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Dependence of Paper Surface and Volume Resistivity on Electric Field Strength

P. Sirviö
Stora Enso Oyj, Imatra Research Centre, FI-55 800 Imatra, Finland and
Åbo Akademi University, Department of Physical Chemistry, Porthaninkatu 3-5, FI-20 500 Turku, Finland
E-mail: petri.sirvio@storaenso.com

K. Backfolk
Stora Enso Oyj, Imatra Research Centre, FI-55 800 Imatra, Finland

R. Maldzius
Vilnius University, Sauletekio av. 9, LT-10222 Vilnius, Lithuania

J. Sidaravicius
Vilnius Gediminas Technical University, J.Basanavicius str. 28, LT-03224, Lithuania

E. Montrimas
Vilnius University, Sauletekio av. 9, LT-10222 Vilnius, Lithuania

Abstract. *Toner transfer efficiency in electrophotography and the resulting image quality are influenced by the resistivity of the substrate. Resistivity measurements are, however, often made using electric fields that are lower than those used in the transfer of toner in electrophotography. The dependence of surface and volume resistivity on electric field strength, including fields similar to those utilized in the toner transfer of electrophotographic printers, has been studied. Resistivities of paper samples with differences in grammage, filler content, and calendering were evaluated utilizing electrodes with a geometry in accordance with the ASTM D257 (volume resistivity) and raker-type electrodes (surface resistivity) applying electric fields of between* 10^2 *and* 10^5 V/cm. *The surface resistivity and especially the volume resistivity of paper were found to be strongly dependent on the electric field strength, the characteristics of this dependence being influenced by paper properties. The study of the field dependence further indicated that the Poole-Frenkel type of hopping drift of ions could be applied to conduction in paper, although the electric field dependence was overlapped by paper compression effects. Shottky's model was considered also, but it seems that the role of contact effects is small. © 2008 Society for Imaging Science and Technology.*
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INTRODUCTION

Electrical and dielectric properties of paper play an important role in electrophotographic printing. It is known that toner transfer efficiency and image quality depend on paper resistivity.[1–4] Toner is transferred to the paper from the photoreceptor or from an intermediate belt or drum by an electric field. When the toner image is transferred to paper, the electric field strength must be high enough to detach toner particles from the photoreceptor or from the intermediate transfer surface where toner particles are held by electrostatic and adhesion forces.[1,5] An electric field is applied to the paper by corona charging or by a biased roller. In both cases, the electric field in the nip between the paper and photoreceptor depends on the electrical and dielectric properties of the paper.[6–9] Qualitatively, the manner in which the paper electrical properties influence the image transfer efficiency is known and described. On the other hand, paper resistivity is closely related to the paper handling by the printer. If the resistivity is too high, problems with paper feeding arise due to static electricity. In general, the resistivity requirements for paper handling and for image transfer are opposing. Paper handling requires a low electrical resistance, whereas image transfer is often more effective with a higher resistance.

The role of the electrical properties is not, however, understood in detail, and the quantitative requirements for the electrical properties of paper in electrophotography are not strictly defined. For example, Lim[10] pointed out that the surface resistivity range accepted and usually adopted in the paper industry is 10^{10}–10^{12} Ω. Kulmala et al.[11] considered, in agreement with Lyne,[12] the same surface resistivity range. It must be noted that paper is subjected to high electric fields during image transfer. The electric field strength in the transfer nip is in the range of 10^5–10^6 V/cm, but paper conductivity is usually measured at lower electric fields. Simula,[13,14] for example, measured paper DC resistivity at an electric field of approximately 10^4 V/cm (papers ~100 μm thick, 100 V applied). Lim[10] reported that he did not observe any change in resistivity when the applied voltage was varied from 90 to 500 *V*. On the other hand, it has been

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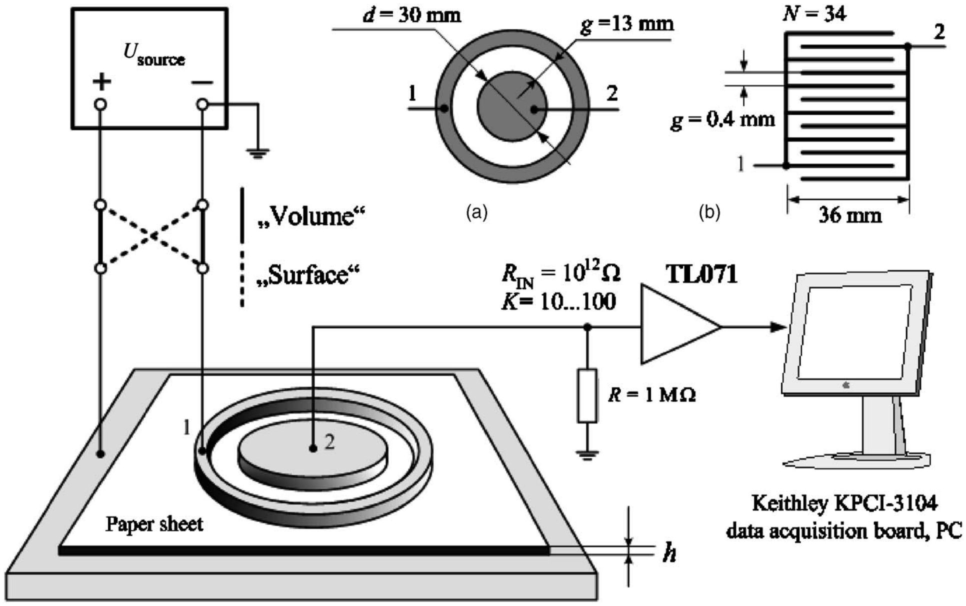

Figure 1. Measurement of surface and volume resistivity. Electrodes: (a) volume resisitivity measurement, (b) surface resistivity measurement. U_s=voltage source, R=measurement resistor, U_m=voltage on the measurement resistor, h=paper thickness, N=number of electrodes in one rake.

reported[3,15] that paper resistivity depends on the electric field strength. This field dependence is attributed to the mechanism of ionic drift in the fiber network.[15–18] According to Murphy,[19] these charge carriers are cations that can move through hydroxyl groups when water molecules are associated with these groups. If there is some type of hopping drift mechanism, the conductivity should be field dependent, as has been shown, for example, by Lin,[17] who considered the decrease in energy or potential barrier between two dissociated sites due to the electric field. A hopping charge carrier drift is well known in organic[20–22] and amorphous[23] semiconductors and in inhomogeneous materials.[24] Hanneson et al.[25] investigated the electrical conductivity of capacitor tissue papers. In their data, at high voltages, the logarithm of the steady state current was proportional to the square root of the applied voltage. The Schottky theory and the Poole-Frenkel effect were discussed as possible mechanisms.

The published data concerning paper conductivity is thus partly contradictory, and it is thus difficult to understand the mechanism and role of paper resistivity in toner transfer, to better determine the optimal electrical properties for different paper types. Therefore, it is necessary to investigate how paper resistivity depends on the electric field strength. This paper describes an investigation of paper surface and volume resistivities at different electric field strengths, including fields that are similar to those usually used in image transfer in electrophotographic printers.

EXPERIMENTAL

The DC volume resistivity of paper was evaluated in accordance with ASTM D257.[26] The DC surface resistivity was evaluated using raker-type electrodes because small distance between electrodes enables one to measure surface resistivity at maximal (before electric breakdown) electrical field strength. A schematic diagram of the circuit and electrodes used is presented in Figure 1. A voltage was applied either to the circular plate and the bottom electrode (volume resistivity measurement) or to the raker-electrode (surface resistivity measurement) by switching from “volume” to “surface.” The ring electrode is grounded in volume mode and the bottom electrode is grounded in surface mode. In the latter case, the electrical current “surface electrode – bottom electrode – the second surface electrode” is excluded. Another way to exclude this current path is to place an insulator between the paper sample and bottom electrode. In experiments with papers listed in the Table I, both surface resistivity measurement modes yield the same resistivity values, as is shown in the example presented in Figure 2. Accordingly, all experimental values of the surface resistivity presented in this paper were obtained without insulator between the paper and bottom electrode. Nevertheless, it must be noted that in the surface mode the surface resistivity is a resultant of real surface resistivity and resistivity of the some part of the paper volume neighboring the paper surface.

The electric current flowing through or across the paper is equal to the current flowing through the external resistor, i.e., to the ratio of the voltage U_m to the resistance R of the external resistor, and was recorded by a Keithley KPCI-3104 data acquisition unit.

The voltage U_s between the electrodes was measured and the resistance of the paper R_p is given by

$$U_s/R_p = U_m/R, \tag{1}$$

that is,

$$R_p = (U_s/U_m)R. \tag{2}$$

In the case of the volume resistivity,

Table I. Properties of trial papers manufactured on a pilot paper machine and calendered on a laboratory coater.

Paper #	Calendering level	Grammage [g/m^2]	Thickness[a] [μm]	Density[a] [g/cm^3]	Ash content 525°C[%]
1	C	95	144	0,66	0
2	C	161	217	0,74	0
3	C	234	333	0,70	0
4	C	91	139	0,65	15
5	No calendering	157	263	0,60	15
5	B	157	218	0,72	15
5	C	157	205	0,77	15
6	C	228	295	0,77	14
7	C	93	138	0,67	28
8	C	159	203	0,78	29
9	C	225	275	0,82	29

[a]Determined from dielectric measurement, pressure 25 kPa.

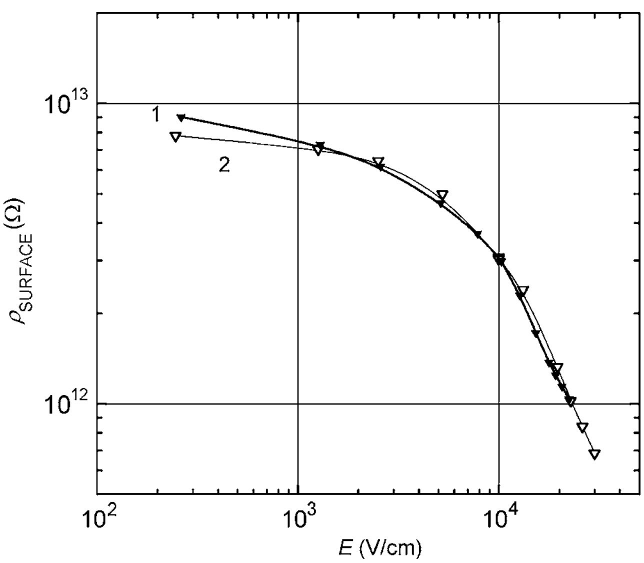

Figure 2. Surface resistivity versus electric field strength for paper 6: (1) paper sample placed on the bottom electrode, (2) an insulator placed between the paper and the bottom electrode.

$$R_p = \rho_{volume} 4h/\pi(d+g)^2. \quad (3)$$

Since the effective radius of the measurement area (cf., ASTM D257) is $(d+g)/2$, i.e.,

$$\rho_{volume} = R_p \pi(d+g)^2/4h, \quad (4)$$

$$\rho_{volume} = (U_s/U_m) R \pi(d+g)^2/4h, \quad (5)$$

where d is the diameter of the central plate electrode, g is the width of the annular gap between the circular plate and the ring and h is the paper thickness (Figure 1, Scheme a).

In the case of surface resistivity,

$$R_p = \rho_{\text{surface}} g/2N, \quad (6)$$

that is,

$$\rho_{\text{surface}} = R_p 2N36/g, \quad (7)$$

$$\rho_{\text{surface}} = (U_s/U_m) R2N36/g, \quad (8)$$

where $2N$ is the number of electrodes and g is the distance between the electrodes (Figure 1, scheme b). All the measurements were performed at 23±1°C and 50±2% relative humidity after keeping the papers for not less than 8 h in this environment. The volume resistivity was calculated from the resistance values using paper thickness values obtained under a pressure equal to that used in a dielectric measurement at 500 V/cm electric field strength (pressure 25 kPa).

Mechanical pressure was maintained constant in all measurements. Because some kind of hysteresis effect was observed in the resistivity measurements (described further in this paper), the resistivity measurements (except in the hysteresis investigation) were done so that the measurement with the highest electric field in the sequence was made first and the following measurements were performed by stepwise decreasing the electric field.

The papers investigated (Table I) were made on a pilot paper machine targeting to filler contents of 0%, 15%, and 30% (precipitated calcium carbonate) and grammages of 90, 160, and 230 g/m^2. Paper was internally sized with alkyl ketene dimer (AKD), and cationic starch was used with the AKD (1.5 kg/ton) and as a wet end additive (8 kg/ton), respectively. A two-component retention system was used with bentonite and polyacryl amide (PAM) additives, 1.7 and 0.2 kg/t, respectively. The paper was not surface sized and no colorants or fluorescent whiteners were used. Sets of samples were then calendered on a laboratory soft-nip calender (soft and hard rolls, speed 25.5 cm/s) at a temperature of 100°C and a pressure of 25 kN/m (calendering level B in Table I), and the sheets were run through the nip twice, so that both sides of the sheet were calendered in the same way. Samples were also produced by calendering both sides

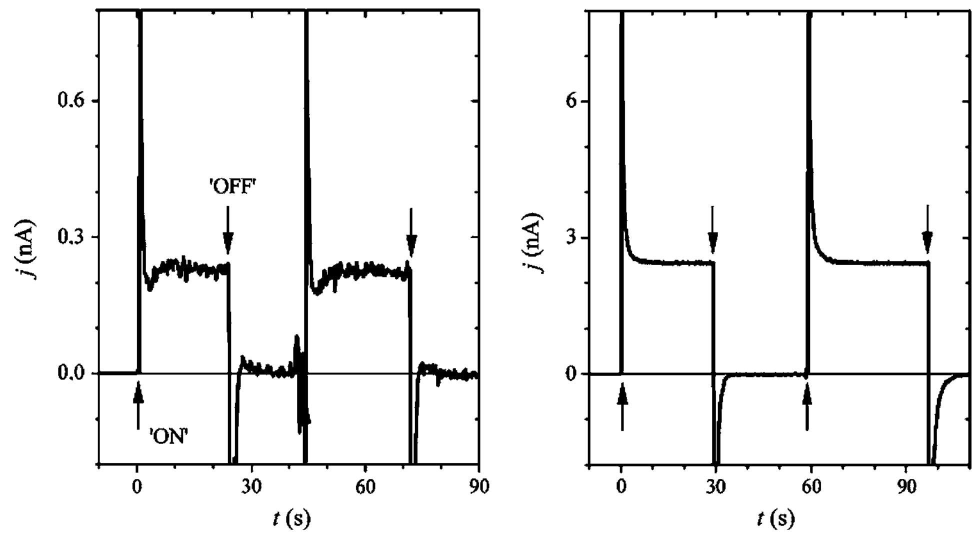

Figure 3. Time dependence of the current on the resistor R (Figure 1) after application of constant voltage: (a) paper 2, surface mode, 10 V, (b) paper 8, volume mode, 100 V. Arrows indicate switching voltage on or off. Peaks related to switching are caused by the measurement circuit RC.

twice at a nip pressure of 50 kN/m and 100°C calender temperature (calendering level C). Calendering treatment, grammage, thickness, density, and ash content of the samples are presented in Table I.

RESULTS AND DISCUSSION

The surface and volume resistances of papers were measured with different DC voltages applied to the electrodes. After the voltage is applied, both the surface resistivity and the volume resistivity change and they reach a constant value after 10–30 s (Figure 3). This value is considered to be the true resistivity value. A similar time dependence was observed for all the papers investigated.

Some differences in the kinetics of resistivity change were observed with different applied voltages. Such behavior was observed with all the papers but it is not yet well explained.[3,15] Possible explanations include polarization effects, changes in the electrical field distribution in the bulk, and compression of the paper. The smoothening of the paper as a result of the electrostatic pressure can also influence the contact resistance between the electrodes and the paper.[15] Paper compression is observed, but this compression occurs more rapidly than the change in paper resistivity, and its contribution can be seen only during short times. Besides, the effect of paper pressing on the surface resistivity must be less than the effect on volume resistivity. In the case of surface resistivity measurement, paper is pressed only under electrode elements and other surface is free, while all the volume is pressed during measurement of volume resistivity. More probable causes are, therefore, the polarization and the field redistribution. Lim[10] suggested that the decrease in resistivity after the application of the voltage was due to compression, which, however, contradicts at least partly our observations on the investigated papers, and it can be concluded that the time-dependent resistivity is caused by several factors.

In the present study, both the surface and volume resistivities of the papers were found to depend significantly on the strength of the electric field (Figure 4). The field dependence was different for the surface and volume resistivities. As the electric field strength increased, both the resistivities decreased. The character of the resistivity dependence on the electric field strength depends on paper properties such as density and filler content. The interrelation of surface and volume resistivities in commercial papers with different filler contents in a given electric field has been described by Simula.[14] From his data, the magnitude of the electric field can be estimated. He measured the electrical properties of papers at fields of approximately 10^4 V/cm and his results were comparable with those in Figure 4. In other references,[10,27] data are presented on the relation between surface and volume resistivity (or conductivity) measured on commercial papers. These results contradict each other, which may be due to differences in these commercial samples, e.g., in the conductivity of the surface sizing, or to differences in the electric field applied. Figure 4 also shows the effect of filler addition on resistivity. Surface resistivity of trial points with 15% and 28% filler (PCC) was higher than with the corresponding trial points for papers without filler, which is in line with the results of Soetanto et al.[28] This effect is influenced by higher filler content decreasing the equilibrium moisture content of paper. However, volume resistivity results did not show any clear dependency between filler content and resistivity.

Figure 5 shows the way in which the surface and volume resistivities are influenced by the paper thickness for papers made of the same pulp, at different applied voltages. Analogous to the data presented in Figure 4, both surface and volume resistivities decreased significantly with increasing electric field, the surface resistivity decreasing less than the volume resistivity. The surface resistivity was almost inde-

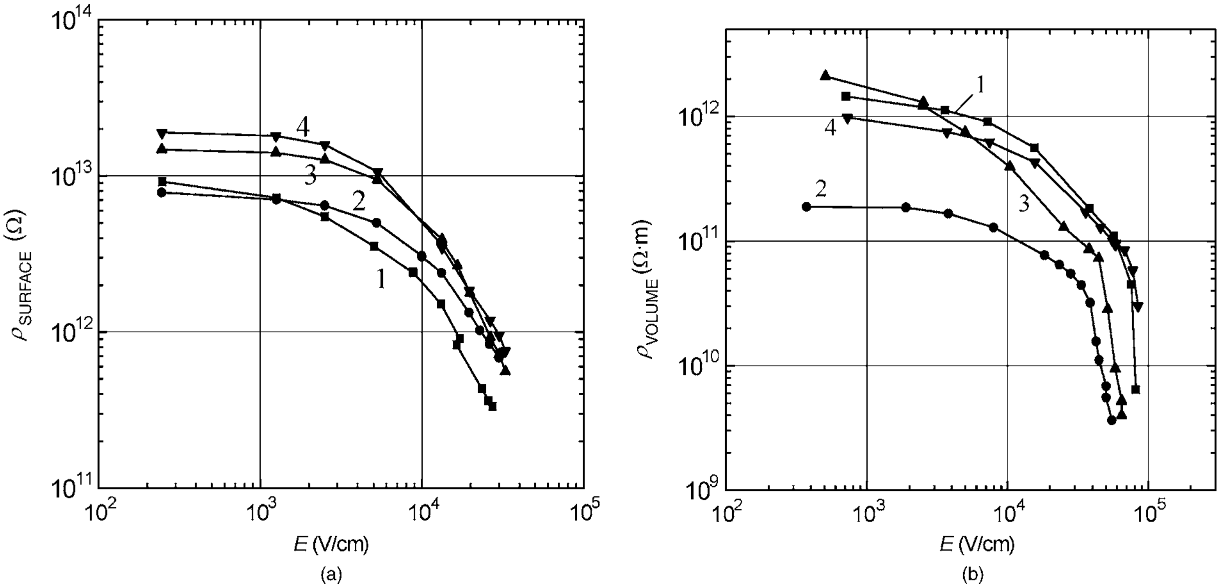

Figure 4. Surface (a) and volume (b) resistivity versus electric field strength for papers 1: without filler; 2 and 3: with 15% PCC filler; 4: with 28% PCC filler.

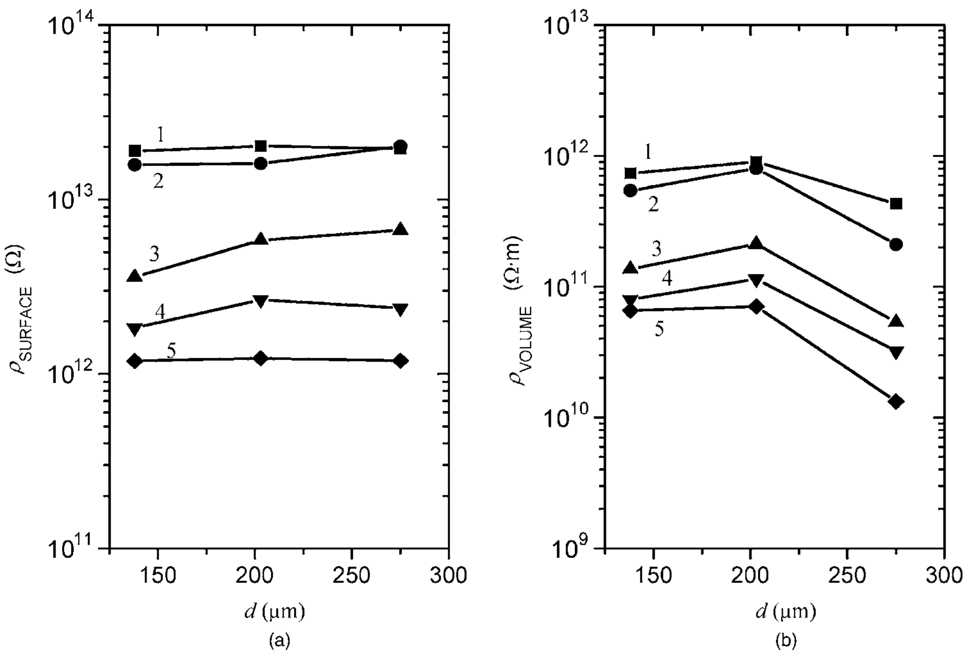

Figure 5. Surface (a) and volume (b) resistivity versus paper thickness (papers 7–9) at different applied voltages: (1) 10 V, (2) 100 V, (3) 500 V, (4) 750 V, (5) 1000 V.

pendent of paper thickness. This was expected. However, volume resistivity tends to decrease with increasing thickness despite that electric field decreases with thickness. Evaluation of electric field influence (Figure 4 and results not shown) only emphasizes the effect. Causes of such volume resistivity decrease are not clear and possibly can be attributed to the differences in paper structure and consequently to the differences in formation of space charges.

Since the paper is compressed by the electric field forces, it is of interest to investigate papers calendered to different levels (Figure 6). The calendering differences mean that papers in Figure 6 differed in surface roughness, varying from Print-surf roughness of 4.2 to 7.2 μm (measured in accordance with the ISO 8791-4 standard with 1.0 MPa clamping pressure), and also had different densities, ranging from 0.60 to 0.77 g/cm^3. The surface resistivity is almost independent of the density. The volume resistivity at low electric fields increased with increasing paper density. This result contradicts Lim's result.[10] The reason is not clear. Notable is that the volume resistivity was independent of the density at high electric fields (above 10^4 V/cm). It can be assumed that at different densities, the moisture and cellulose interactions in pilot papers, which have not been surface sized and which in this specific case also contain a relatively

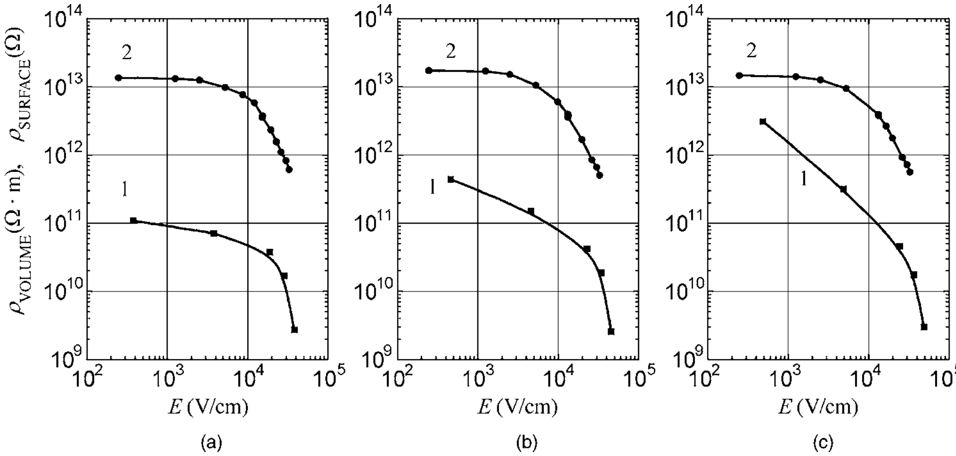

Figure 6. Volume (1) and surface (2) resistivity dependence on calendering level of paper 5. Paper density, g/cm^3: (a) 0.60, (b) 0.72, (c) 0.77. Print-surf roughness, μm: (a) 7.2, (b) 5.0, (c) 4.2.

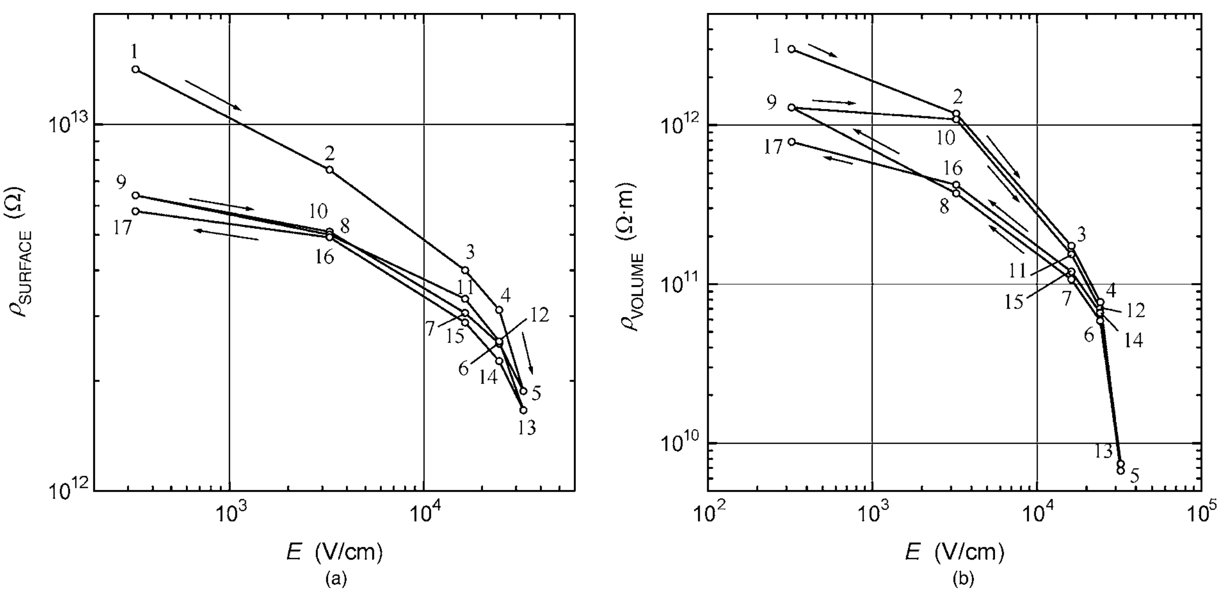

Figure 7. Surface (a) and volume (b) resistivity as a function of applied electric field for uncalendered paper 5 during cycling. Numbers indicate the sequence of measurements.

low amount of ions, differ from those in commercial papers investigated by Lim at low electric fields. In connection with the calendering and smoothening of paper, the influence of the paper-electrode contact on resistivity measurement needs to be considered. Surface smoothening improves the contact and thus decreases the resistivity. Our results show that surface resistivity does not depend on roughness, and volume resistivity at low electric fields increases with density even though the paper is then also smoother. The latter effect can be partially influenced by the lower equilibrium moisture content of papers with higher density. It can be concluded that contact effects do not have any significant role, though results reported do not allow fully excluding the influence of these effects.

Resistivity measurements were also performed by increasing the voltage on the electrodes stepwise for consecutive measurements. Since the electric field itself may lead to changes in paper properties, successive measurements may give different resistivity values. Therefore, the measurements were repeated with successively decreasing voltages. Figure 7 shows that both the volume and the surface resistivities were lower when the measurements were made with decreasing voltage after the measurements were first made with increasing voltage. Further cycles with increasing voltage and decreasing voltage gave approximately repeatable resistivity values, with the same dependence on the electric field strength. It is believed that this effect is influenced by a change in paper thickness (and consequently density) caused by the electrostatic pressure. Indeed, calculation of the electrostatic force between the electrodes gives, at the highest electric field, a pressure of up to approximately 140 kPa. Such a pressure leads to a decrease in paper thickness[29–31] and a decrease in roughness. Partial recovery occurs after the pressure is removed.[29] After repeated cycles, the paper deforma-

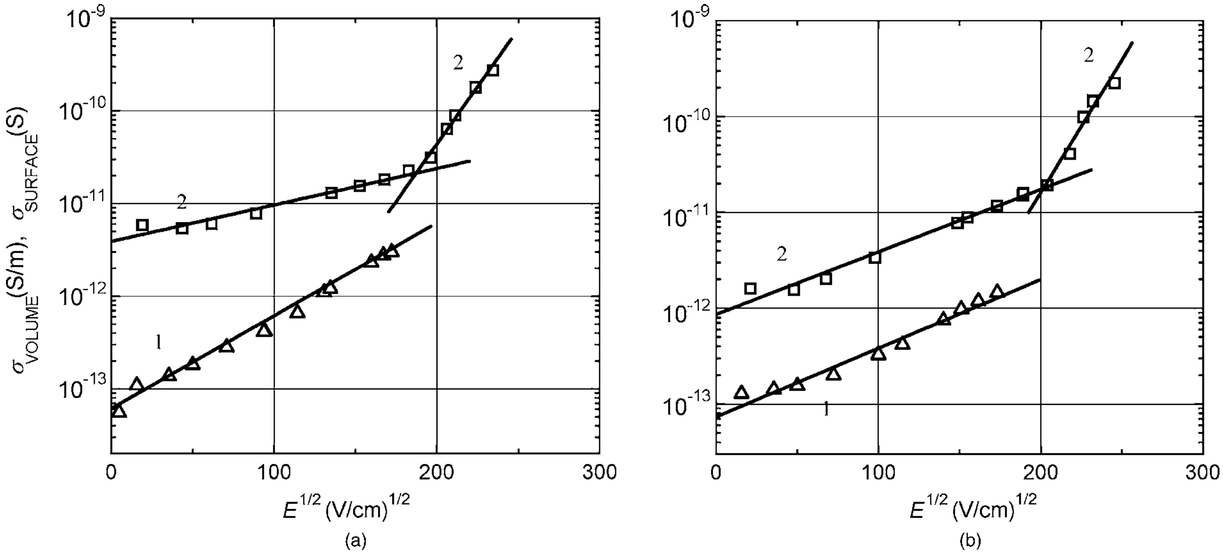

Figure 8. Log conductivity plotted as a function of the square root of electric field (Poole-Frenkel effect): (1) surface conductivity, (2) volume conductivity; (a) paper 1 (no filler), (b) paper 4 (15% filler).

tion reaches a stable value. The electric field was always switched on during cycling without relaxing, so possible space charges in paper did not relax between the measurements. The mechanisms and the effect of density on resistivity are thus different between Figure 6, where changes in paper properties are caused mainly by the irreversible calendering effects, and Figure 7, where the changes are caused by alternations in the electric field.

That paper resistivity is dependent on electric field strength is mentioned in several publications.[3,15,32] This dependence is attributed mostly to the mechanism of the drift of ions; i.e., to some sort of hopping of ions from one site to another. Sites are separated in space and consequently by an energetic barrier. Such a mechanism is well known for the drift of holes or electrons in organic semiconductors.[20] In general, the hopping drift mobility of charge carriers is dependent on the electric field. This dependence is often attributed to the reduction in the barrier between sites (Poole-Frenkel effect), and the dependence of the charge carrier mobility on the electric field is expressed as

$$\mu = \mu_0 \exp(\alpha\sqrt{E}), \tag{9}$$

where μ_0 is the charge carrier mobility at zero electric field and α is the Poole-Frenkel parameter.

Phenomenologically, the electrical conductivity σ of any material may be expressed in terms of the density of charge carriers n, the electronic charge of the carrier e, and the mobility μ of the carrier, as $\sigma = en\mu$. Conductivity in papers is an ionic phenomenon and we can assume that, for a constant paper composition, constant temperature and humidity, and assuming that the dissociation of ionogenic species in paper does not depend on the electric field, the density of charge carriers (ions) is constant. The conductivity will then be dependent only on the mobility of the ions, and the dependence of log μ on $E^{0.5}$ will be linear. In this study, this dependence for surface conductivity is linear over a wide range of electric field strengths, Figure 8 (further increase of electric field was impossible because of electrical breakdown). The volume conductivity shows two linear regions. This result shows that a hopping mechanism of ionic movement in the papers is quite reasonable for the surface conductivity. In the case of volume conductivity, the situation is more complicated. The hopping mechanism of ionic movement is overlapped by changes in thickness and density. An exponential dependence of conductivity on the electric field can be explained by the Shottky effect; i.e., the influence of electric field on the charge carrier injection from electrodes. The intensity of charge carrier injection influences the electrical current through the paper and hence the "apparent" resistivity. The injection in turn depends on the contact condition at the paper-electrode interface. This phenomenon was investigated theoretically by Chen and Tse.[33] The role of contact effects were considered earlier by Hanneson et al.,[25] but they, on the basis of experimental results, assumed that Shottky's effect is improbable in papers. Our results (surface resistivity independence on the paper calendering level and roughness, Figure 6(a)) confirm indirectly the assumption made by Hanneson et al. On the other hand the slope of dependence of log μ on $E^{0.5}$ depends on the filler content (Figure 8) and on other factors, for example, on salt content. Therefore, it is not possible to fully exclude the contact effect, but this requires a more detailed investigation.

CONCLUSION

The surface and volume resistivities of paper are strongly dependent on the electric field strength. This dependence is influenced by thickness, density, and filler content of the paper substrate. The volume resistivity is more affected by the electric field strength and this is attributed to the electrostatic pressing of the paper and the influence of the electric field on ion mobility. The surface resistivity depends less on the electric field, which is explained by a smaller influence of paper pressing and thus more direct relationships between ion mobility and electric field. The dependence of paper conductivity on the electric field has been studied using the Poole-Frenkel approach, and it was found that a model of hopping drift of ions can be applied to paper, although the electric field dependence is overlapped by paper compression effects. Also, the role of contact effects needs more detailed investigation in papers of different composition, though it seems that these effects do not play a significant role.

REFERENCES

[1] L. B. Schein, *Electrophotography and Development Process* (Laplacian Press Morgan Hill, CA, 1996).

[2] G. Goldman, *The World of Printers* (Oce Printing Systems GmBH, Loughton, UK, 2002).

[3] C. A. Baum, *Electrical Properties: I. Theory. In Handbook of Physical and Mechanical Testing of Paper and Paperboard*, Vol. **2** (Marcel Dekker, New York, 1985), pp. 171–200.

[4] O. Charin and E. Suveizdis, *Electrophotography* (MSUP Moscow State University of Printing, Moscow, 2006) (in Russian).

[5] D. A. Hays and J. C. Sheflin, "Electrostatic adhesion of ion and triboelectric-charged particles," J. Electrost. **63**, 687–692 (2005).

[6] M. Schleusener, "Modeling of electrostatic to toner image transfer," *Proc. IS&T's NIP7: Int'l. Congress on Adv. in Non-impact Printing Technologies* (IS&T, Springfield, VA, 1991) pp. 167–175.

[7] M. C. Zaretsky, "Performance of an electrically biased transfer roller in Kodak ColorEdge™ CD Copier," J. Imaging Sci. Technol. **37**, 187–191 (1993).

[8] J. W. May and T. N. Tombs, "Electrostatic Toner Transfer Model," *Proc. IS&T's NIP13: Int'l. Congress on Adv. in Non-impact Printing Technologies* (IS&T, Springfield, VA, 1997) pp. 71–76.

[9] I. Chen and Ming-Kai Tse, "The role of dielectric relaxation of media in electrophotography (I): Modeling of electrostatic transfer," *Proc. IS&T's NIP15: Int'l. Congress on Adv. in Non-impact Printing Technologies* (IS&T, Springfield, VA, 1999) pp. 155–158.

[10] P. Y. W. Lim, "Resistivity of non-impact printing papers," *Proc. IS&T's 11th Int'l. Congress on Adv. in Non-impact Printing Technologies* (IS&T, Springfield, VA, 1995) pp. 401–404.

[11] A. Kulmala, H. Paulapuro, and P. Oittinen, "Paper requirements for electrophotographic printing," *Proc. IS&T's 10th Int'l. Congress on Adv. in Non-impact Printing Technologies* (IS&T, Springfield, VA, 1994) pp. 466–470.

[12] B. L. Lyne, "Paper requirements for non-impact," *Proc. Int'l. Printing and Graphic Arts Conf.* (TAPPI, Atlanta, GA, 1988) pp. 89–97.

[13] S. Simula, "Electrical and thermal properties of paper," Thesis for the degree of Doctor of Technology (KCL PSC Communications, Espoo, Finland, 1999).

[14] S. Simula, "Electrical properties of digital printing papers," *26th IARIGAI Int'l. Research Conf.* (IARIGAI, Munich, Germany, 1999).

[15] J. Gullichsen and H. Paulapuro (Series editors) and K. Niskanen (Book editor) "*Papermaking Science and Technology, Book 16. Paper Physics*" (Fapet Oy, Jyväskylä, Finland, 1998) pp. 305–317.

[16] J. H. Brown, R. W. Davidson, and C. Skaar, "Mechanism of electrical conduction in wood," For. Prod. J. **13**, 455–459 (1963).

[17] R. T. Lin, "A study of the electrical conduction in wood," For. Prod. J. **15**, 506–514 (1965).

[18] W. E. Smith, "Determining interfiber bonding by electrical conductivity," Tappi J. **53** 1944–1947 (1970).

[19] E. J. Murphy, "The dependence of the conductivity of cellulose, silk and wool on their water content," J. Phys. Chem. Solids **16**, 115–122 (1960).

[20] P. M. Borsenberger and D. S. Weiss, *Organic Photoreceptors for Electrophotography* (Marcel Dekker Inc., New York, 1998).

[21] N. Jubran, K. Law, Z. Tokarski, R. Moudry, J. Baker, Hwan-Koo Lee, V. Gaidelis, J. Sidaravicius, and E. Montrimas, "Novel Hole Transport Materials and their Application for Electrophotography," *Proc. IS&T's NIP18: Int'l. Congress on Adv. in Non-impact Printing Technologies* (IS&T, Springfield, VA, 2002) pp. 674–677.

[22] D. H. Dunlap, "Hopping transport in molecularly doped polymers: On the relation between disorder and a field-dependent mobility," J. Imaging Sci. Technol. **40**, 291–298 (1996).

[23] A. Cesnys, G. Juska, and E. Montrimas, "Charge carrier transfer at high electric fields in noncrystaline semiconductors," in *Semiconducting Chalcogenide Glass II, Properties of chalcogenide glasses; Semiconductors and Semimetals* Vol. **79** (Elsevier, Amsterdam, 2005) pp. 15–55.

[24] V. Skorokhod, R. P. N. Veregin, and M. S. Hawkins, "Effects of coating and compaction on the Poole-Frenkel behavior of xerographic carriers," J. Imaging Sci. Technol.. **45**, 565–570 (2001).

[25] J. E. Hanneson, R. Raman, and J. Hart, "Electrical conductivity of tissue paper," Tappi J., **54**, 955–958 (1971).

[26] ASTM Standard, D257-93, *DC Resistance of Insulating Materials* (ASTM International, West Conshohocken, PA, 1993).

[27] S. Sapieha, R. Seth, and P. Lepoutre, "Electrical conductivity and paper structure," Sven. Papperstidn. **87**, R127–R132 (1984).

[28] S. Soetanto, W. McKean, and P. Lim, "Effect of alkaline papermaking on copy paper properties," *Proc. Pan-Pacific Pulp & Paper Technology Conf.* (Japan TAPPI, Tokyo, 1992) pp. 187–195.

[29] M. Jackson and L. Ekström, "Studies concerning the compressibility of paper," Sven. Papperstidn. **67**, 807–821 (1964).

[30] T. Yamauchi, "Measurement of paper thickness and density," Appita J. **40**, 359–366 (1987).

[31] T. Yamauchi, "Compressibility of paper measured by using a rubber platen thickness gauge," Appita J. **42**, 222–224 (1989).

[32] J. Josefowitcz and Y. Deslandes, "Electrical conductivity of paper: Measurement methods and charge transport mechanisms," in *Colloids and Surfaces in Reprographic Technology*, edited by M. Hair and M. Croucher (American Chemical Society, Washington, DC, 1981), pp. 493–531.

[33] I. Chen and M. Tse, "Electrical characterisation of semiconducting devices for electrophotography," J. Imaging Sci. Technol. **44**, 462–465 (2000).