Trimble Project

Smart and Intelligent Concrete

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Executive Summary

This project aimed to perform proof of concept experiments to determine the feasibility of integrating Carbon Nanotubes (CNT) printed films and wires with the concrete. CNTs are multifunctional and chemically very stable materials and can lead to making concrete structures that are interactive, smart, and intelligent. Some of the new functionalities, such as heating, EMI shielding, sensing, and structural monitoring can lead to safer, greener, and comfortable buildings. This can be achieved by integrating carbon nanotube-based conductors and sensors within concrete structures, effectively creating nerves within the skeleton of the building.

The work presented in this report demonstrates that the Double Walled CNT inks can easily be printed for making a few micrometers thick conducting wires on a very rough concrete surface. These films are very robust and do not get damaged during the poring and the setting process of the concrete. We have studied the stability of these wires which have been buried in the concrete block for a few months and found these to be very stable during this period. In comparison, copper wire corrodes and becomes an open circuit in a few days.

The study presented in this short research project demonstrates that it is feasible to introduce new functionalities to the concrete. Printing of carbon conductors, heater, and temperature sensors has been demonstrated. However, there is a lot more work that is still needed to be done to understand the very long-term (decades-long) stability, the effect of humidity and pressure.

We hope that the ideas presented in this research will provide an opportunity to find new and innovative applications and help to establish collaboration with the leading industrial and academic partners.

Background & Objectives of the Project

Due to the growing interest in 3D printed homes, smart and intelligent infrastructure, and continuous structural monitoring, there is a need for integrating electronic components and sensors with concrete and masonry structures. The expected growth of electric and driver-less vehicles also demands a paradigm shift in road infrastructure, so that roads can interact with vehicles and also provide services like charging while driving. There have been many research groups and companies working on the concept of smart and intelligent concrete structures. Electromagnetic interference (EMI) shielding, self-heating, self-healing, energy harvesting, structural monitoring are some of the smart features which have been introduced to the concrete.[1] To perform smart functions many properties such as stress, strain, temperature, humidity, cracks need to measure which demand installing sensors inside or outside the concrete structures. Optical fibres[2] and piezo-electric materials[3] have been in use for structural health monitoring. Concrete-filled will conductive fibers[4] have been tested for measuring strain and crack formations. Conventional and MEMS temperature and humidity sensors have been tested installing inside the concrete.[5] Low sensitivity, poor durability, and stability, high implementation, and service cost are the key challenges which are still needed to be overcome before these technologies can be implemented. If sensors are embedded inside the concrete, these must be resilient enough to survive the harsh chemical and physical conditions and connected to the outside world for measurements and data collection. Furthermore, these sensors and wires should not alter the structural properties of the concrete.

In this project, we have tested an idea of printing sensors and conductors on and inside the concrete which is small, chemically stable, provide good sensitivity, cost-effective, and also provides multifunctional features. Printing can be a very cheap and convenient method for integrating electronics with concrete and roads on a very large scale. Carbon nanotubes are one the most chemically stable materials and can be exposed to harsh environments without being degraded. In comparison, metal conductors such as copper are prone to corrosion. The objective of this project is to demonstrate that CNT-based conductors and sensors can be printed on the concrete surface and be embedded in concrete without losing their performance. Paving the way for making smart and intelligent concrete structures.

During this project, the following questions were addressed as set in the original proposal.

(1) Can continuous conducting CNT wires, of thickness a few micrometers, can be printed on a concrete surface?
(2) How the conducting properties of the CNT wires evolve when embedded in the concrete?
(3) To measure the conductivity of the printed wires as a function of strain, temperature, and humidity.
(4) To perform local heating of the concrete using CNT electrodes.

We have been able to answer almost all of these questions. Which provided us a great insight into integrating electronic wires and components with the concrete. Measurements and the analysis is reported in the following sections.

Carbon Nanotubes Conductive ink for Concrete

Concrete structures such as bridges, tunnels, and buildings, and very big structures, and a large quantity of ink is required to embedding conductors and sensors in the concrete. Therefore, any process which produces carbon conductive ink must be scalable and can produce high conductivity ink. The ink used in this project is made by ourselves with double-wall carbon nanotubes (DWCNT) and is produced using a very scalable microfluidization dispersion technique. The carbon conducting films made using this ink have a sheet resistance of less than 0.5 Ohm/square/mil. The method for creating this ink is discussed in detail in our recent publication and the figure below shows the schematic of the dispersion process.[6]

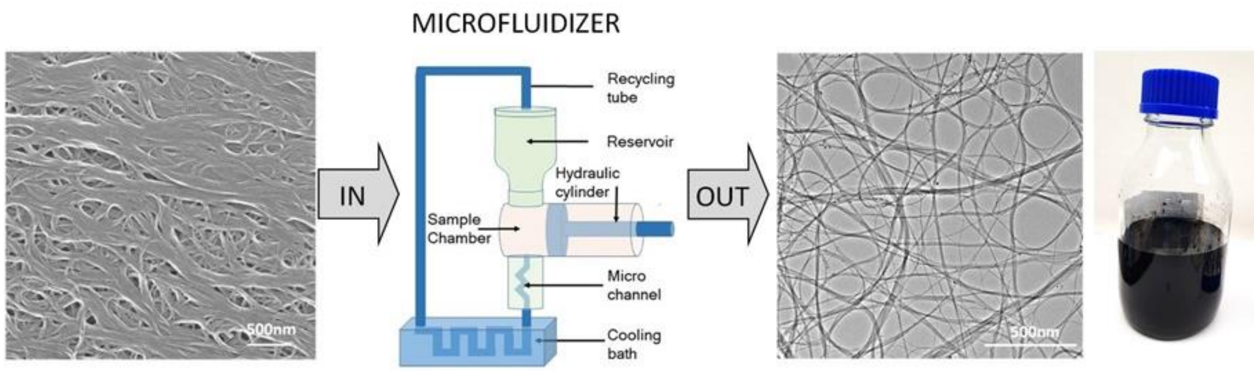

Figure 1: A schematic of the microfluidization dispersion process. The Left (and the right) side images show the undispersed (and the dispersed) CNTs.

Properties of the ink used in this project are as follows:

Properties of ink/film	Values
Material	DWCNT
Medium	Water
DWCNT Concentration in the ink (mg/ml)	3
Viscosity of the ink (Pa-s)	>1
Electrical Conductivity of the film (S/m)	3.0×10^5
Thermal Conductivity of the film (W/m-K)	42±3

Integration of CNT Conductors within Concrete

To understand the integration of CNT conductors with the concrete, we have made a comparison with the four different types of conductors: (1) Printed CNT films, (2) CNT wires, (3) Freestanding CNT film/strip, and (4) Copper wire.

Printed films were directly drawn on the concrete surface through a stencil. The concrete block was made with commercially available wet concrete and is set in the form of a small pillar using a cylindrical mold. CNT wires used for the comparison were 25µm in diameter and were bought from DexMat, US. Free-standing films were made in our lab and their thickness was about 5µm. To perform electrical contacts, silver pads were placed at the end of the wires. A comparison has also been made with a Cu wire of diameter 25µm. In total seven of these samples were used for comparison. As shown in the figures below.

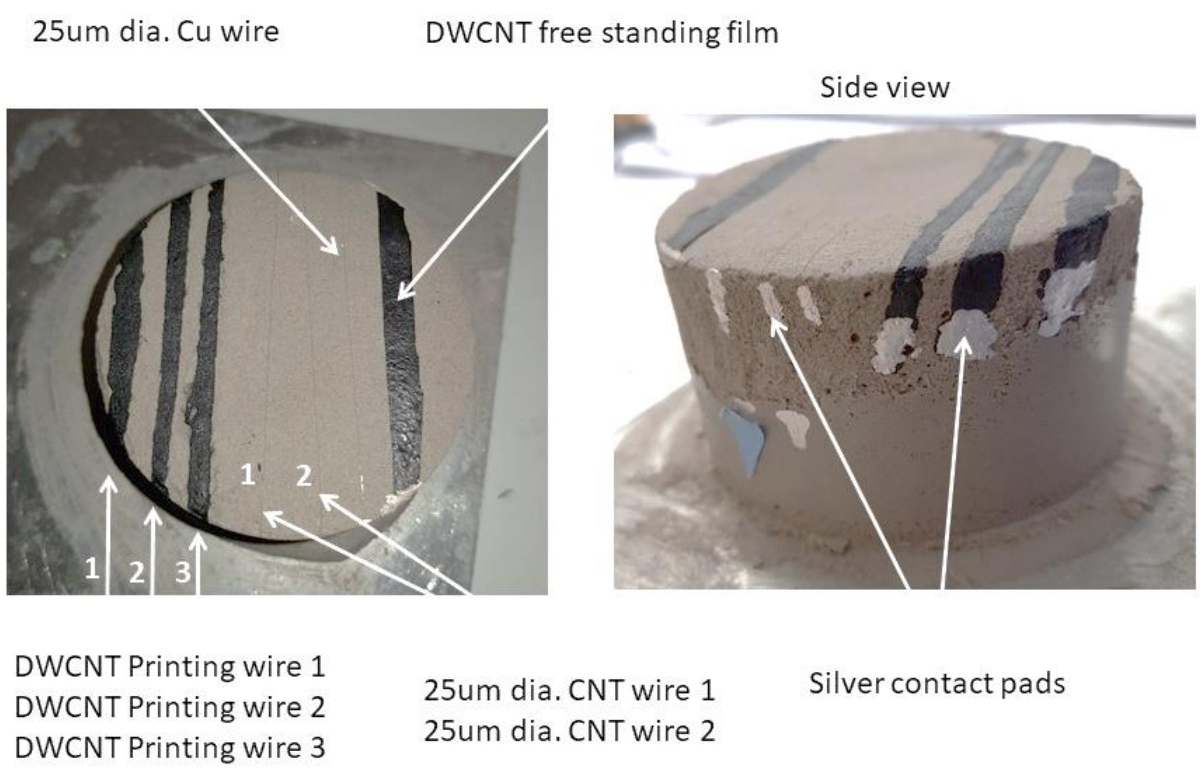

Figure 2. Four different types of conducting wires connected/printed on the concrete pillar surface. A side view shows the silver contacts attached to the wires, for electrical measurements.

Electrical Properties of CNT and Cu Wires During Concrete Setting Time:

Having attached the conducting wires to the concrete surface, wet concrete was poured on the wires to bury these wires inside and their resistance was observed as a function of time as shown in the graph below.

Copper wires had the lowest resistance of 2.5Ω and the resistance did not change during the initial setting period of 3 hours. Resistance of the 25µm CNT wires was also very stable during this period. Whereas, the resistance of all the printed films and free-standing film/Strip increased within the first 15 minutes and then gradually started to saturate. As the concrete is poured, these films become wet and their temperature also changes which has caused this change. As the surface area of these 25µm wires is much smaller than printed wires, no significant change was observed in these wires.

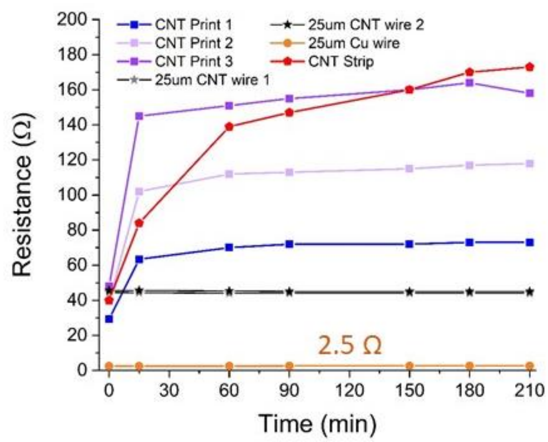

Figure 3: Left, Wet concreted poured on the wires. Right: Change in the resistance of wires as a function of time, after pouring the concrete.

Long Term Electrical Performance of Wires Inside Concrete:

Figure 4a shows the change in resistance of CNT wires and films and the Cu wires during the setting period of the top concrete block. Block was left to settle overnight. As the concrete starts to settle, the resistance of the CNT wires started to decrease towards their original resistance values. Whereas, the copper resistance increased to hundreds of mega-ohms and in two days became an open circuit. This clearly shows that copper wires are oxidized in the concrete where was carbon wires retained their properties as the moisture/water contents are reduced in the concrete.

Having buried these wires in the concrete we observed their resistance for 85 days and the results are presented in figure 4b. which shows that the resistance of the 25µm CNT wires and the printed films

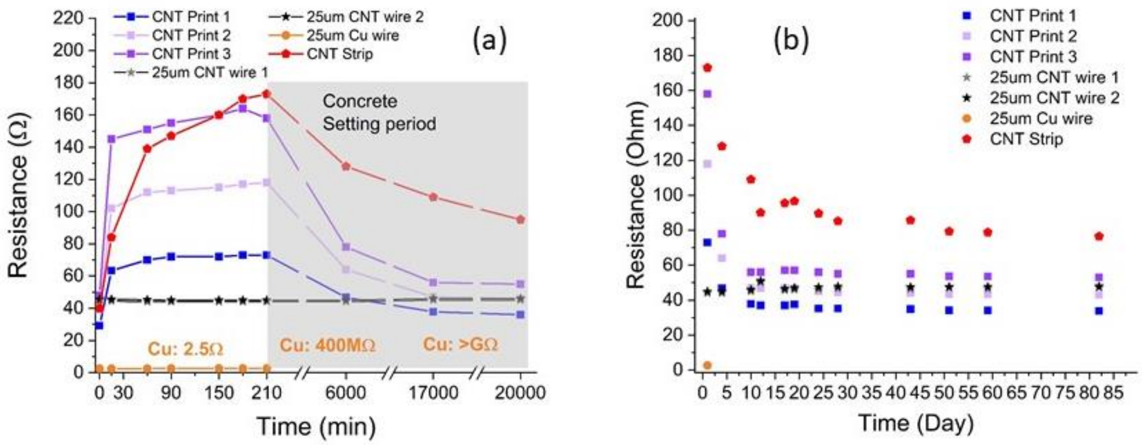

Figure 4: (a) Change in resistance of wires during the concrete setting period. (b) Long term stability of wire resistance over 85 days.

was very stable. Free-standing films/strip took a much longer time to reach a stable resistance, which can be due to the fact that it's both surfaces, the top and bottom were exposed to the water in the concrete, which may have taken longer to dry.

These measurements show that printed CNT films can be embedded in the concrete and are chemically very stable. Furthermore, due to their sensitivity to moisture and temperature, they have the potential for being used as temperature and humidity sensors. Based on these measurements CNT films have been tested as a multifunctional material.

Multifunctional Carbon Conductors as a Heater and a Sensor

Figure 5 shows a multifunctional device where two CNT conducting films are printed on a concrete surface. One of the coil-shaped conductors is used as a heater element whereas the second CNT conductor is used as a temperature sensor, as indicated in the figure below.

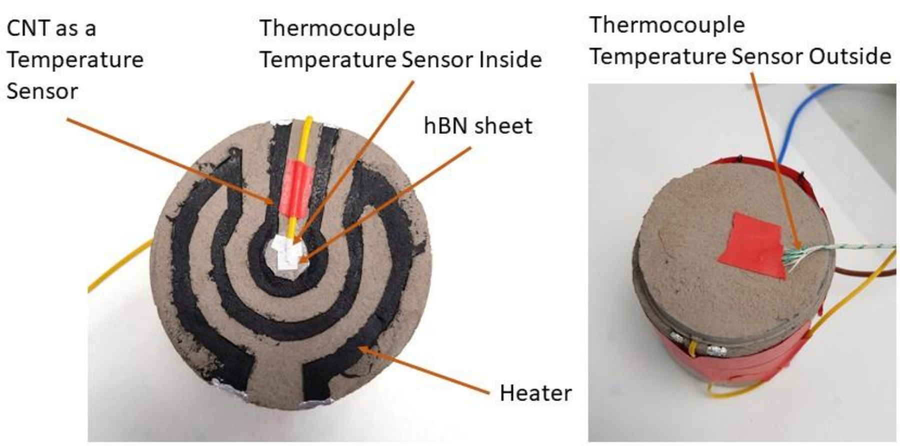

Figure 5 CNT films are embedded in the concrete pillar. CNT films are used as a heater and the temperature sensor. Two thermocouples are installed, one inside and the other at the top of the pillar.

To calibrate the CNT sensor, a thermocouple is placed at the center of the concrete pillar. To protect the thermocouple material from corrosion, the thermocouple is covered with a sheet of hexagonal boron nitride (hBN), which has also been made in our lab. An hBN is used because it is thermally conductive but at the same time, it is an electrically insulating material. After printing, the second layer of concrete is cast on the top, as shown in figure 5. Concrete is left to set for one week.

The resistance of the heating element was about 140Ω. Figure 6a shows the temperature observed by the thermocouples placed inside (red dots) and outside (blue dots) the concrete pillar. The top sensor measures the surface temperature which is less than the temperature inside due to the radiative and convection heat losses. A voltage of 37.5 Volts was required to input power of 10W and heat the concrete block to about 60^{o}C.

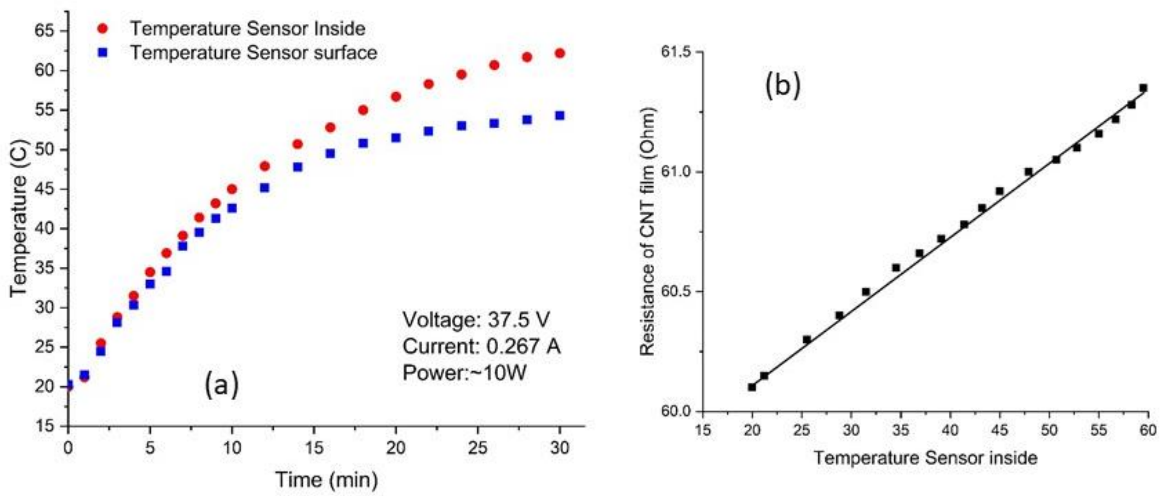

Figure 6: (a) Temperature at the inside and the outer surface of the concrete pillar. (b) A calibration curve of the CNT sensor.

Figure 6b shows the calibration curve of the CNT resistive sensor printed inside the concrete and is calibrated against the thermocouple placed inside, at the center of the concrete block. It shows that the resistance has a linear temperature dependence and the sensitivity is $(\Delta R/R) \times 100 = 0.05\%$ per ^{o}C change in temperature. This type of heater can be embedded just below the concrete surface and can be used for deicing applications for runways, roads, and pathways. In our experiment, 10W of power took about half an hour to bring the surface temperature from 20^{o}C to 55^{o}C. It gives the power consumption of 0.005 kWh and the energy consumption per unit area was 0.013 kW-h/m^2. This is low enough to be used for practical applications. Power consumption can be improved further by placing a thermally insulating layer underneath the heater. A more detailed power consumption analysis is required for low-temperature conditions which were outside the scope of this study.

Conductive Concrete

There is a growing interest in making multifunctional concrete that can not only be used as a structural material but can also perform other functions such as heating, EMI shielding, temperature sensing, and electrical grounding.[7] To introduce these functionalities, we performed some preliminary experiments and made a composite material using out DWCNT ink and the concrete mixture. Both our ink and the concrete are water-based therefore very easy to form such a composite. Figure 7 below shows the mixing process where concrete is mixed with our conductive ink and copper electrodes are placed in the block for performing electrical measurements.

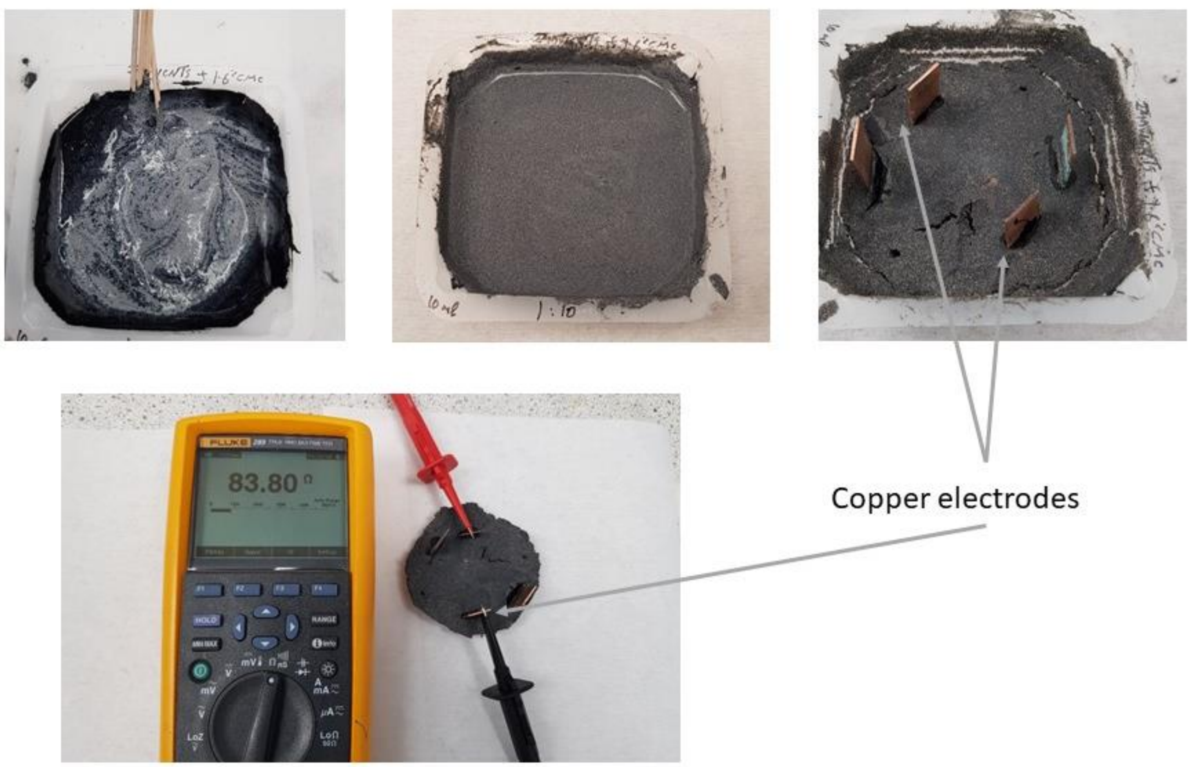

Figure 7: Mixing of DWCNT ink with the concrete. Copper electrodes are inserted before the concrete is set and are used for making electrical measurements.

To make this mixture 0.1 wt% of DWCNTs were mixed in the concrete. The sheet resistance and the resistivity of the conductive concrete were ~50 Ω/□/cm and ~15 Ohm-cm respectively.

The resistivity of the concrete was low enough that it can be used as a heater using a low voltage power supply. Figure 8 shows that about 25Volts are required to heat the concrete to about 80^{o}C in about 5 minutes. Figure 8a is the IV curve of the concrete and gives resistance of about 50Ohm. Figure 8b shows the change in temperature as a function of power density and gives an estimated value of convection coefficient of 29. Figure 7d shows the temperature of the concert after the respective power is applied for 5 minutes. These measurements show that the concrete can be used as a heater and due to its low resistance can also be used as a grounding/earth application.

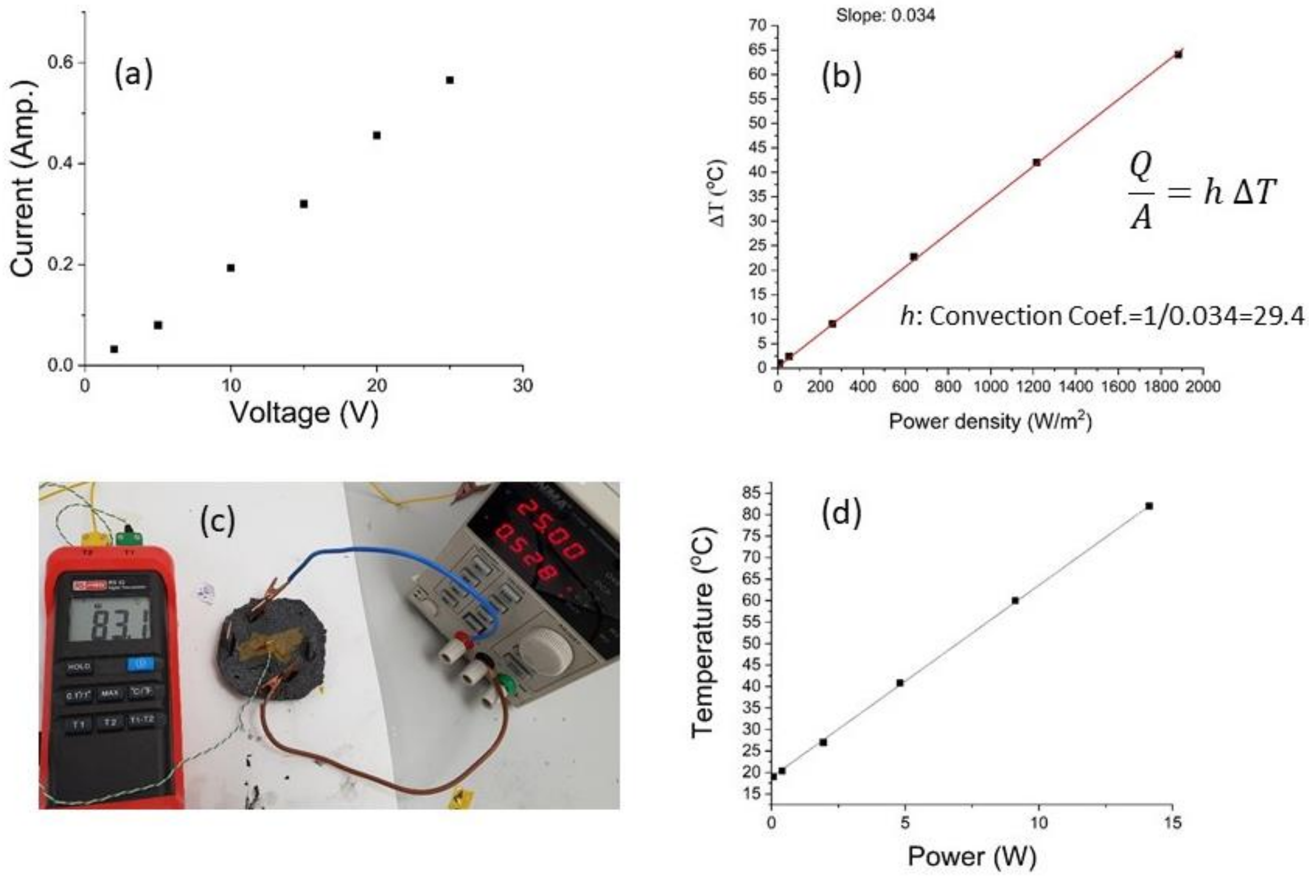

Figure 8: Electrical measurement of the conductive concrete made with the DWCNT ink.

Conclusion and Future Work

Measurements presented in this work demonstrate that DWCNT conductive electrodes can be integrated with the concrete and provide long-term stability inside the concrete. In addition, can be used as a heating and sensing element.

These thin conducting films can also be used for structural monitoring for example the resistance of these films is also very sensitive to any micro-cracks formation inside the concrete and therefore can provide structural health information. If these films can be fit into bridges, tunnels, and buildings, they can provide vital information after the structure heath after earthquakes. Some of the other applications can be the remote charging of the electric cars on the road while driving or parking state. We have shown that these carbon wires are very resilient to the harsh condition therefore, they also have the potential for using as conductor or as a sensor in sewerage and nuclear reactors where communication may be required across a thick concrete wall. Carbon heated embedded in the concrete can also be a very good candidate for making smart and weather resilient runways.

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