Transportation Infrastructure Precast Innovation Center (TRANS-IPIC)

University Transportation Center (UTC)

Precast concrete with self-powering defrosting capability
UB-24-EP-01

Quarterly Progress Report
For the performance period ending June 30, 2025

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Collaborators / Partners:
None

Submitted to:
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TRANS-IPIC Quarterly Progress Report (Section 1 – 7, 5 pages max.):

Project Description:

1. Research Plan - Statement of Problem

   This project is aimed at developing precast concrete with self-powering defrosting capability. Defrosting capability has long been shown to be effective in cement-based materials by resistance (Joule) heating, provided that conductive admixtures are used to reduce the resistivity (Chung, 2004). Short carbon fiber is the most cost-effective conductive admixture to greatly lower the resistivity (Chen and Chung, 1993), so that resistance heating becomes effective. Short steel microfiber is even more effective than short carbon fiber (Wang, Wen and Chung, 2004), but it is much higher in price.

   The main challenge relates to self-powering, which means the provision of electric power without any external energy source (such as solar panels and wind turbines), i.e., the powering capability is built-in to the concrete. The embedment of batteries or battery components in concrete for supplying energy is not desirable, due to the short service life of batteries compared to concrete structures and the difficulty of replacing the embedded batteries. Moreover, the embedment weakens the concrete structure and the battery disposal is of environmental concern. Pyroelectricity may be rendered to concrete for the sake of self-powering under temperature variation by the use of pyroelectric admixtures such as lead zirconotitanate (PZT), which is expensive, needs to be poled, and suffers from depoling tendency. Poling requires the application of a high electric field, which is challenging when the concrete is substantial in size.

   The proposed self-powering approach is based on a novel concept that does not involve any of the concepts mentioned above. Rather, it exploits the electrical energy in a capacitor. During discharge, energy is released from the capacitor. During charging, energy is provided to the capacitor. The proposed concept involves the capacitance changing upon a change in temperature, thereby causing discharge or charge of the capacitor.

2. Research Plan - Summary of Project Activities (Tasks)

   Original timeline:

   Task 1 (Month 1). Preparation of the capacitor units by 3D printing, with selection of the polymer and the dimensions of each of the layers in a capacitor unit. Ordering the needed materials and supplies.

   Task 2 (Month 2). Testing the capacitor units by capacitance measurement during imposed cooling (capacitor charge, from above 0°C to below 0°C) and during subsequent imposed heating (capacitor discharge, from below 0°C to above 0°C).

   Task 3 (Month 3-4). Prepare precast concrete specimens of thickness around 1 inch, with inclusion of fine and coarse aggregates and the three admixtures (carbon fiber, capacitor units and latex, as listed above) and selection of the aggregate and admixture proportions.

   Task 4 (Month 4). Measure the electrical resistivity of the specimens obtained in Task 3. If the resistivity is not lower than that of conventional concrete by a few orders of magnitude, the carbon fiber content will be increased (e.g., from 1% to 2% by mass of cement) and then Tasks 3 and 4 will be repeated.

   Task 5 (Month 5-6). Test the precast concrete specimens obtained in Task 3 (or repeated Task 3) by measuring the temperature continuously upon imposed cooling (capacitor charge) and during subsequent automatic heating (capacitor discharge) for assessing the effectiveness of self-powering defrosting.

   Task 6 (Month 6). Devise the research plan after the proposed 6-month project and evaluate the pavement-related technology implementation feasibility. Prepare the final report.

Project Progress:

3. Progress for each research task

   Task 1 100% completed to date
   Task 2 100% completed to date

Task 3 100% completed to date
Task 4 80% completed to date
Task 5 80% completed to date
Task 6 0% completed to date

A. Capacitor design improvement

The original design involves a capacitor consisting of three layers, which are all 3D-printed, with the outer two layers being conductive and the inner layer being nonconductive. In this quarter, it was found that the fabrication of the sandwich by 3D printing is better done by separately printing the three layers and then joining them together. After this, it was found that it would be even better and simpler to replace each of the outer two conductive layers by a metal foil attached to the nonconductive layer by using an adhesive. The metal foil is attractive, partly because it is much more conductive than the conductive 3D printed material, which is carbon black filled polymer. Furthermore, the joining of the conductive and nonconductive layers to form a sandwich is simpler if the conductive layers are metal foils rather than 3D-printed layers. With the replacement of the two conductive 3D-printed layers by two metal foils, only the middle nonconductive layer is 3D-printed. (Fig. 1)

The capacitance decreases with increasing thickness, such that it is directly related to the reciprocal of the thickness. Moreover, the capacitance is proportional to the area of the capacitor. It was found in this quarter that the thickness of the middle 3D-printed nonconductive cannot be less than 0.1 mm, due to the difficulty of printing such a thin layer of adequate quality. Thus, the current design of the capacitor is that the capacitor has a 0.1-mm thick middle 3D-printed nonconductive layer sandwiched by two metal foils.

In the last quarterly report, it was mentioned that the capacitance is much higher for the case of the 3D-printed line direction being in the out-of-plane direction than in the in-plane direction. This statement was found in this quarter to be not correct. The printing of lines that are in-plane is much simpler than that of lines that are out-of-plane. Therefore, in this quarter, the printed lines are in-plane.

(a) *(b)*

Fig. 1 Capacitor. (a) A square capacitor with metal leads protruding in opposite directions. (b) Capacitor with metal leads connected to the LCR meter by two electrical clips.

B. Permittivity determination

By varying the thickness and plotting the reciprocal of the capacitance vs. thickness, a roughly linear curve was obtained. The slope of this line is inversely related to the relative permittivity κ of the nonconductive layer. Thus, κ at room temperature was found to be 3.5, which is reasonable for a polymer.

C. Characterization of capacitor embedded in cement

The abovementioned capacitor (with PLA as the dielectric layer and steel foils as the two conductor plates) was embedded in cement paste (Fig. 2). The capacitance is 30 μF at room temperature (20°C). This capacitance is much higher than the value expected for a capacitor of the dimensions *and dielectric permittivity κ used. In the absence of cement, the capacitance is lower by 5 orders of magnitude. In other words, the embedding of the capacitor in cement increases the capacitance by 5 orders of magnitude. The embedment of the capacitor in cement also decreases the resistance by a factor of 310. The decrease in resistance is expected, due to the fact that the conductivity of cement is much higher than that of air.*

Fig. 2 A capacitor embedded in cement, with electrical leads in the form of steel foils protruding from the cement.

The large increase in capacitance upon embedment of the capacitor in cement is not expected. It cannot be due to the resistance decrease, which would decrease the capacitance instead of increasing it. It is partly attributed to the fringing electric field enabled by the cement around the capacitor. The fringing field increases the capacitance, because it makes the area of the capacitance to be effectively larger. In addition, the large increase in capacitance is attributed to the dielectric behavior of the cement, which is mainly an ionic conductor. The significant contribution of the cement to the observed effect of embedding the capacitor in cement on the capacitance is consistent with the fact that the capacitance decreases with the curing time. It is known that as curing occurs, the ionic conductivity of a cement-based material decreases. However, cement alone (in the absence of the embedded capacitor) does not exhibit a large capacitance, due to the limited permittivity. Therefore, the high capacitance observed with the capacitor embedded in cement is attributed not just to the cement and not just to the embedded capacitor, but to the combination (coexistence) of cement and the embedded capacitor. At this point, the scientific origin of the large capacitance increase is not completely clear. From a practical viewpoint, the large observed capacitance when the capacitor is embedded in cement is attractive for the use of the present technology for defrosting.

D. Studying the effect of cooling on the capacitor embedded in cement

The capacitance decreases upon cooling, i.e., from 28 μF at room temperature (20°C) to 9.3 μF at -20°C. This corresponds to a fractional change in capacitance of -0.67, This trend is attributed to the decrease of the relative permittivity κ of the 3D-printed polymer layer with decreasing temperature, as expected from the entropy-driven decrease in mobility of the polymer molecules as the temperature decreases. This trend cannot be due to the thermal contraction of the dielectric layer, as the thermal contraction would have caused the capacitance to increase (not decrease) upon cooling. This means that the capacitor discharges (with the capacitance decreasing) upon cooling, thereby providing energy for anti-frosting (i.e., preventing frosting) and/or defrosting. During heating, the capacitance increases, due to the increase in the relative permittivity κ, so that the capacitor charges. The charging occurs automatically (i.e., self-charge).

The capacitance decrease upon cooling is accompanied by a resistance increase. This resistance change is attributed to the fact that the capacitance and resistance are not independent electrical quantities. According to physics (the Kramers Kronig relationship), the permittivity and resistivity are not independent of one another. A decrease in permittivity tends to be correlated with a decrease in resistivity, because a low resistance limits the electric field, thereby hampering the polarization (i.e., the separation of the positive and negative change centers) in the dielectric material.

E. Energy assessment

The energy of the capacitor is given by (1/2) CV^2, where C is the capacitance and V is the amplitude of the AC voltage applied to the capacitor. In the experiment of this work, V = 1 Volt. Thus, the energy prior to cooling is calculated to be 1.4×10^{-5} J. The change in energy upon cooling from 20°C to -20°C is thus given by (1.4×10^{-5} J) (0.67) = 9.4×10^{-6} J.

The latent heat of melting of ice is 334 J/g. Hence, the amount of ice that can be melted by one capacitor is [(9.4×10^{-6})/334] g = 28 mg. In practice, multiple capacitors can be connected in parallel electrically in order to provide a higher capacitance. For example, if 10 capacitors are connected in parallel, the amount of ice that can be melted is expected to be 280 mg = 0.28 g.

F. Implementation considerations

In practical implementation of the technology, the capacitance does not need to be measured, as the capacitance changes with the temperature even when it is not measured. The abovementioned capacitance measurement is needed for developing the capacitor and characterizing the temperature effect. However, voltage needs to be applied to provide energy according to (1/2) CV^2. Defrosting occurs automatically upon cooling and the defrosting ability is automatically restored upon subsequent heating. The voltage application is necessary during the time period in which defrosting may be needed, with the need indicated by the temperature that is separately sensed.

For the defrosting method of this work, the energy input (1/2) CV^2 is needed only during the initial charging of the capacitor embedded in the concrete. After the completion of the initial charging, the voltage needs to be maintained, without the need for additional energy input. Furthermore, the voltage required is low, such as 1 V, both during the initial charging and for the voltage after the charging. The voltage is not applied to the concrete, but is applied to the capacitor embedded in the concrete. This is why the voltage does not need to be high.

When the temperature is persistently low, defrosting needs to be performed using the following procedure. The capacitor at the low temperature is first charged by voltage application (energy input), followed by complete removal of the voltage for discharging (energy output) at the same low temperature. This procedure may be repeated to provide more defrosting.

Energy loss occurs during charge or discharge of the capacitor, due to the current flow in the cement-based material next to the capacitor. The current must accompany the charge or discharge. Joule heating results from the current. During charge, the energy loss is not desirable, if the temperature is such that defrosting is not necessary. However, during discharge, this energy loss provides Joule heating, which is an additional mechanism of defrosting.

G. Comparison of proposed defrosting and conventional defrosting involving resistance heating

The conventional defrosting method involving resistance (Joule) heating requires current application and it suffers from the fact that the concrete needs to be conductive, as enabled by the presence of a conductive admixture, which is required to decrease the resistivity of the concrete by a few orders of magnitude. In contrast, the method of this project does not require any particular admixture for the concrete, so it is less expensive than the resistance heating method. Moreover, the energy application for resistance-based heating for defrosting is high; the power is given by I^2R, where I is the current and R is the resistance, and the energy is given by the product of the power and time. Energy needs to be provided continuously. Furthermore, the voltage required is high in order for the current I to be substantial, since the resistance R is not very low for concrete, even when it contains a conductive admixture, with R being particularly large when the concrete structure is large. The higher is R, the higher is the voltage needed for providing the required current I.

Compared to the conventional defrosting method involving resistance heating, the proposed technique has the following advantages, (i) the energy requirement is much lower, (ii) the voltage requirement is much lower, and (iii) no conductive admixture or any particular admixture is required. This project provides not only a new technology, but it provides new science which still needs to be unraveled. The implementation protocol still needs to be developed.

4. Percent of research project completed
   80% completed

5. Expected progress for next quarter
   The next quarter will involve Tasks 4-6.

6. Educational outreach and workforce development
   A lecture was given online for State Key Laboratory of Silicate Materials for Architectures, Wuhan University of Technology, Wuhan, China, on April 14, 2025. It was titled "Carbon fiber multifunctionality". The lecture was attended by about 250 people, who were primarily graduate students.

7. Technology Transfer
   None

<u>Research Contribution:</u>

8. Papers that include TRANS-IPIC UTC in the acknowledgments section:
   None

9. Presentations and Posters of TRANS-IPIC funded research:
   None

10. Please list any other events or activities that highlights the work of TRANS-IPIC occurring at your university (please include any pictures or figures you may have). Similarly, please list any references to TRANS-IPIC in the news or interviews from your research.
    None

Appendix 1: Research Activities, leadership, and awards (cumulative, since the start of the project)

A. Number of presentations at academic and industry conferences and workshops of UTC findings
   - No. = 0

B. Number of peer-reviewed publications submitted based on outcomes of UTC funded projects
   - No. = 0

C. Number of peer-reviewed journal articles published by faculty.
   - No. = 633

D. Number of peer-reviewed conference papers published by faculty.
   - No. = No record

E. Number of TRANS-IPIC sponsored thesis or dissertations at the MS and PhD levels.
   - No. MS thesis = 0
   - No. PhD dissertations = 0

- No. citations of each of the above = 0

F. Number of research tools (lab equipment, models, software, test processes, etc.) developed as part of TRANS-IPIC sponsored research
   - Research Tool #1 (Name, description, and link to tool) = 0
   - Research Tool #2 (Name, description, and link to tool) = 0
   - Research Tool #3 (Name, description, and link to tool) = 0

G. Number of transportation-related professional and service organization committees that TRANS-IPIC faculty researchers participate in or lead.
   - Professional societies
     - No. participated in = 0
     - No. lead = 0
   - Advisory committees (No. participated in & No. led)
     - No. participated in = 0
     - No. lead = 0
   - Conference Organizing Committees (No. participated in & No. led)
     - No. participated in = 0
     - No. lead = 0
   - Editorial board of journals (No. participated in & No. led)
     - No. participated in = 3
     - No. lead = 0
   - TRB committees (No. participated in & No. led)
     - No. participated in = 0
     - No. lead = 0

H. Number of relevant awards received during the grant year
   - No. awards received = 1 (Caltech's Distinguished Alumni Award, 2025) https://engineering.buffalo.edu/home/news/seas.host.html/content/shared/engineering/home/articles/news-articles/2025/chung-named-recipient-caltech-distinguished-alumni-award.detail.html

I. Number of transportation related classes developed or modified as a result of TRANS-IPIC funding.
   - No. Undergraduate = 0
   - No. Graduate = 0

J. Number of internships and full-time positions secured in the industry and government during the grant year.
   - No. of internships = 0
   - No. of full-time positions = 0

References:

[1] D.D.L. Chung, "Electrically Conductive Cement-Based Materials", Adv. Cem. Res. 16(4), 167-176 (2004).

[2] Pu-Woei Chen and D.D.L. Chung, "Carbon Fiber Reinforced Concrete as a Smart Material Capable of Non-Destructive Flaw Detection", Smart Mater. Struct.2(1), 22-30 (1993).

[3] Shoukai Wang, Sihai Wen and D.D.L. Chung, "Resistance Heating Using Electrically Conductive Cements", Adv. Cem. Res. 16(4), 161-166 (2004).