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LONG-TERM STUDY OF A GROUND ENHANCING MATERIAL

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Abstract – This paper presents an analysis of a full span of data assembled from the "National Electrical Grounding Research Project" in order to study the long-term effect of using a "ground enhancing material" in conjunction with various ground electrodes. Results are presented for a period up to 12 years. The resistance of ground electrodes enclosed in the ground enhancing material is compared with results for standard ground electrodes. The data analysis also considers seasonal and longer-term variations in the resistivity of the soil, which can be correlated with the resistance measurements. Based on this long-term experimental study, the paper provides some quantitative conclusions regarding the relative benefit of using the ground enhancing material. Finally, in order to better quantify the electrical and mechanical properties of the material, laboratory measurements were carried out on a range of samples in order to determine the main parameters.

1 – INTRODUCTION

Today's modern facilities require stringent design practices in the area of electrical grounding. Yet, ironically, grounding is not a well-understood area of electrical engineering. This situation is compounded by the fact that it is not easy to conduct studies of the performance of grounding systems, over a long period of time, under actual working conditions. The need for long-term performance data of commercially available ground electrodes is essential to engineers and designers of electrical grounding systems. Such data enable them to provide designs that will be reliable and effective for the life of the installation.

The need for an effective ground has been recognized for decades, mostly by power utilities. The emergence of digital electronics has resulted in more robust requirements for power quality and low impedance grounding systems. Modern electronic devices are highly susceptible to the effects of transient disturbances transmitted over power and data lines. The proper performance of the devices used to protect the electronic equipment, particularly transient voltage surge suppressors, is highly dependent on the existence of an effective, low impedance grounding system. Such a low impedance system is difficult to obtain when soil conditions are very poor, i.e., the soil resistivity is high. In cases like these, "ground enhancing materials" are often used. They help to lower the grounding system resistance.

In 1992, a long-term grounding test study was established with the objective of addressing issues such as the anticipated performance of ground electrodes over time and the effect of environmental conditions on their performance. Called the "National Electrical Grounding Research Project" (NEGRP), this North American study was carried out under the supervision of the National Fire Protection Research Foundation [1-6]. The study focused on the evaluation of commonly used and commercially available ground electrodes. The study has provided performance data over a period of more than 10 years for a variety of soil and climatic conditions. It has been conducted in three phases – in Nevada (Phase 1) commencing in 1992, in Texas, Illinois, New York State, Virginia (Phase 2) commencing in 1997 and in NASA Mofette Field California (Phase 3) commencing in 2001. The specific objective of the test program has been to evaluate the performance and physical integrity of the electrodes over time, as determined by resistance measurements, in soils with varying resistivity values, geological, moisture and temperature conditions. Exothermic, compression and mechanical connections have been used to attach the insulated ground conductor (test lead) to the ground electrodes.

With these aims in mind, Section 2 of the paper presents the data and analysis for one specific part of the NEGRP, namely the study of the long-term effect of using an engineered ground enhancing material, called "GEM", in conjunction with ground electrodes. The results are presented for a total period of up to 12 years at each site. The resistance of ground electrodes enclosed in the GEM is compared with the results for standard ground electrodes. The data analysis also considers seasonal and longer-term variations in the resistivity of the soil, which can be correlated with the resistance measurements. Based on this long-term experimental study, the paper provides some quantitative conclusions regarding the relative benefit of using GEM.

Importantly, in order to better quantify the electrical and mechanical properties of the material, laboratory measurements were carried out on a range of samples in order to determine the main parameters. Section 3 of the paper presents the mechanical properties, including bulk powder density, compression strength, flexural strength, the effect of environmental variables such as temperature and moisture, and shrinkage from slurry to solid state. Finally, Section 4 of the paper reports briefly on additional laboratory measurements of electrical properties that are currently in progress, such as the resistivity variations during the transition from slurry to solid state and the impedance under surge-current conditions.

2 – LONG-TERM STUDY OF GEM

2.1 – DESCRIPTION OF THE DATA

GEM has a long history of usage in scenarios where a reduction in soil resistivity and hence grounding system resistance is needed, by virtue of the terrain in which the grounding system has to be installed. The following analysis of the NEGRP data was carried out in order to better quantify the "performance" of GEM. At the time of writing this report, data collection from the sites appeared to have come to a halt, so the data analysis constitutes the most up-to-date information available.

Data from a total of 9 sites were analysed. The 9 sites and the data span for each are as follows: Balboa (8.4 yrs), Charleston (4.6 yrs), Lone Mountain (11.8 yrs), Pawnee (9.9 yrs), and Pecos (11.4 yrs), in NEVADA, Dallas TEXAS (5.5 yrs), Northbrook ILLINOIS (5.2 yrs), Poughkeepsie NEW YORK (2.9 yrs) and Staunton VIRGINIA (6.4 yrs).

The NEGRP involved the installation and monitoring of many different ground electrodes. Following the naming conventions in the NEGRP study, the specific electrodes analyzed in this paper are:

C. #4 AWG solid copper wire, 25 ft long, centered in 6" x 6" of GEM, with the top of the GEM 6" below grade;
D. #4 AWG solid copper wire, 25 ft long, in 6" x 6" of 2500 psi concrete, with the top of the concrete 6" below grade;
E. 5/8" x 8-ft vertical, copper-bonded ground rod, centered in a pre-drilled 9" hole and encased in GEM;
H. 5/8" x 8-ft vertical, copper-bonded ground rod, driven into virgin soil.

In the Phase 2 sites (Texas, Illinois, New York and Virginia), electrodes C and D were discontinued, so no data is available for these from 1997 onwards.

The connections used in the long-term study were both of the exothermic (CADWELD) and mechanical varieties. Whilst there are well-documented differences in the long-term performance of different connection methods, the overall grounding system resistances were similar during the functional lifecycle of the system. Hence, they were averaged in order to get a single representative value for each electrode type. Values of soil resistivity, temperature and moisture level were taken to be those measured at a depth of 10 feet below the surface.

2.2 – ANALYSIS

The NEGRP long-term data for the four electrodes identified above were plotted, statistics were computed, and a correlation analysis was carried out as a function of the physical variables.

Figure 1 contains a plot of the data for one of the nine sites, i.e., Balboa, Nevada. The top graph shows the soil temperature, moisture and resistivity, and the bottom graph shows the electrode resistance as a function of time.

Table 1 shows the mean values and trends for each of the sites for soil temperature, moisture and resistivity, along with the electrode resistances. The standard deviations quoted are 1σ (but not one standard error of the mean). The parameter Δ_ρ is the percentage change in soil resistivity from the start to the end of the experiment. The value $\Delta_{C,\ D,\ E\ or\ H}$ is absolute change in resistance of a given electrode from start to end. Absolute resistance was quoted here because of the large difference between the electrodes where, for example, a 1 Ω change in an electrode with a very low resistance would be a very large percentage change without it necessarily being a detrimental change in terms of overall performance.

Table 2 presents the results of a correlation analysis carried out on the data. The degree of correlation between soil resistivity and temperature, resistivity and moisture, and between each series of electrode resistance and soil resistivity is presented. A 2σ (95%) significance test was applied to the correlation coefficient in order to rule out the possibility that an apparently significant correlation is in fact from an uncorrelated parent population.

2.3 – RESULTS

The following *specific* conclusions can be made about individual sites or locations:

- Using the Nevada data only, the mean, long-term electrode resistance was:
    - 18 Ω for GEM-encased vs 39 Ω for concrete-encased *horizontal* electrodes
    - 3.6 Ω for GEM-encased vs 19.8 Ω for driven *vertical* rods

  i.e., a 53% and 82% reduction in electrode resistance respectively.
    - Furthermore, there is a corresponding reduction in the *variability* (standard deviation) of the resistance of the electrodes with time, namely 60% and 67% respectively.
- Using the Phase 2 data (Texas, Illinois, New York and Virginia), the mean, long-term electrode resistance was 17.5 Ω for GEM-encased vs 44.5 Ω for driven *vertical* rods, i.e., a 61% reduction in electrode resistance.
    - Furthermore, there is a corresponding reduction in the *variability* (standard deviation) of the resistance of the electrodes with time, namely 63%.
- It is also interesting to note that these reduction factors are relatively constant across different sites and hence soil types and resistivities.
- In Nevada, there is no correlation between soil resistivity and the resistance of electrodes C and D, even though the resistivity varied by a factor of up to 6 from site to site.
- In Nevada, there is no correlation between soil resistivity and the resistance of electrode E, but some correlation between resistivity and the resistance of electrode H.
- In the Phase 2 sites, there is generally a strong correlation between soil resistivity and resistance of the vertical rods.

General conclusions regarding GEM are presented in Section 5 of the paper.

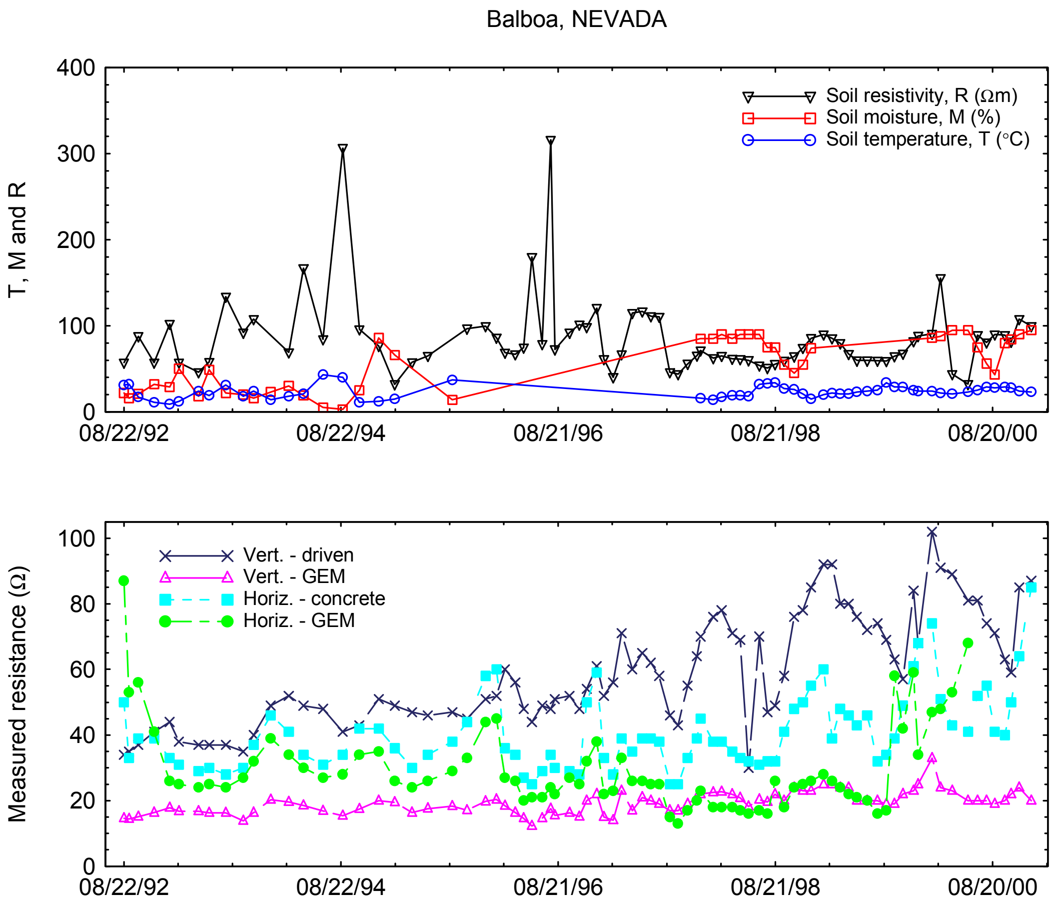

Figure 1 – More than 8 years of grounding resistance data for the Balboa site in Nevada, USA.

Table 1: Mean values and trends for the nine long-term sites in the NEGRP study for soil temperature, T, moisture, M, resistivity, ρ, and electrodes C, D, E and H. Standard deviations quoted are 1σ. Δ_ρ is the percentage change in soil resistivity from the start to the end of the experiment, and $\Delta_{C,D,E,H}$ is the absolute change in resistance of the given electrode from start to end.

SITE	Mean T (degC)	Mean M (%)	Mean ρ (Ωm)	Δ_ρ (%)	Electrode resistance (Ω)							
					C	Δ_C	D	Δ_D	E	Δ_E	H	Δ_H
Balboa, NV	23 ± 7	56 ± 31	85 ± 46	-23	30 ± 13	-7	41 ± 12	+18.6	19 ± 3	+8	59 ± 17	+48
Charleston, NV	23 ± 11	26 ± 15	20 ± 16	-16	35 ± 19	+58	97 ± 87	+108	4 ± 1	+0.5	12 ± 3	+9
Lone Mountain, NV	22 ± 6	50 ± 25	24 ± 16	-54	8 ± 4	+15	13 ± 5	+15	5 ± 4	+3.4	6 ± 2	-1.1
Pawnee, NV	23 ± 7	64 ± 36	13 ± 14	-40	8 ± 7	+20	10 ± 3	+7	3 ± 1	+1.5	11 ± 4	+12
Pecos, NV	23 ± 7	41 ± 17	15 ± 13	-57	9 ± 5	-0.8	32 ± 13	+10	5 ± 2	+2.8	11 ± 7	+20.3
Dallas, TX	19 ± 3	71 ± 27	33 ± 6	-11					4 ± 1	+0.6	7 ± 2	+0.4
Northbrook, IL	11 ± 2	93 ± 5	28 ± 3	-3					6 ± 1	+1.1	11 ± 5	+10.6
Poughkeepsie, NY	10 ± 3	90 ± 3	195 ± 24	-7					46 ± 6	+2.4	131 ± 17	+22
Staunton, VA	14 ± 3	84 ± 8	112 ± 35	-20					14 ± 2	+0.5	29 ± 3	-5

Table 2: Correlation analysis and significance test for the nine long-term sites in the NEGRP study. The significance test was applied using a 2σ or 95% confidence level.

SITE	ρ - T	Signif. ?	ρ - M	Signif. ?	C - ρ	Signif. ?	D - ρ	Signif. ?	E - ρ	Signif. ?	H - ρ	Signif. ?
Balboa, NV	0.246	Yes	-0.383	Yes	0.043	No	0.045	No	-0.121	No	-0.105	No
Charleston, NV	0.030	No	-0.050	No	-0.133	No	-0.050	No	-0.221	No	0.303	Yes
Lone Mountain, NV	-0.008	No	-0.441	Yes	-0.110	No	-0.069	No	0.030	No	0.278	Yes
Pawnee, NV	0.116	No	-0.193	No	-0.093	No	0.003	No	-0.055	No	-0.100	No
Pecos, NV	0.110	No	-0.412	Yes	0.042	No	0.015	No	-0.081	No	-0.058	No
Dallas, TX	0.288	Yes	-0.498	Yes					0.641	Yes	0.718	Yes
Northbrook, IL	-0.562	Yes	-0.202	No					0.707	Yes	-0.068	No
Poughkeepsie, NY	-0.763	Yes	-0.569	Yes					0.767	Yes	0.778	Yes
Staunton, VA	0.059	No	0.042	No					0.665	Yes	0.672	Yes

3 – LABORATORY MEASUREMENTS OF MECHANICAL PROPERTIES

Although the primary function of any ground enhancing material is to reduce the electrical resistance, the mechanical properties of the material also have an indirect role on overall performance. Shrinkage of the material should be accounted for accurately to improve installation and minimize direct exposure of the ground electrode to the surrounding soil. The mechanical integrity of the GEM is suspected to influence the long-term corrosion resistance of the electrode – cracks in the GEM are larger pathways for corrosion agents to directly reach the electrode surface. Key variables suspected of influencing the mechanical strength are the *mix ratio* (initial water content), *curing time*, *temperature*, and *moisture / humidity* levels. GEM can be installed either directly in its dry powdered form or by mixing the powder with water to form a slurry. The recommended mix ratio of water to GEM is 5.7 to 7.6 liters of water per 11.3 kg. The water volume percentage of the mixture for a mix ratio of 5.7 and 7.6 liters is 27% and 33%, respectively.

3.1 BULK DENSITY

The dry powdered form of GEM has a density which ranges from 0.7 – 1.1 g/cm^3, depending on compaction level. Weight and dimensional measurements were also taken just before compression testing in order to calculate the density of cured specimens. The solid density of cured specimens at 5.7 and 7.6-liter mix ratios is approximately 1.2 and 1.4 g/cm^3, respectively. Shrinkage of GEM from slurry to solid form was measured using a 10 ml graduated cylinder with 0.1 ml graduations. The average shrinkage was found to be approximately 2%. This shrinkage does not include the water (< 5% of total volume) which pools on top of any container of GEM slurry due to settling and evaporates easily. In typical installations in soil, a portion of this water is absorbed into the surrounding medium.

3.2 COMPRESSIVE STRENGTH

Compressive strength was measured following ASTM C109 [7]. Although GEM is substantially different than concrete, standard ASTM test methods which are commonly used to test concrete were followed as much as possible to improve repeatability. The GEM slurry was mixed by hand with the specified quantity of water and poured into rigid 50-mm cube molds for curing.

Figure 2 shows the effect of *cure time* and *mix ratio* on compressive strength. Each data point represents a set of 3 or 6 identical specimens which were used to calculate the standard deviation of each set – the error bars on each point represent one standard deviation. In most cases, the standard deviation is less than 10% of the compressive strength which indicates satisfactory repeatability. A linear regression is included for each mix ratio to help clarify the major trends.

The following key results were obtained:

- Compressive strength increases with cure time at all mix ratios. On average, the strength of the 5.7-liter mix increases by at least 50% from 175 to 500 hours curing time; at least 500% from 24 to 240 hours for the 6.6-liter mix; and at least 100% from 120 to 500 hours for the 7.6-liter mix.
- Compressive strength increases with decreasing mix ratio. Compressive strength of the 5.7-liter mix is more than 100% greater on average than the 7.6-liter mix ratio. However, there is a minimum mix ratio – approximately 5.7 liters – which produces a uniform mixture.
- A comparison of strength between 5.7 and 6.6 liter mix ratios is inconclusive without further study. The strength is comparable between 150 and 250 hours; however more data is required for the 6.6-liter mix beyond 250 hours.
- In order from highest curing rate to lowest curing rate, the order is 6.6 (4.5 x 10^{-3} MPa/hr), 5.7 (2.3 x 10^{-3} MPa/hr), and 7.6 (7.6 x 10^{-4} MPa/hr). Therefore, on average the curing rate of the 5.7-liter mix is 3 times as great as the 7.6-liter mix.

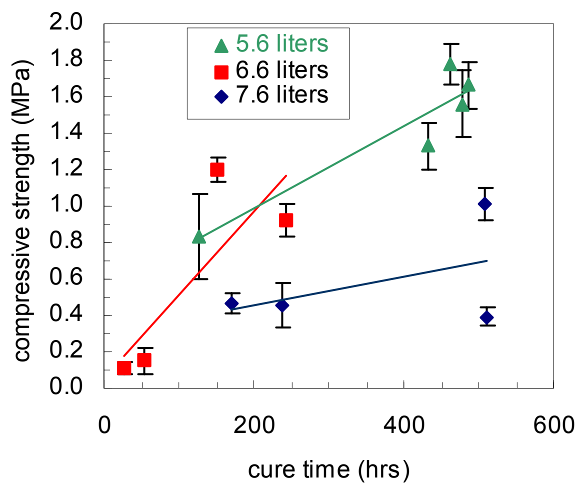

Figure 2 – Compressive strength of GEM for a range of curing times (27 – 511 hrs) and mix ratios (5.7, 6.6, 7.6 liters).

Figure 3 highlights the effect of *cure temperature* on compressive strength for various cure times. Although more study is required to fully characterize the useful range of mix ratios, cure time, and temperature, the following results were reached:

- Compressive strength increases with increasing cure temperature. On average, a cure temperature of 28°C increases the compressive strength by at least 80% compared to a 7°C cure temperature for the 5.7-liter mix (up to 195 hrs) and at least 90% for the 6.6-liter mix (up to 319 hrs).
- The effect of cure temperature can be quantified in terms of strength gained per degree Celsius of temperature increase. In these terms, the 5.7-liter mix gains strength at 3.9 x 10^{-2} MPa/°C and the 6.6-liter mix gains strength at 3.5x10^{-2} MPa/°C.

3.3 – FLEXURAL STRENGTH

Flexural strength is another key measure of mechanical durability. Flexural strength tests were performed following ASTM C293 [8] for center-point loading of simple beams. The specimen beam dimensions were 355.6 mm x 101.6 mm x 101.6 mm. All of the specimens were cured at room temperature, 21 ± 1°C. Flexural strength is defined in terms of a modulus of rupture given by $R = 3 P L / 2 b d^2$, where R is the modulus of rupture, P is the maximum applied load, L is the span length, b is the average specimen width, and d is the average specimen depth.

The effect of cure time on flexural strength at two mix ratios (6.6, 7.6 liters) is shown in Figure 4. Each data point represents a single specimen, and a linear regression is included for the mix ratio at 6.6 liter to clarify the fundamental trendline. Similar to the compressive strength, flexural strength increases with decreasing mix ratio. Increasing cure time also leads to increased flexural strength, although at a mix ratio of 7.6 liters the increase is small. The modulus of rupture increases 100% from 50 to 250 hours at a 7.6-liter mix ratio.

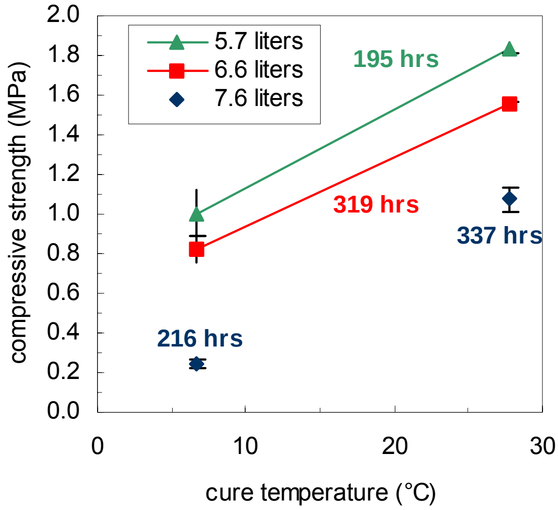

Figure 3 – The effect of temperature on compressive strength of GEM at different mix ratios and curing times. The cure time is indicated for separate data points (7.6 liter) or for all points associated with a linear regression (5.7, 6.6 liters).

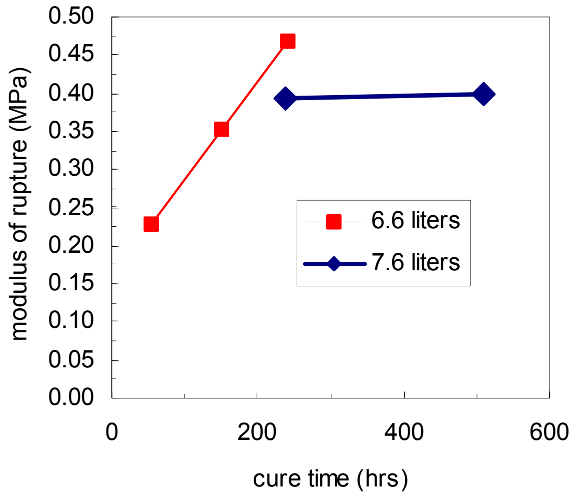

Figure 4 – The effect of cure time on the flexural strength at different mix ratios (6.6, 7.6 liters).

4 – PRELIMINARY LABORATORY MEASUREMENTS OF ADDITIONAL ELECTRICAL PROPERTIES

4.1 - VOLUME RESISTIVITY

One of the most important electrical properties of GEM is the volume resistivity. A new series of long-term volume resistivity measurements is currently underway, and only preliminary results are reported here. Standard “Miller soil boxes” and two measuring devices, namely a UNILAP GEO X and a SATURN GEO, both manufactured by LEM Instruments, are being used for the ongoing measurements.

The four-point or Wenner method has been used to measure the resistance of GEM samples. The resistance values were used to calculate the GEM resistivity using the following formula $\rho = R \times A/L$, where ρ is the resistivity in Ωm, R is the resistance in Ω, A is the cross-sectional area of the box in m^2, and L is the length between the inside edges of the inner measurement electrodes in m. The Miller box is designed to simplify the formula by providing a value of A/L close to unity. However, this simplification applies only if the Miller box is completely filled with the material under test. Since there was no guarantee this was the case, a more accurate cross-sectional area was measured and used in the resistivity calculations.

The GEM was prepared as a slurry using typical mix ratios (see Section 3). The resistivity of the material is being measured over periods of days, weeks and months at appropriate intervals. At the time of writing, the measurements were still underway.

The aim of these measurements is to provide more accurate quantification of the resistivity of GEM under different conditions. Some of the initial results that have been obtained are as follows:

- Resistivity in the dry powder form is < 0.4 Ωm.
- The resistivity of GEM in an isolated, cured and, hence, very dry state is slightly more than tap water and very damp clay taken from soil outside.
- The variation in resistivity from a slurry to a fully cured state can be quite large, indicating that final measurements on grounding systems employing any ground enhancing material should be taken on fully cured systems.

4.2 - SURGE IMPEDANCE OF GEM

Often, grounding measurements are made with low-magnitude DC (or low frequency) currents. However, under lightning transient conditions, the behaviour of grounding systems can be quite different. Hence, experiments are also under way to measure the performance of GEM under surge current conditions.

Figure 5 shows the voltage and current waveforms from a test on a GEM sample using a 3kA, 8/20 µs surge current. The response is very much a resistive one with, perhaps, some signs of local ionisation upon application of the impulse. The impedance in this case was close to the DC resistance value, but note that this measurement was taken on an isolated GEM sample in a Miller soil box. Further tests of this kind and also with GEM in soil are planned, particularly with our in-house high-current surge generator, which is capable of producing 8/20 μs impulses at 150 kA and 10/350 μs at around 7 kA.

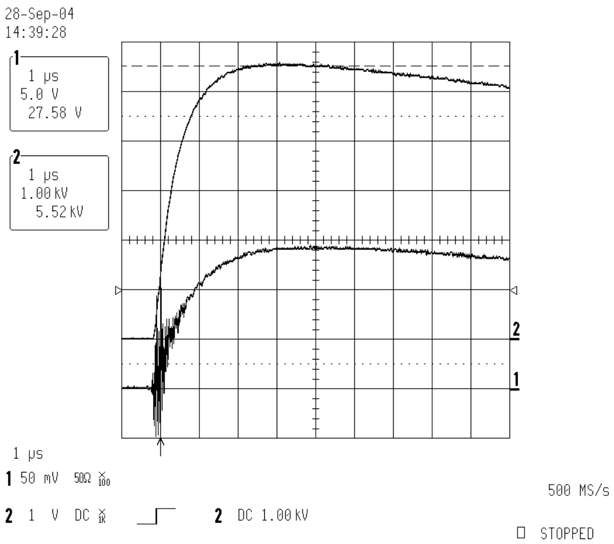

Figure 5 – Voltage and current waveforms from a test on GEM using a 3kA, 8/20 μs surge current.

5 - CONCLUSIONS

The following *general* conclusions can be made from the results:

- The results confirm the expected variation of soil resistivity with moisture or water content, i.e., a negative correlation (increased moisture ⇒ lower resistivity). However, in four of the nine sites, the relationship was not significant. This may have been due to the change in the method of moisture measurement midway through the NEGRP, which resulted in an apparent jump in the moisture levels.
- The results show only a very weak correlation between soil temperature and resistivity, highlighting the fact that classical or textbook relationships between these variables are not necessarily obvious in long-term field data when other variables are also present.
- Interestingly, all of the sites displayed a net *decrease* in soil resistivity with time. It is not possible to tell from the data whether this decrease is real or due to measurement issues.
- On the other hand, almost all of the electrode measurements at each site showed a tendency of the resistance to *increase* over time. A decrease in soil resistivity would be expected to result in a decrease in electrode resistance measurements. Over the same long time interval, there was no significant change in the mean temperature or soil moisture content (although there appears to be a step increase in some of the moisture readings around 1997, when the moisture meter used to take measurements was changed to a "Delmhorst" unit).
- Clearly, the performance of GEM in reducing electrode resistance and the seasonal and long-term variability in this parameter is very good. For all electrode types investigated, the reduction factor for grounding system resistance, seasonal and long-term variability is much better than 50%.
- Mix ratio, cure time, and temperature all influence compressive and flexural strength substantially. Compressive and flexural strength increase with decreasing mix ratio (less water). Both compressive and flexural strength increase with increasing cure time at all mix ratios. Additionally, compressive and flexural strength increase with increasing cure temperature.

6 – REFERENCES

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