Summary of Characterization and Performance Enhancement of Cement-Based Thermoelectric Materials

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Abstract

The article “Characterization and Performance Enhancement of Cement-Based Thermoelectric Material” specifically provides insight into optimizing concrete, a material that has become a staple in civil infrastructure, to harvest thermal energy which can be then converted into electrical energy. With the rapid increase of urbanization, the study of enhancing concrete would help mitigate the Urban Heat Island effect, the phenomenon where urban, man-made areas are much warmer than surrounding rural areas. It then writes about the figure of merit (ZT), a dimensionless parameter that shows the performance of a Thermoelectric (TE) material, which relies on the Seebeck coefficient (*S*), Electrical Conductivity (EC or σ), Thermal Conductivity (TC or κ) and absolute temperature (T). The relationship between these parameters is shown to be $ZT = T * (S^2 * \sigma)/\kappa$. To maximize the performance of a TE material, the Seebeck coefficient, EC, and T must be large and TC must be small. The researchers, Jani, R., Holmes, N., West, R., Gaughan, K., Liu, X., Qu, M., Orisakwe, E., Stella, L., Kohanoff, J., Yin, H., & Wojciechowski, B, then analyzed and compared the properties of various additives to concrete to find the TE material that maximizes ZT. Due to the properties of EC and TC, improving one of these qualities typically worsens the other in terms of ZT. To determine the ZT of a material, there are various ways to measure: a DC or AC method. Most studies involving cement typically use DC methods, yet it is found that this can cause polarization errors in cement so AC methods are preferred. When TE materials are exposed to high temperatures inaccuracy in measured properties can be as high as 50% which is why samples should undergo similar conditions including sample size and temperature. In conclusion, Cement-Based TE materials show promising results but further work should consider its limitations including sample size and measurement method.

Materials & Methods

In this study, the researchers used "CEM I 42 5 R," a fine-grained cement mix that hardens quickly and is known for its high early and ultimate strength. Although this concrete is not typically recommended for large construction projects, it does show promise in smaller structures. This concrete provided an affordable and reliable base that the researchers could use to test out the effectiveness of different add-in materials on. This concrete was also convenient as it only required water to also be added into the mix. The researchers used a water-to-cement ratio of 0.45, which means that there were approximately 0.45 pounds of water used for every pound of cement mix in the final mixture. This ratio was chosen because a water-to-cement ratio between 0.45 to 0.5 is commonly used to mitigate the water permeability and improve the durability of the concrete- with values closer to 0.45 showcasing more strength. In addition, the researchers used bismuth trioxide powder- which ranges from $50-$100 per 100 grams- and ferrous oxide powder- which can be found for about $3 per pound through online stores. Both powders were measured and found to have very fine particles, 50 and 53 microns. These powders were then mixed into the concrete mixture, totaling 5% of the concrete when measured by mass.

Table 2. CEM I cement chemical composition as provided by Irish Cements.

Contents	Percentage (%)
SiO_2	18.29%
Al_2O_3	5.08%
Fe_2O_3	2.78%
CaO	63.89%
SO_3	2.64%
F. Cao	1.57%
Loss on Ignition (LOI)	2.79%
Na_2O Eq. (Alkali Equivalent)	0.59%

Here, the chloride content of the cement is not included as it was not available from the reports.

Table 1. Pictured here is a table from the study, providing the composition of the cement the researchers used without the metal oxide powders added.

To test how the metal oxides would affect the concrete's Seebeck coefficient, the researchers prepared three distinct batches: a control with just the water and concrete mix, a batch with the bismuth oxide powder, and a batch with the ferrous oxide powder. They first mixed the dry ingredients- the mix and any metal oxide powders- together to ensure an even distribution and then added water. The concrete was then cured for 24 hours and placed in 20±1°C water for a week, allowing it to properly form and simulate weathering. Once the concrete was properly formed, the researchers created a setup to measure the Seebeck coefficient. This was done by using a silicone mat heater to simulate the heat that concrete may normally absorb as a part of a building or bridge on one of its sides and exposing the other side of the concrete to room temperature. The concrete samples were also surrounded by insulators to ensure that outside factors in the lab would have a minimal influence on the data collected. A Data Acquisition Unit and Digital Multimeter was connected to the sample to record the voltage difference and thermal distribution throughout the concrete.

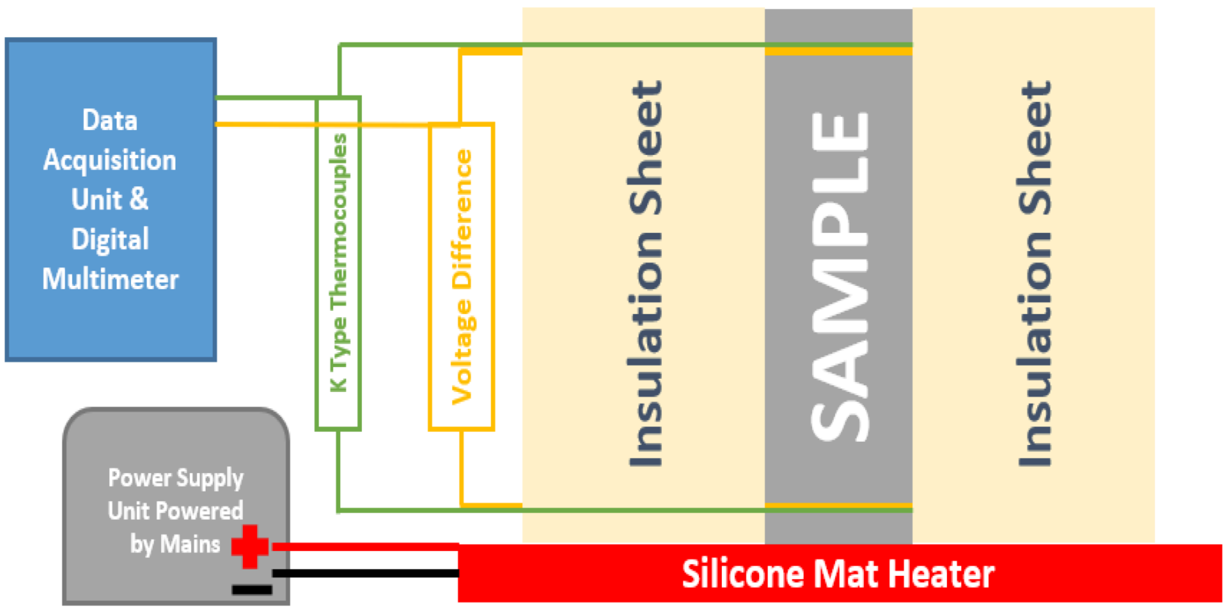


Figure 1. Displayed here is a diagram specifying the experimental setup that the researchers used to measure the Seebeck coefficient.

The setup shown above also utilized other parts such as binds and weights to ensure its stability, and copper meshes were used as points to measure the voltage and temperature differences throughout the concrete. In addition to performing tests on the temperature and voltage differences of the samples, the researchers also found the electrical conductivity of the samples through connecting copper wires to the meshes and calculating the electrical resistance observed by the data acquisition and digital multimeter. The inverse of the resistance was then taken, giving the electrical conductivity.

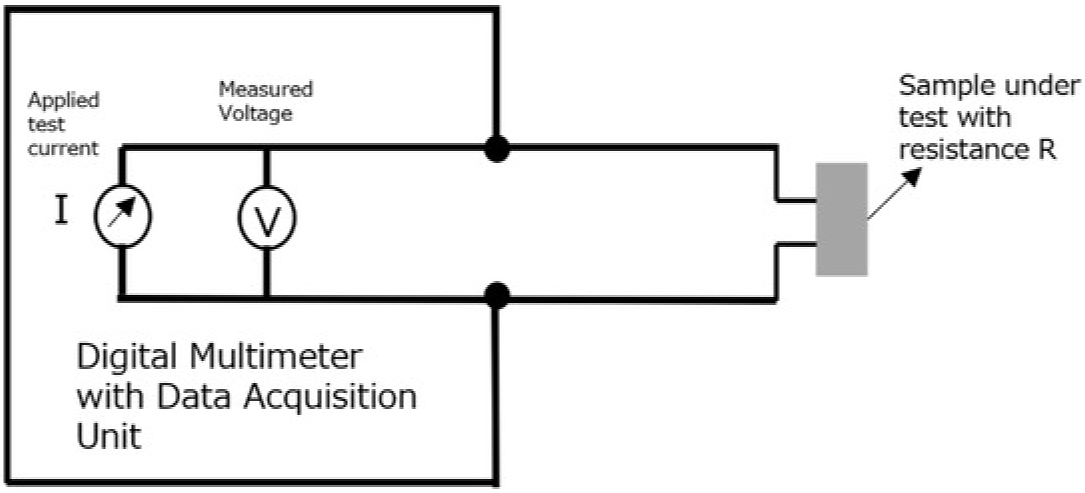
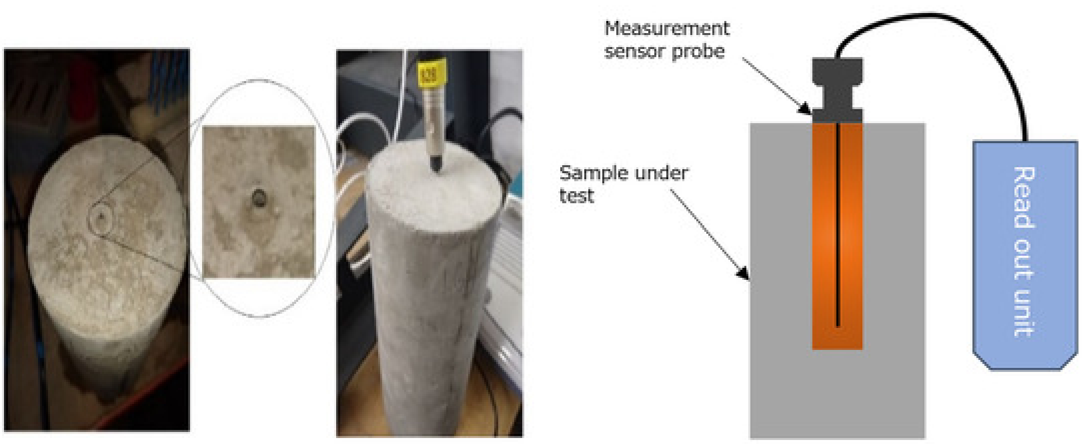


Figure 2. Displayed here is a diagram specifying the experimental setup that the researchers used to measure the electrical conductivity of the concrete.

Lastly, the thermal conductivity of the concrete was found though inserting a sleeved THERMTEST TLS-100 thermal conductivity and resistivity meter into a cylindrical portion of the concrete at room temperature for 10 trials and recording the data found by the inserted meter.



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Analysis

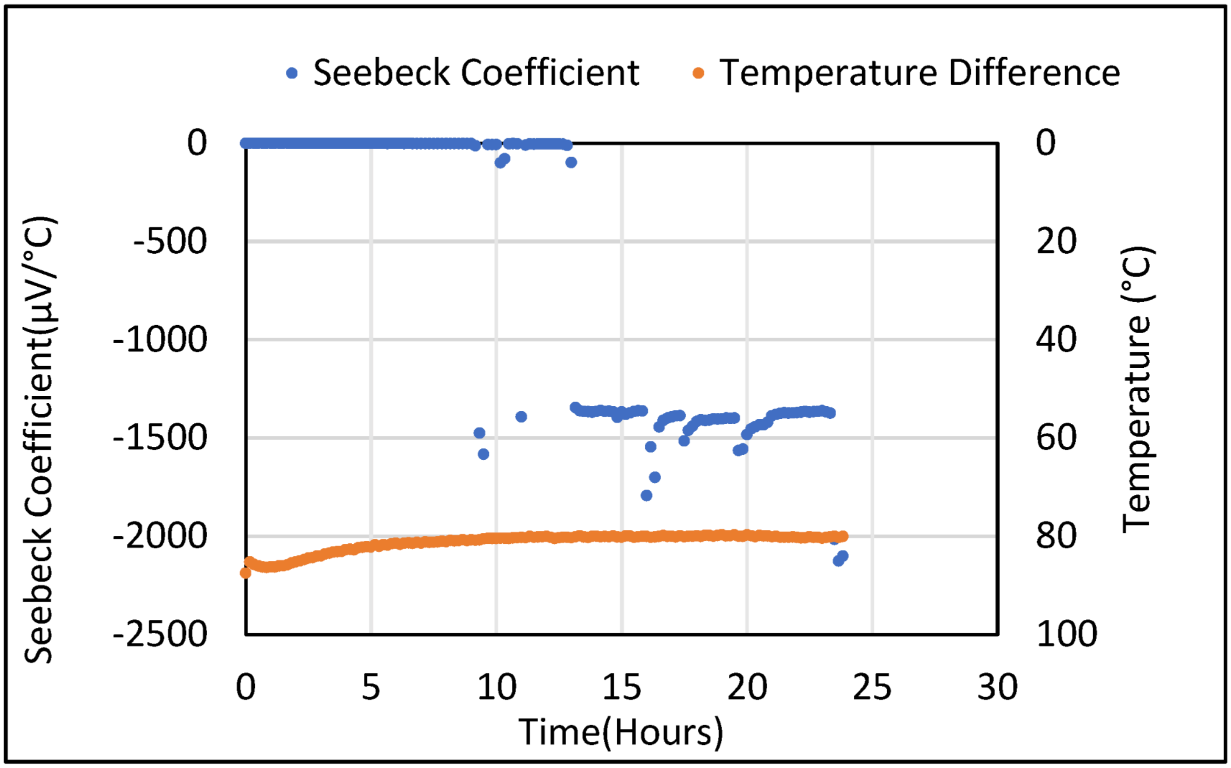

Figure 3. The graph pictured displays the Seebeck coefficient and Temperature gradient of plain cement over a time period of 24 hours. The temperature stayed relatively constant and while the Seebeck coefficient was constant at first, after 10 hours an error appeared.

With a fixed temperature gradient, plain cement displayed a constant Seebeck coefficient, though, after around 10 hours, some error appeared. A sort of sinusoidal pattern had occurred with the Seebeck coefficient, which had regularly appeared in the rest of the trials. This error was later discovered by the researchers to be caused by an unstable multimeter along with the drying process of the cement. As moisture went away, the concrete would be less electrically conductive, lowering its Seebeck coefficient.

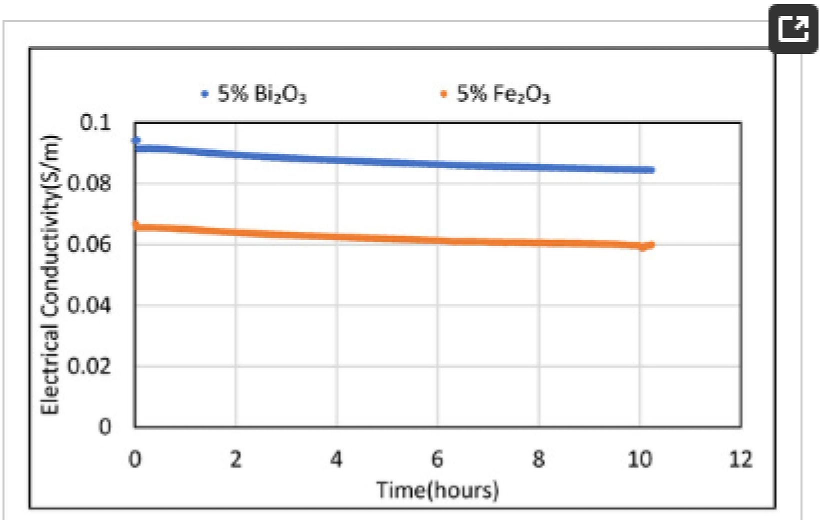

Figure 4. *Pictured above are two graphs that show Electrical Conductivity for the Bismuth Oxide and Iron(III) Oxide samples, shown in blue and orange respectively.*

The results of these trials resulted with quite a bit of error, as is evident with all the noise in the graph of the Bismuth Oxide trial. This ambiguity within the results prompts a discussion later in the paper. Cement doped with Bi_2O_3 had the highest electrical conductivity (EC), followed by the control, the Fe_2O_3 sample having the lowest EC. Regarding thermal conductivity, the control, as expected, had the highest, while The Fe_2O_3 sample had the least. While the drying process reduced conductivity due to loss in moisture content, voltage interference through measurements also decreased over time. Overall, these results show that cost-effective fillers, such as the metal oxides tested in the paper, are useful in increasing the thermoelectric effectiveness of concrete. The biggest takeaway, however, is that the drying process significantly worsens the thermoelectric effects of concrete. This has implications on the sustainability of cement-based thermoelectric materials in the long term and prompts further alteration in our experimental design to account for such change.

References

Jani, R., Holmes, N., West, R., Gaughan, K., Liu, X., Qu, M., Orisakwe, E., Stella, L., Kohanoff, J., Yin, H., & Wojciechowski, B. (2022). Characterization and Performance Enhancement of Cement-Based Thermoelectric Materials. *Polymers*, *14*(12), 2311–2311. https://doi.org/10.3390/polym1412231