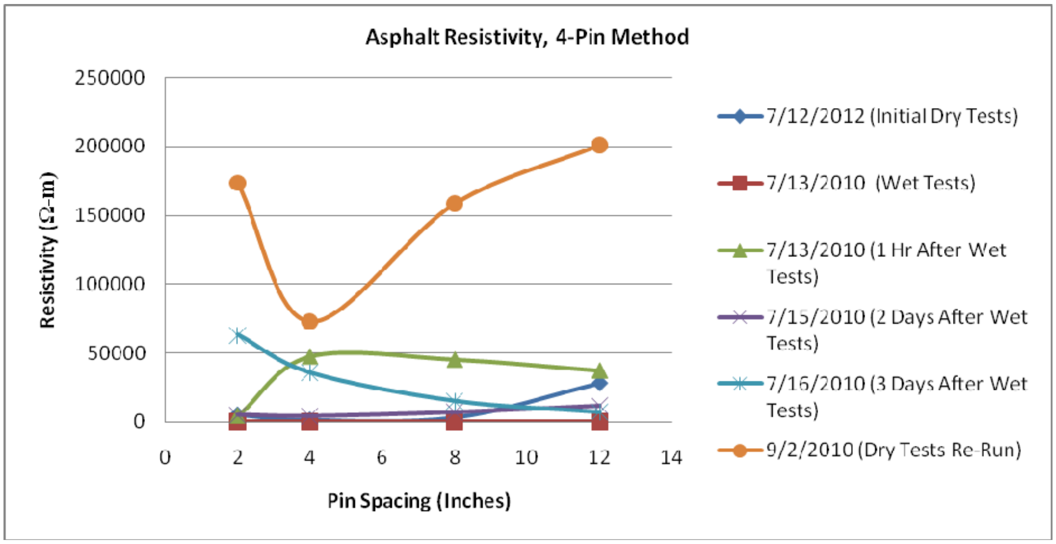


Figure 3-35 – Asphalt Resistivity at Different Pin Spacing and Moisture Conditions

The measured resistivities of the asphalt at different pin spacing and different moisture conditions do not seem to have any consistency or trends. This is primarily due to difficulties in establishing a low resistance contact between the nails (used as pins) and surrounding asphalt.

Gravel Resistivity Data Determined from Volume or Container Method

The data for gravel resistivities are presented in a bar chart format in Figures 3-36 through 3-38. Each figure shows the resistivities of 1½ ' crusher run and #57 and #34 washed gravel samples for one environmental condition. As mentioned previously, each sample was first tested in dry condition followed by saturating the sample with tap water and finally draining the water off the container.

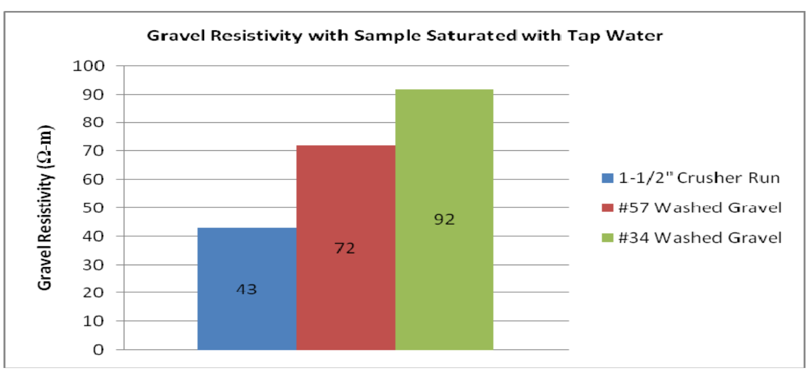


Figure 3-36: Resistivity of Gravel Samples (Sample Saturated with Tap Water)

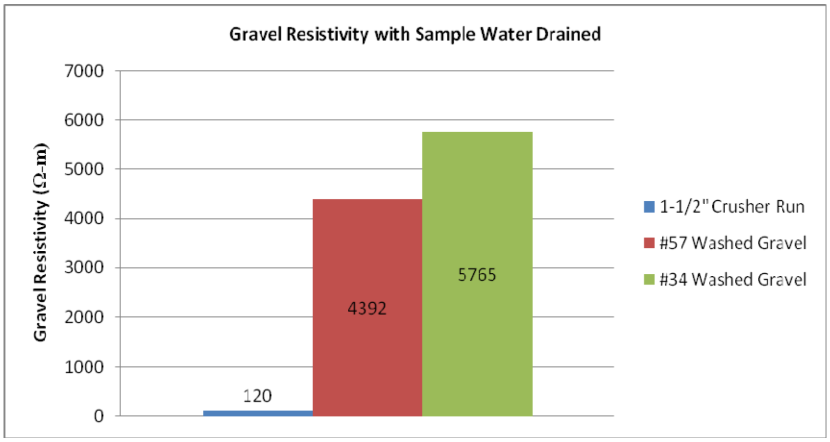


Figure 3-37: Resistivity of Gravel Samples (Sample with Water Drained)

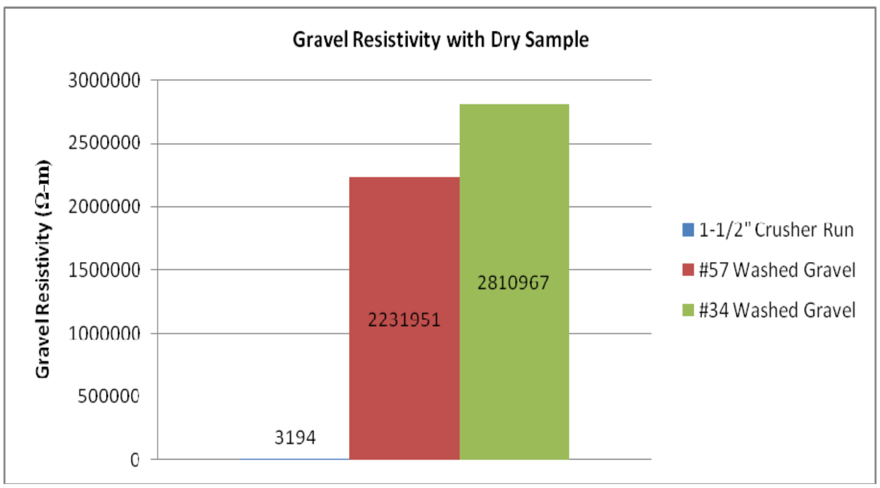


Figure 3-38: Resistivity of Gravel Samples (Sample Dry)

The data in Figures 3-36 through 3-38 clearly indicate superiority of #34 and #57 washed gravels compared to 1½" crusher run in protecting a worker. The data also indicate that the resistivity of washed gravel increases by a couple orders of magnitude just by draining the water from the container.

SECTION 4.0 CONCLUSIONS

The following conclusions were made in this project:

General

- The protective characteristics of a surfacing material are highly dependent upon its moisture content. A surfacing material is less effective in protecting a worker when it is wet.
- Crushed stones mixed with their own dust are significantly less effective compared to washed stones even in wet conditions.
- Dusty gravel retains the moisture for a long time increasing the time duration during which it is less effective. In comparison, the washed gravel dries out fast recovering its insulating properties.
- Among the washed gravels, the gravel with larger sized stones performs somewhat better than their smaller sized counterparts.
- Between concrete and asphalt, protective characteristics of asphalt are significantly better in almost any environmental condition.

Gravel and Asphalt Resistivity

- Overall the resistivity of washed gravel (#34 and #57) as measured using the volume method are significantly higher compared to 1½" crusher run gravel. The difference in their resistivity increased dramatically with the drying of the material.
- The resistivity of the asphalt bed at different pin spacing (4-Pin Method) and different moisture conditions did not seem to have any consistency or trends. This is primarily due to difficulties in establishing a low resistance contact between the nails (used as pins) and the surrounding asphalt.

Open Circuit Touch Voltage

- No significant difference was noted between the voltages measured from the pin to ground grid and those measured from worker's boots to ground grid.
- For a given ground grid current, the open circuit touch voltage primarily depends on the soil resistivity and the layout of the ground grid. Among various locations that were tested, the open circuit touch voltage increased with the distance from the center of the ground grid. The maximum touch voltages were measured at three feet outside the ground grid corners.
- Overall, the touch voltages increased with the drying of the surfacing material and soil.
- In the case of asphalt, the open circuit voltages could not be measured accurately using the Fluke 87 meter, particularly for the dry surface conditions. This was due to difficulty in achieving a low resistance contact between the nails and the surrounding asphalt. The measured voltages, as a result, were lower than what they should have been (Figure 3-5). A similar trend was observed in the case of #34 and #57 gravel in dry conditions due to high boot to surface contact resistances (Figures 3-15 and 3-16).

Open Circuit Step Voltage

- The step voltages at all measured locations are lower than corresponding touch voltages.
- Similar to touch voltages, the step voltages increase as the gravel and concrete beds continue to dry.
- Unlike touch voltages, the step voltages are higher near the center of the ground grid.

Exposure Current or Closed Circuit

- Between wet and dry conditions, the wet condition causes the maximum exposure current for each type of surfacing material including the native soil..
- In wet conditions, the exposure currents are significantly higher for concrete and 1 ½" crusher run compared to washed gravels (#34 and #57) and asphalt.
- In wet conditions, the performance of 1 ½" crusher run and concrete is almost the same as the native soil.
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- As expected, the highest exposure currents were measured three feet outside the ground grid corners.
- In the case of washed gravel and asphalt, the change in exposure currents are much more dramatic (several orders of magnitudes) compared to the change in the open circuit touch voltage.

Thevenin's Equivalent Resistance

- The contact resistance at the feet and overall resistivity of the surfacing material have significant influence on Thevenin's equivalent resistance protecting a worker. Both of these variables, in turn, are highly dependent on the moisture content of the surfacing material.
- In the case of each surfacing material, the lowest Thevenin resistances were calculated for the wet surface conditions.
- In the case of asphalt and washed gravel, the Thevenin's equivalent resistances dramatically increased (several orders of magnitudes) as the surfaces became dry.
- For most surface covering materials and for relatively wetter environmental conditions (wet and one hour after wet tests), the Thevenin resistances were consistent at all test locations. As the surfaces became dry, the resistances at various locations changed significantly, particularly in the case of washed gravel and asphalt beds.

SECTION 5.0 EQUIPMENT

Digital Multimeter: Fluke 87, CQ-4007
Fluke 87, CQ-4020
Fluke 87, CQ-4028

Ammeter: Fluke Amprobe 3000, CQ-4021

Soil Resistivity: AEMC CQ-4026

Step up transformer: HPS 15kV Type ANN 240-480 Step up Transformer

SECTION 6.0 REFERENCES

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[9] Thomson, P., "Resistivity Tests on Soil and Concrete", Internal Report, Los Angeles Department of Water and Power, August 8, 1977.