Characterization of Semi-Insulating Devices in Electrophotography by the Electrostatic Charge Decay (ECD) Technique

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Characterization of Semi-insulating Devices in Electrophotography by the Electrostatic Charge Decay (ECD) Technique

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A technique for characterizing electrophotographic (EP) devices using open-circuit voltage decay with complementary charging current measurements is described. The efficacy of this method, known as Electrostatic Charge Decay (ECD) technique, has been demonstrated on many semi-insulating EP components including charge rollers, development rollers, transfer rollers, transfer belts, and paper. In this paper, the principle behind the technique is presented. Also, the practical implementation in a commercial instrument, including dielectric relaxation measurement, current measurement, and full-device mapping, is illustrated with experimental results that demonstrate the relevance of the technique to EP.

Introduction

The prevailing method for characterizing electrophotographic (EP) devices uses closed-circuit constant voltage measurements to determine a device "resistance". However, it is well known that the resistance determined by this method is often inconsistent and does not always correlate with device performance. The origin of such difficulties and complexities is due to the non-Ohmic nature of the semi-insulating materials used to construct the EP devices. It has been shown with a first principle charge transport theory that full characterization of such materials involves specification of charge density, charge mobility and its field dependence, and interfacial charge injection.[1,2,3] Therefore, a more appropriate technique for characterizing such materials is an open-circuit voltage decay method known as Electrostatic Charge Decay (ECD), in combination with complementary charging current measurements.[4,5,6] The efficacy of the ECD technique has been demonstrated on many semi-insulating EP components including charge rollers, development rollers, transfer rollers, transfer belts, and paper. However, the determination of this large number of parameters over a large area of samples is not convenient for practical purposes, such as quality control. It is desired to have a single parameter that reveals the effects of all the above transport parameters and can be determined efficiently over a large area. We shall introduce an "equivalent resistance" R_{eq} as such a figure of merit. In the next section, the definition and the principle for the determination of its value are described. This is followed by descriptions of the practical implementation of the technique in a commercial instrument that performs dielectric relaxation measurement, charging current measurement, and full-device mapping. Experimental results on samples of EP devices are presented to demonstrate the practical relevance of this technique to EP

Principle of Equivalent Resistance Measurements

An area of sample under the corona charger is represented by an equivalent resistance R_{eq} and a capacitance C in parallel, as shown in Fig. 1. A well-known empirical relation between the charging current density J_C and the surface voltage V is,[5]

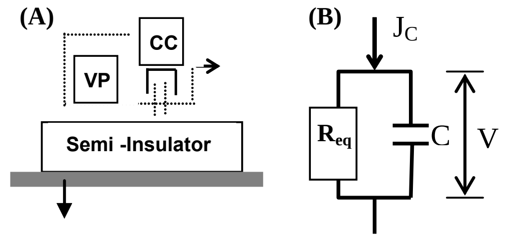

Fig. 1. (A) Schematic of ECD experimental setup, with corona charger (CC) and voltage probe (VP); (B) Equivalent circuit for the sample.

$$J_C = J_{mx}(1 - V/V_{mx}) = J_{mx} - V/R_{ch} \quad (1)$$

where J_{mx} and V_{mx} are two empirical parameters and $R_{ch} = V_{mx}/J_{mx}$ represents the charger resistance. The equivalent circuit equation for charging the sample is,

$$C(dV/dt) + V/R_{eq} = J_{mx} - V/R_{ch} \quad (2)$$

with a solution for the surface voltage V as,

$$V(t) = J_{mx}R_x[1 - \exp(-t/\tau)] \quad (3)$$

where, $R_x = R_{eq}R_{ch}/(R_{eq} + R_{ch})$ (4)

and $\tau = CR_x = CR_{eq}R_{ch}/(R_{eq} + R_{ch})$ (5)

Substituting (3) in (1), the charging current density is,

$$J_C(t) = J_{mx}R_x[1/R_{eq} + (1/R_{ch})\exp(-t/\tau)] \quad (6)$$

An apparent resistance R_{ap} at a time t is defined by,

$$R_{ap}(t) = V(t)/J_C(t) = R_{eq}[1- \exp(-t/\tau)]/[1+ (R_{eq}/R_{ch})\exp(-t/\tau)] \quad (7)$$

For $t >> \tau$, $R_{ap} = R_{eq}$. With the charger and the sample both stationary, one can measure the asymptotic value of current density, calculate the corresponding asymptotic voltage from Eq.(1), and obtain the asymptotic value of R_{ap} which is equal to R_{eq}. With a scanning charger and voltage probe (as in Fig.1), the charging time may not satisfy the condition: $t >> \tau$.

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Furthermore, the current and voltage measurements are not simultaneous for a given position, or the two measurements are not for the same position at a given time.

Let the sizes (in the scan direction) of charger, probe and the space in between be denoted by W_C, W_P and W_S, respectively. With a scan speed s, the charging time is $t_C = W_C/s$. After the charger passes over a position x_o by a time t_d, the voltage decays as,

$$V(t_d) = V(t_C)\exp(-t_d/R_{eq}C) \quad (8)$$

The voltage measured by a probe V_{av} is the average of voltages from $x = x_o - W_S$ to $x_o - W_S - W_P$, corresponding to the decay time from $t_d = t_S$ to $t_S + t_P$, (see Fig.2), where $t_S = W_S/s$ and $t_P = W_P/s$.

$$V_{av} = V(t_C)\{\int_{ts}^{ts+tp} \exp(-t_d/R_{eq}C)dt_d\}/t_P = V(t_C)(R_{eq}C/t_P)\{\exp(-t_S/R_{eq}C) - \exp[-(t_S+t_P)/R_{eq}C]\} \quad (9)$$

where $V(t_C)$ is given by Eq.(3).

The current is measured under the charger ahead of the probe. Thus, the measured current density J_{av} is the average of local current density over W_C, corresponding to time t = 0 to $t = t_C$, (see Fig. 2). Using Eq.(6) for $J_C(t)$, we have,

$$J_{av} = \int_0^{Wc} J_C(t)dx/W_C = \int_0^{tc} J_C(t)s dt/W_C = J_{mx}(R_x/R_{eq}t_C)\{t_C + (\tau R_{eq}/R_{ch})[1-\exp(-t_C/\tau)]\} \quad (10)$$

The apparent resistance for each speed s (or charge time t_C) is defined as the ratio of two measurable quantities V_{av} and J_{av}:

$$R_{ap} = V_{av}/J_{av} = f(R_{eq}) \quad (11)$$

It is a unique function of R_{eq}. Thus, R_{eq} can be determined from measured R_{ap} by interpolation of Eqs.(9)-(11). Figure 3 shows examples of R_{ap} calculated as a function of R_{eq}. The variables and parameters are expressed in a set of normalized units defined below.

Variable	Units	Typical value
Width	W_C	0.3 cm
Voltage	V_{mx}	10^3 Volts
Current density	J_{mx}	13×10^{-6} A/cm^2
Capacitance	C	5×10^{-11} F/cm
Resistance	$R_{ch}=V_{mx}/J_{mx}$	0.75×10^8 Ω.cm^2
Time	$t_o = CR_{ch}$	3.75×10^{-3} sec
Speed	$s_o = W_C/t_o$	80 cm/sec

With this set of normalized units, the R_{ap} vs. R_{eq} relation is determined with only three input parameters: W_S, W_P and s, expressed in the normalized units. In Fig. 3(A), the widths, W_S and W_P are fixed, and the scan speed s is varied. In Fig. 3(B) W_P and s are fixed, and W_S is varied. It can be seen that R_{ap} becomes insensitive to change in R_{eq} at large R_{eq}/R_{ch} values. The sensitive range can be shifted by changing the scan speed s and/or the spacing W_S. Lower speeds or larger spacing extend the sensitive R_{eq} range to higher values.

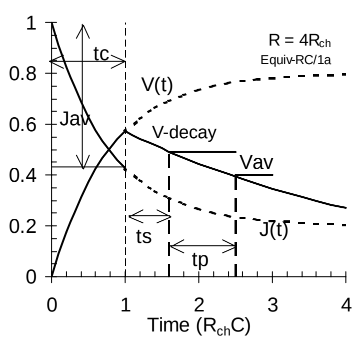

Fig.2. Time relations of measured current and voltage with scanning charger and probe.

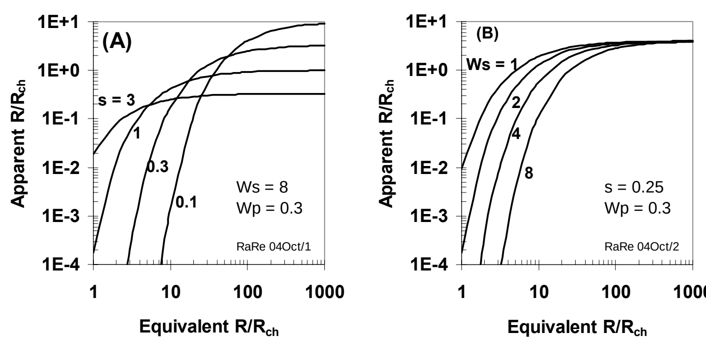

Fig. 3. Numerical examples of Rap vs. Req

Equipment, Experiments and Results

The equivalent resistance measurement technique described above is implemented in a commercially available equipment (DRA-2000L)[8]. Fig. 4 shows the configuration of this system, which consists of a scanner where semi-insulating devices and materials such as charge roller, development roller, transfer roller and print media can be analyzed or mapped. A belt test fixture is also available for devices such as intermediate transfer belt (not shown). In operation, the device is loaded into the scanner using an appropriate set of adaptors. The control software allows the user to select different types of measurements including: charge scan (single or multiple track), voltage decay and charging current (at a user-specified location), and partial or full-body mapping. All measurements are under computer-

Fig. 4 DRA-2000L Dielectric Relaxation Analysis System

controlled and the results are reported in voltage (V), current (I), apparent resistance (R_a), and equivalent resistance (R_e). Typically, the results are presented as voltage-position, current-position, resistance-position, false-color maps, voltage-time, and current-time as shown in Figs. 5-7. The results in Figs. 5-7 were obtained in a case study on analysis of intermediate transfer belts. The equivalent resistance is derived from voltage and current measurements using the methodology described above.

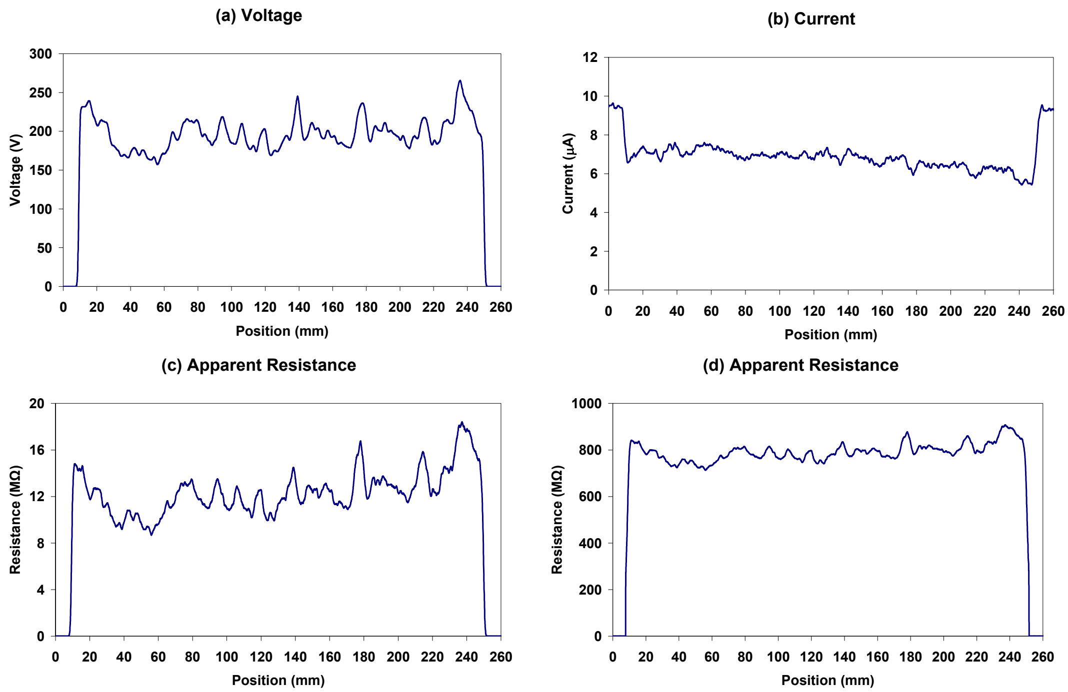

Fig. 5 Typical DRA-2000L test results: a. ECD voltage, b. current, c. apparent resistance, and d. equivalent resistance. Example is from measurements on an intermediate transfer belt.

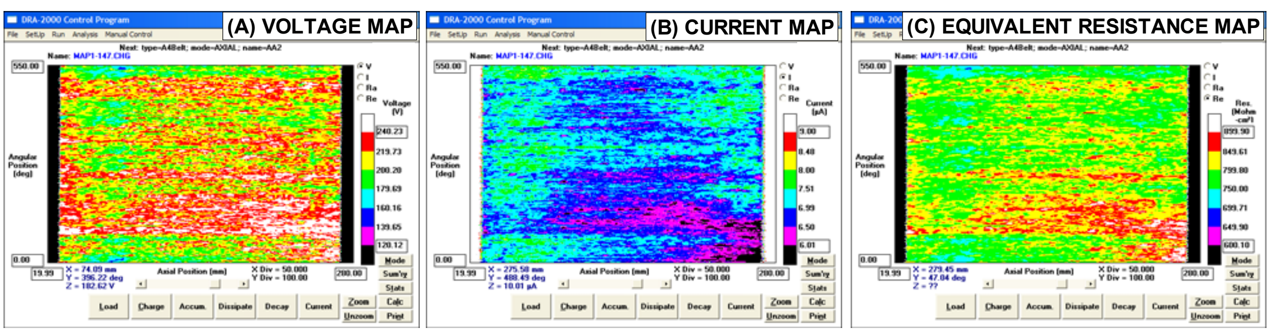

Fig. 6 (A) Voltage, (B) Current, and (C) Equivalent Resistance Maps for the same sample in Fig. 5.

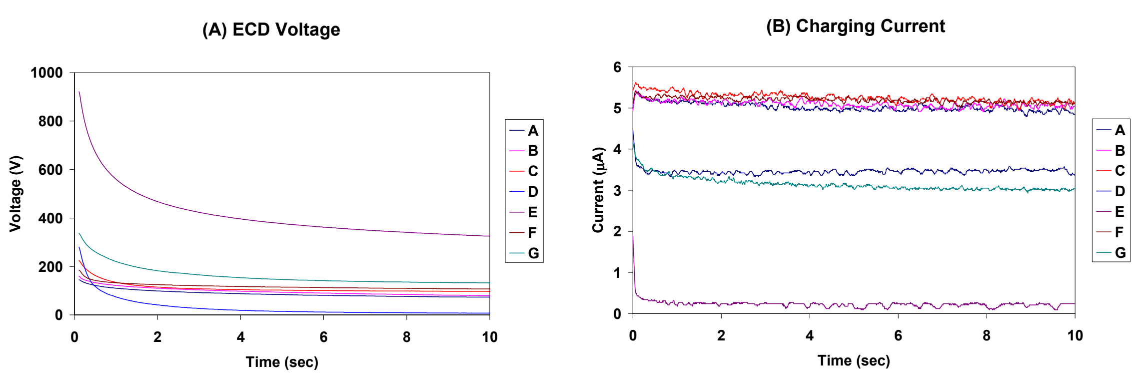

Fig. 7 (A) Voltage and (B) Charging Current as a function of time for 7 intermediate transfer belt samples.

In Fig. 8, similar results on analysis of print media (paper) for electrophotography are shown.

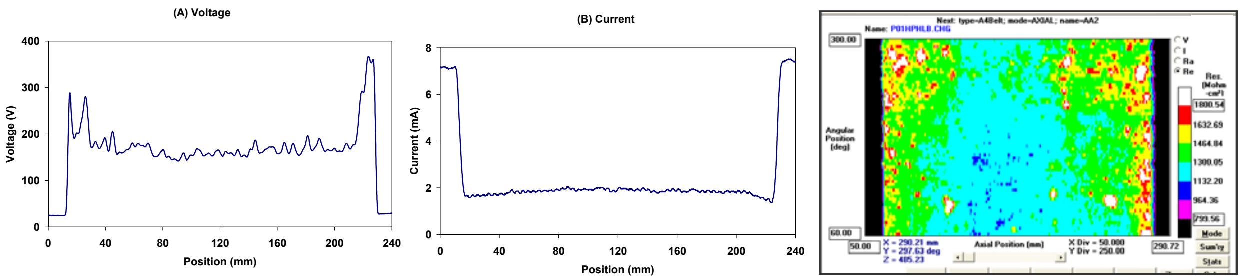

Fig. 8 (A) Voltage, (B) Current and (C) Equivalent Resistance Map for an electrophotographic paper sample.

Discussion and Conclusions

The equivalent resistance R_{eq} is fundamentally different from the conventional resistance obtained from closed-circuit constant voltage measurements. It is deduced from the two quantities V_{av} and J_{av} obtained from open-circuit measurements during charging and discharging of the sample, as in the practical EP applications. In addition, the virtual electrode of corona charging enables efficient scanning over a large area of sample to detect spatial non-uniformity in electrical properties.

In this analysis, it is assumed that R_{eq} at a location is constant with time. In reality, the resistance in semi-insulators is likely to change with voltage and hence, with time. Thus, it should be reminded that the model is an approximation enabling a simplified analytic treatment of the complex problem. The deduced R_{eq} is only an average value over the voltage range of interest.

Calculations of the charging voltage, current, and the apparent resistance using a first principle transport theory in terms of the transport parameters mentioned in Introduction yield similar time dependence as given by Eqs. (3), (6) and (7).[7] There exists a range of charging time in which the voltage, current and R_{ap} values change significantly with the values of intrinsic charge density and strengths of injection from the surface and/or substrate. This is an indication that the apparent resistance, defined by Eqs. (7) or (11), can reflect the roles of these transport parameters and can be used as a convenient figure of merit for the EP applications of the devices.

References

1. I. Chen and M.-K. Tse, Electrical characterization of semi-insulating devices for electrophotography, J. Imag. Sci. Tech. Vol. 44, no. 5, p. 462 (2000)
2. I. Chen and M.-K. Tse, Dielectric relaxation in transfer media for electrophotography, Japan Hardcopy, 2000, p. 153
3. I. Chen and M.-K. Tse, Electrical characterization of transfer media for electrophotography, IS&T's NIP16, p. 208 (2000)
4. M.-K. Tse, D. Forrest and F. Y. Wong, Predicting charge roller performance in electrophotography using electrostatic charge decay measurements, IS&T's NIP-11, p. 383 (1995)
5. I. Chen and M.-K. Tse, Characterization of semi-insulating devices in electrophotography with corona charging current measurements, IS&T's NIP-17, p.92 (2001)
6. M.-K. Tse and I. Chen, Charge mobility determination using electrostatic charge decay technique, Japan Hardcopy (ICIS), 2002, p. 535.
7. I. Chen and M.-K. Tse, unpublished.
8. Quality Engineering Associates (QEA), Inc. www.qea.com.