INFLUENCE OF DRYING TEMPERATURE AND GRAPHITE CONCENTRATION ON THE PERFORMANCE OF GRAPHITE-BASED CONDUCTIVE INK

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Abstract:

This paper examines how drying temperature influences the electrical and mechanical properties of graphite-based conductive ink. Special emphasis was placed on electrical conductivity and abrasion resistance. The ink formulations were prepared using graphite powder with a particle size below 20 µm as the conductive component, while a commercially available water-based printing ink served as the binder. To evaluate the influence of filler loading on the formation of conductive networks, graphite was incorporated at concentrations of 30 wt.% and 40 wt.%. To ensure a uniform coating layer, the inks were applied onto a smooth polymer-coated paper substrate using a glass rod. The printed samples were dried for 15 minutes at four different temperatures (60 °C, 80 °C, 100 °C, and 120 °C). Electrical performance was assessed via surface resistance measurements, while abrasion resistance was used to assess the durability and adhesion of the conductive layers. Based on the measurements, it was found that both drying temperature and graphite concentration significantly influence the performance of the coatings. Improved electrical conductivity was observed at higher graphite content, while drying at moderate temperatures promoted better particle contact and a more stable conductive network. However, excessively high drying temperatures led to reduced mechanical stability, likely due to binder degradation. In our experiment, particular attention was given to maintaining constant homogenization, application with a glass rod and drying time. This paper contributes to a better understanding of the role of processing parameters in graphite-based conductive inks and supports the optimisation of formulations and drying conditions for functional printed materials.

Keywords: conductive ink, graphite, abrasion resistance, ink drying

1. INTRODUCTION

The development of conductive inks for printing and applications in functional printed materials is becoming increasingly important, especially in the context of flexible electronics, RFID antennas, sensors, and interactive surfaces. Key formulation parameters of such inks include the choice of conductive fillers (e.g., graphite, graphene, carbon nanotubes), the ratio of filler to binder and processing conditions. Drying rate and drying temperature are particularly significant parameters. High temperature can cause binder degradation and a deterioration in the mechanical resistance of the coating. At the same time, too low temperature can result in weak cohesion of graphite particles and high electrical resistance [1, 4, 6]. Previous studies have shown that increasing the concentration of graphite fillers allows the formation of a better conductive network and reduces surface resistance [1, 5, 9]. A review on carbon-based conductive inks indicates that filler concentrations in metal or carbon-based inks can range approximately from 30% to 80% of the dry filler mass [1].

The drying process has a dual role. Elevated temperatures can improve contact between graphite particles and reduce resistance, but they may also cause shrinkage, stress, microcracks, or binder degradation, leading to reduced abrasion resistance [2, 3, 4]. Marchianò et al. analysed the drying process of water-based graphite conductive inks, showing that inadequate drying can lead to surface

cracks and defects in printed electrodes [2]. For water-based graphite ink formulations, optimising suspension, viscosity, drying, and filler–binder interactions is particularly important [2, 8]. Marchianò et al. reported that drying at 100 °C after ink application on a flexible substrate provided good electrochemical performance [2], while Leng et al. demonstrated that high conductivity can be achieved even at moderate drying temperatures (around 80 °C), avoiding issues with substrates and binders [3]. S.S. Azim et al. investigated how the graphite content in epoxy binder affects the resistance and adhesion of the coating [4]. Similar results were obtained for hybrid graphite-carbon systems [9].
The goal of our team is to develop simple graphite-based conductive inks that are accessible and biocompatible, and this paper aims to investigate how graphite concentrations (30% and 40%) and drying temperatures (60 °C, 80 °C, 100 °C, and 120 °C) contribute to the understanding and optimisation of graphite-based conductive inks. The results can help define optimal drying and formulation conditions for achieving the best electrical conductivity and mechanical resistance [1–4, 6–9].

2. MATERIALS AND METHODS

2.1. Materials

For the preparation of conductive printing layers, water-based printing ink was employed as the binder matrix. Graphite powder (Sigma-Aldrich, particle size < 20 µm) was incorporated into the ink formulation at concentrations of 30 wt% and 40 wt%, respectively. The ink mixtures were homogenized by mechanical stirring until a smooth and uniform paste was obtained, ensuring optimal dispersion of graphite particles within the aqueous medium. The prepared inks were applied onto the paper substrates using a glass rod coating technique. It provided a controlled and uniform film thickness across the entire sample surface. After coating, samples were dried in a laboratory oven at four different temperatures: 60 °C, 80 °C, 100 °C, and 120 °C (each for 15 minutes). The temperature conditions were selected to examine the influence of drying temperature on the structural stability and surface homogeneity of the printed layers. The paper used for printing was a coated paper (UPM Finesse White Gloss, 300 g/m²). The higher-grammage paper provided better mechanical stability during coating and reduced deformation and wrinkling compared to thinner substrates. This paper provides a reliable surface for uniform ink deposition and allows accurate evaluation of the coating's morphological and optical properties under controlled conditions.

2.2. Electric resistance testing

The electrical conductivity of the printed coatings was evaluated using a simple conductivity test circuit based on the Technic Conductivity Test Apparatus design (Technic Inc., USA). The circuit consisted of a 4.5 V DC power source, a light-emitting diode (LED), an ammeter and the printed conductive trace connected in series. When the circuit was closed, the current flow through the printed path was measured using the ammeter, and the brightness of the LED served as a qualitative indicator of conductivity. This setup allowed for a quick comparative assessment of the electrical performance of coatings with different graphite contents and drying conditions. The tests were conducted at ambient laboratory temperature, and each measurement was repeated three times to ensure repeatability. The voltage drop across the LED was measured separately to determine the actual voltage applied to the printed line. Based on the measured current (I) and the calculated voltage on the line (V_{line}), the electrical resistance of the printed trace was obtained from Ohm's law($R_{\text{line}} = V_{\text{line}}/I$). The sheet resistance (R_s) was then calculated using the geometrical relationship:

$$R_s = R_{\text{line}} \cdot \frac{W}{L}$$

where $W = 3\ \mathrm{mm}$ is the width and $L = 28\ \mathrm{mm}$ is the length of the printed conductive line. This normalisation allows for direct comparison of samples with different geometries and provides a reliable measure of the intrinsic electrical performance of the printed coatings.

2.3. Mechanical testing

The rub resistance of the graphite-based conductive prints was evaluated using a Hanatek Rub and Abrasion Tester (tribometer). This test method is employed to determine the durability of a dried coating when subjected to frictional contact, either against another surface or material. The test aims to assess the tendency of the conductive layer to wear off or transfer due to mechanical abrasion. The goal of this test was to determine whether the graphite coatings remained electrically conductive after the rubbing test.

Microscopic analysis was performed using an Olympus BX51 optical microscope (Olympus, Japan) equipped with a DP72 digital camera (12.8 megapixels, 4140 × 3096 pixels). The system enables high-resolution image capture under magnification up to 1500×, providing low-noise, high-sensitivity imaging suitable for detailed observation of micro structured coatings. Images were acquired at 40× magnification for printed samples containing 30 wt.% and 40 wt.% graphite, dried at 60 °C, 80 °C, 100 °C, and 120 °C. All images were processed and analysed using the Fiji distribution of ImageJ (NIH, USA), which allows for reproducible and quantitative evaluation of surface morphology and texture.

3. RESULTS

The electrical performance of the printed coatings was evaluated by measuring the current flow through the conductive lines in a simple circuit. The results, expressed as sheet resistance (Ω/m^2) (Table 1), show a clear dependence on both the graphite concentration and the drying temperature.

Table 1: Sheet resistance (R_s) of printed conductive coatings containing 30 wt.% and 40 wt.% graphite at different drying temperatures

Drying Temperature (°C)	30 wt.% Graphite (R_s [Ω/m^2])	40 wt.% Graphite (R_s [Ω/m^2])
60	127.5 ± 2.1	37.8 ± 0.7
80	327.8 ± 32.3	25.7 ± 0.5
100	85.9 ± 2.1	20.3 ± 0.2
120	141.2 ± 13.2	23.5 ± 0.7

For the 30 wt.% graphite formulation, the sheet resistance values ranged from approximately 85.9 Ω/m^2 to 327.8 Ω/m^2, with the lowest resistance obtained at 100 °C. At this temperature, the coating exhibited the highest current and, consequently, the best electrical conductivity. Samples dried at lower (60 °C, 80 °C) or higher (120 °C) temperatures showed higher resistance, indicating incomplete particle connection at low temperature and potential microstructural stress or binder contraction at excessive heating.

In the 40 wt.% graphite coatings, ranging between 20.3 Ω/m^2 and 37.8 Ω/m^2, confirming that the higher graphite content significantly enhances electrical conductivity by promoting particle-particle contact and network formation. Like the 30 wt.% samples, the minimum resistance was again observed at 100 °C, which corresponds to the temperature where microstructural analysis also revealed the most uniform and compact surface texture.

Based on the measurements, our results demonstrate that both the graphite loading and drying temperature strongly influence the electrical response of the coatings. The optimal combination of low sheet resistance and structural homogeneity was achieved for coatings dried at 100 °C. That sample exhibited approximately four to six times lower resistance than the 30 wt.% samples under the same conditions.

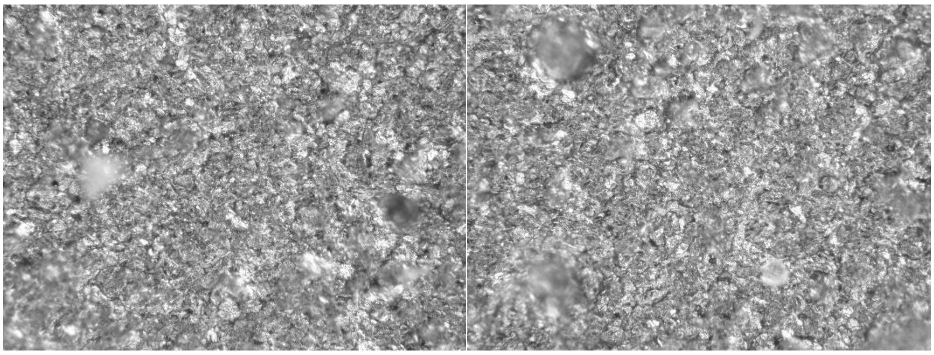
Table 2: Sheet resistance (R_s) of printed conductive coatings after abrasion testing

Drying Temp (°C)	30 wt% – Sample 1	30 wt% – Sample 2	40 wt% – Sample 1	40 wt% – Sample 2
60	85.62 ± 0.65	99.99 ± 2.95	50.84 ± 1.28	25.60 ± 0.53
80	187.27 ± 2.55	89.26 ± 4.59	30.05 ± 1.24	29.56 ± 1.95
100	103.84 ± 1.39	471.34 ± 24.12	23.36 ± 0.15	23.57 ± 0.35
120	78.15 ± 2.63	145.09 ± 4.13	45.42 ± 0.97	47.42 ± 1.54

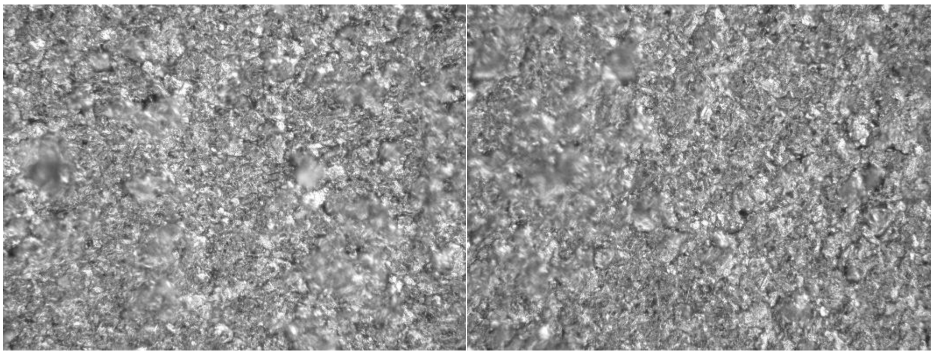
The measurements (Table 2) revealed notable differences in the electrical stability of the coatings depending on graphite content and drying temperature. Samples containing 40 wt% graphite exhibited consistently lower sheet resistance values after rubbing compared to the 30 wt% coatings. That confirms that a higher concentration of conductive particles improves both electrical conductivity and mechanical durability. For both formulations, the lowest sheet resistance was obtained at 100 °C, indicating that this drying temperature promotes optimal interparticle contact and a stable conductive network. In contrast, coatings dried at lower (60 °C, 80 °C) or higher (120 °C) temperatures showed higher resistance and greater variability between samples. It suggests less uniform film formation or partial disruption of the conductive pathways. Coatings with 40 wt% graphite dried at 100 °C showed the best balance between conductivity and abrasion resistance.

The captured micrographs were first converted to 8-bit grayscale and enhanced using the CLAHE (Contrast Limited Adaptive Histogram Equalisation) algorithm to improve local contrast and emphasize particle boundaries. Segmentation was performed using Otsu's thresholding, followed by particle analysis to determine the number of detected graphite domains. Also, it determines their total and average projected area and the percentage of surface coverage. The same grayscale images were used for Gray Level Co-occurrence Matrix (GLCM) texture analysis using a custom macro script in Fiji. Texture parameters (contrast, energy, homogeneity, and correlation) were calculated at a pixel offset distance of 5 px in four angular orientations (0°, 45°, 90°, 135°) and averaged to describe the uniformity and organisation of the surface.

The visual inspection of the microscopic images presented in Figures 1 (a–d) and 2 (a–d) revealed noticeable differences in the surface morphology of the printed conductive coatings depending on the drying temperature and graphite content.

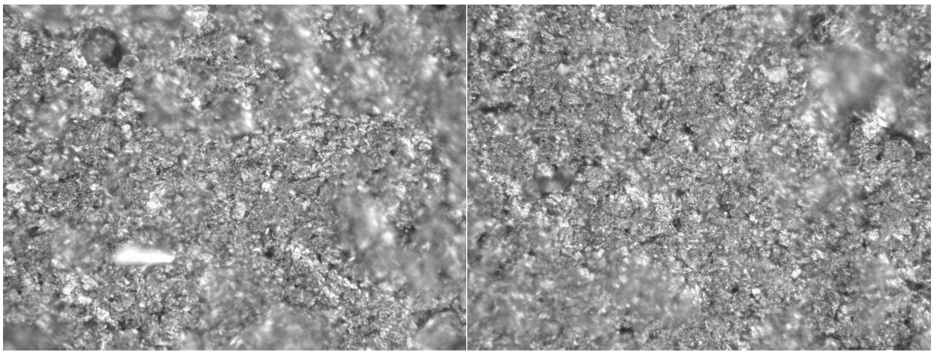


a) b)

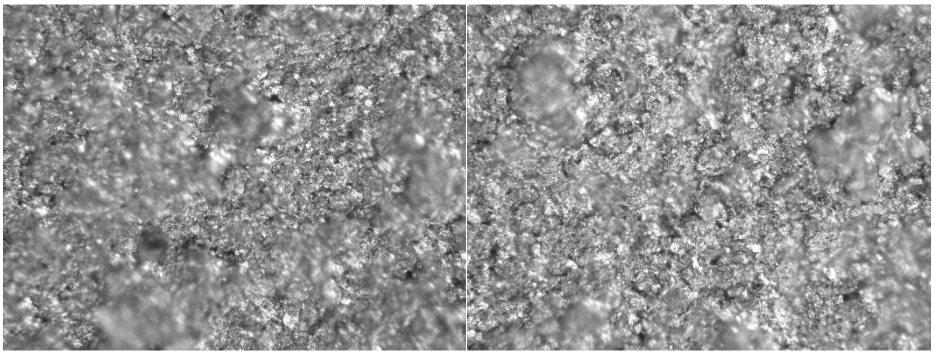


c) d)

Figure 1: 30 wt.% graphite a) 60°C, b) 80°C, c) 100°C, d) 120°C



a) b)



c) d)

Figure 2: 40 wt.% graphite a) 60°C, b) 80°C, c) 100°C, d) 120°C

The microstructural and textural analyses showed a clear influence of both drying temperature and graphite content on the morphology of the printed conductive coatings.

Table 3: Surface morphology and texture parameters of 30 wt.% and 40 wt.% graphite coatings dried at various temperatures

Sample	Count	Area/%	Contrast	Homogeneity	Correlation
30 wt%/60°C	2676	51.534	34.739	0.333	0.804
30 wt%/80°C	2074	60.965	32.637	0.344	0.800
30 wt%/100°C	1836	60.017	31.748	0.342	0.809
30 wt%/120°C	1752	62.164	30.301	0.349	0.808
40 wt%/60°C	1264	59.731	21.072	0.419	0.864
40 wt%/80°C	1883	58.546	26.558	0.381	0.828
40 wt%/100°C	1078	61.586	17.996	0.433	0.872
40 wt%/120°C	2388	56.395	29.228	0.388	0.834

For the formulation containing 30 wt.% graphite, the number of graphite particles decreased with increasing temperature (from 2676 at 60 °C to 1752 at 120 °C), while their average projected area and total surface coverage increased. This shows the gradual coalescence of smaller graphite domains into larger agglomerates. The result is a continuous conductive network. The mean grayscale intensity also increased, suggesting a reduction in surface porosity and improved optical uniformity. The optimal morphology was achieved between 80 °C and 100 °C. At that temperature, coverage exceeded 60 %, and the surface exhibited a balanced texture characterised by moderate contrast and high homogeneity.
For the 40 wt.% graphite formulation, the overall coverage remained high (56–62 %) but showed stronger fluctuations with temperature. The particle count and average size varied irregularly, reflecting local aggregation and partial fragmentation of the graphite phase. GLCM analysis confirmed the observation that the lowest contrast (17.99) and highest homogeneity (0.433) occurred near 100 °C, indicating the most uniform surface at this temperature. At both lower (60 °C) and higher (120 °C) drying temperatures, contrast increased and homogeneity decreased. It implies a rougher and more heterogeneous structure due to incomplete drying or matrix contraction at elevated temperatures.
When comparing the two formulations, increasing graphite content from 30% to 40% led to improved particle connectivity and higher baseline homogeneity at lower temperatures. It reflects enhanced percolation within the conductive network. The higher filler concentration also reduced the structural stability of the coating upon heating, which caused greater textural variation and local irregularities at extreme temperatures.
For both formulations, the most favourable microstructural properties were observed at around 100 °C, suggesting an optimal particle distribution and the formation of a dense, uniform conductive film.
The abrasion test performed on the coating containing 40 wt.% graphite dried at 80 °C revealed a decrease in the number of detected graphite domains and a simultaneous increase in their average size.

Table 4: Surface morphology and texture parameters of 40 wt.% graphite coatings dried at 80 °C before and after the abrasion test

	Count	Area/%	Contrast	Homogeneity	Correlation
Before abrasion	1883	58.546	26.558	0.381	0.828
After abrasion	1326	59.995	18.444	0.436	0.874

Smaller, weakly adhered particles were removed by rubbing, leaving behind larger and more compact agglomerates firmly embedded in the polymer binder.

The total surface coverage slightly increased, and the mean brightness became higher, indicating a smoother and more uniform surface.
GLCM texture parameters confirmed these findings: contrast decreased from 26.6 to 18.4, while homogeneity and correlation increased, suggesting improved structural uniformity and surface compactness after abrasion.
From the abrasion test, it was observed that the conductive layer retained good structural integrity and that the remaining graphite phase exhibited enhanced uniformity and adhesion to the substrate.
The combined morphological, textural, and electrical analyses clearly demonstrate the strong influence of both graphite content and drying temperature on the performance of the printed conductive coatings. Microscopic observations (Figures 1 and 2) showed that increasing the drying temperature led to gradual particle coalescence and improved surface uniformity up to 100 °C, while higher temperatures (≥120 °C) caused localised cracking and binder shrinkage. These visual trends were supported by texture analysis parameters, where coatings dried at 100 °C exhibited the highest homogeneity and correlation values, indicating the formation of a compact and well-connected microstructure.
Electrical measurements further confirmed these observations. For both graphite concentrations, the sheet resistance decreased with temperature, reaching its minimum at 100 °C, consistent with optimal particle packing and reduced interparticle gaps. Coatings containing 40 wt% graphite showed up to a sixfold improvement in conductivity compared to those with 30 wt%, emphasizing the role of conductive filler concentration in establishing continuous pathways for electron transport.
After the abrasion test, 40 wt% coatings retained low sheet resistance values and exhibited only minor variation between repeated measurements, suggesting excellent mechanical integrity and electrical stability of the conductive network. In contrast, 30 wt% coatings were more sensitive to mechanical stress, showing higher variability and partial loss of conductivity.

Based on the measurements, it was found that the combination of 40 wt% graphite and a drying temperature of 100 °C gives coatings with the most favourable structural, morphological, and electrical properties. This formulation provides a reliable balance between high conductivity, coating uniformity, and abrasion resistance.
Although the rub resistance of the printed samples was visually assessed on a five-point scale, this evaluation was not the main focus of the study. Our primary goal was to determine whether the samples retained electrical conductivity after rubbing. Samples dried at 100 °C showed the lowest resistance and the highest conductivity, suggesting optimal particle connectivity and a homogeneous coating structure.

4. CONCLUSION

Both graphite concentration and drying temperature were found to affect the electrical, morphological, and mechanical performance of printed conductive coatings. An increase in graphite content from 30 wt.% to 40 wt.% led to improved electrical conductivity. At the same time, higher filler loading contributed to improved surface uniformity and greater resistance to mechanical abrasion.
Drying temperature proved to be an equally important processing parameter. Among the investigated conditions, drying at 100 °C consistently provided the most favourable balance between electrical conductivity and structural stability. At this temperature, the coatings exhibited a compact microstructure, high surface homogeneity, and the lowest sheet resistance values for both graphite concentrations. Drying at lower temperatures led to incomplete particle contact, while excessive heating caused localised structural defects and reduced mechanical integrity, likely associated with binder shrinkage and degradation.
The abrasion tests showed that coatings containing 40 wt.% graphite maintained stable electrical performance even after mechanical stress, indicating strong adhesion to the substrate and a robust conductive network. In contrast, coatings with 30 wt.% graphite showed greater variability in resistance values, highlighting their increased sensitivity to mechanical loading.

Overall, the combination of 40 wt.% graphite and a drying temperature of 100 °C proved to be an optimal formulation within the scope of this study. From a practical perspective, these findings are particularly relevant for printing on paper-based substrates.
This system combines high conductivity, good surface uniformity and abrasion resistance, which makes it suitable for potential application in flexible and wearable electronic devices. Future work will aim to improve environmental compatibility, electrical efficiency and long-term stability.

5. ACKNOWLEDGMENTS

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6. REFERENCES

[1] Y. Qin et al., *A Review of Carbon-Based Conductive Inks and Their Applications.* Coatings, 2023, 13(10):1769.

[2] V. Marchianò et al., *Tailoring Water-Based Graphite Conductive Ink Formulation for Enzyme Stencil-Printing: Experimental Design to Enhance Wearable Biosensor Performance. Chem. Mater.*, 2024.

[3] T. Leng et al., *Screen-Printed Graphite Nanoplate Conductive Ink for Flexible Electronics.* (Preprint, 2019).

[4] S. S. Azim et al., *Studies on Graphite Based Conductive Paint Coatings. Surf. Coat. Technol.*, 2006.

[5] Y. Z. N. Htwe et al., *Printed Graphene and Hybrid Conductive Inks for Flexible, Wearable Electronics. Mater. Today Commun.*, 2022.

[6] A. Dey et al., *The Development of an Affordable Graphite-Based Conductive Ink for Printed Electronics. Materials*, 2025.

[7] B. Eghan et al., *Systematic Review of Conductive Inks for E-Textiles. SAGE Open Mater.*, 2025.

[8] P. G. Karagiannidis et al., *Microfluidization of Graphite and Formulation of Graphene-Based Conductive Inks. ACS Nano*, 2017.

[9] T. C. de Oliveira Cândido et al., *Development and Characterization of Conductive Ink Composed of Graphite and Carbon Black for Application in Printed Electrode. Analytica*, 2023, 4(4):513-526.

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