Impactful Resilient Infrastructure Science and Engineering (IRISE)

-Project Scope of Work-

(FY 2023-24 (IRISE Year 6) Annual Work Program)

SUMMARY PAGE

Project Title: Self-Heating Concrete Pavement Systems with Surface-Mounted Heating Elements

Person Submitting Proposal: Dr. Amir H. Alavi
Dr. Lev Khazanovich

Proposed Funding Period: February 1, 2024 - January 31, 2026

Project Duration: 24 months

Project Cost: $191,492.68

Project Title: Self-Heating Concrete Pavement Systems with Surface-Mounted Heating Elements

Problem Statement:

Public and private roadway operators spend millions of dollars annually on snow and ice removal, which is a particularly expensive operation for PennDOT and municipalities across Pennsylvania. Snow and ice are typically removed with specialized equipment, or with deicing and anti-icing chemicals. However, these methods can be time-consuming and harm both the pavement’s durability and the environment [1,2]. For example, PennDOT alone uses over 2500 trucks and 801,453 tons of salt annually to clear nearly 91,800 snow-lane miles [3]. In 2019, the U.S. used an estimated 27 million tons of rock salt for snow and ice removal [4]. This high usage rate of salt may not be sustainable, as it could salinize up to 50% of the world's cultivable land by 2050, unless corrective strategies are developed [5]. Furthermore, conventional snow and ice removal methods can delay or shut down transportation networks, reducing their capacity. According to a report by the FHWA [6], the average speed and mobilization capacity of U.S. freeways can decrease by 5%-40% and 12%-27%, respectively, during snow/ice accumulation and freezing temperatures.

Numerous studies have investigated innovative approaches to improve the process of removing snow and ice. Such methods include the use of hydronic-heated pavements [7,8] and phase-change materials [9]. However, these methods circulate potentially toxic chemicals into the environment and may degrade the mechanical performance of concrete [1,2]. Over the past two decades, conductive concrete pavement systems have been studied extensively. These systems remove snow and ice with their own self-heating capacity [1,2,10-12]. One notable study implemented a self-heating concrete bridge deck containing steel fibers/shavings, carbon, and graphite products on a highway bridge in Roca, Nebraska, as part of a field demonstration project sponsored by the Nebraska Department of Roads [13]. In another significant demonstration project, Malakooti et al. [1] designed and tested multiple slabs with different electrode configurations at the Iowa DOT headquarters (Fig. 1). This study showed promising results for snow and ice removal in various winter weather conditions [1]. However, despite their successful performance, current electrically conductive heated concrete pavement technologies are typically limited to new pavement constructions and are not easily

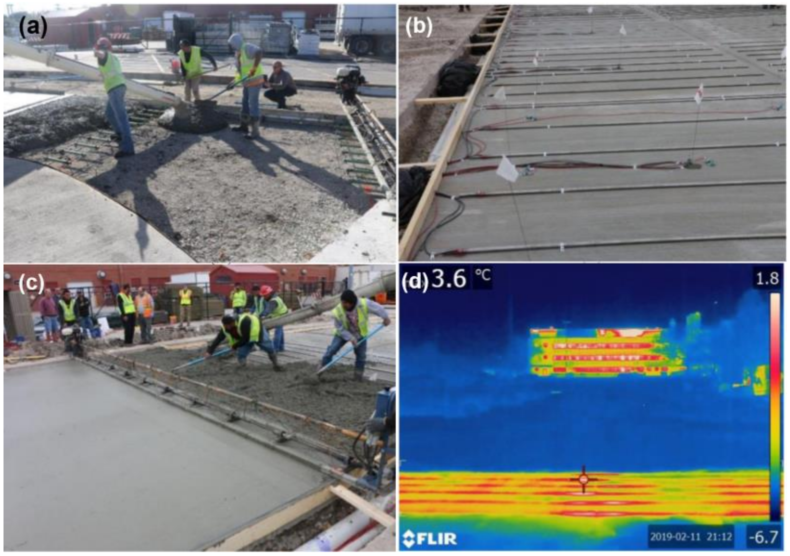

Fig. 1. Self-heating electrically conductive concrete slabs constructed at the Iowa DOT headquarters, as reported in [1]: (a) Slab placement. (b) Installing stainless-steel electrodes and wiring. (c) Placing and compacting conductive concrete layer. (d) Infrared thermography showing self-heating performance.

applicable to the vast network of existing pavement systems. As shown in Figs. 1a-c, constructing self-heating conductive concrete slabs/decks is complex and costly. It involves placing and screeding PCC slabs, installing stainless-steel electrodes and sensor wiring, placing PVC conduit, and finally, placing and compacting the conductive concrete layer [1]. Another challenge for wide adoption of current self-heating conductive concrete systems is the maintenance difficulties, particularly the replacement/repair of embedded electrode bars or coils in case of failure.

Project Objectives:

To overcome the challenges mentioned above, we propose a feasibility study on using surface-mounted heating elements for the automated removal of snow and ice from concrete pavement systems. This technology can be implemented on both existing and new pavements and would electrify the pavement, automate snow and ice removal operations, and eliminate the need for deicing chemicals. Unlike existing self-heating concrete systems, the proposed technology is designed to generate heat primarily on the surface of the pavement where ice and snow accumulate. This approach is expected to require less power than fully embedded self-heating systems.

Project Scope:

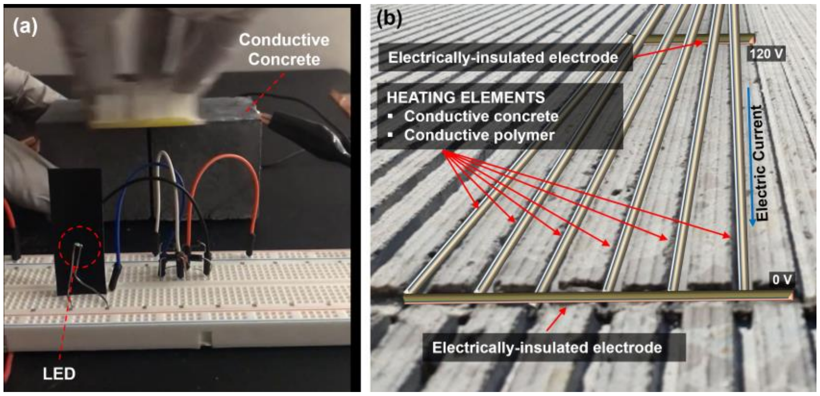

Fig. 2. (a) Conductive concrete developed at Pitt powers an LED [14]. (b) Vision for self-heating concrete pavement with surface-mounted heating elements partially filling the grooves.

The research team has recently developed a conductive concrete using inexpensive graphite powders and utilized it to create a nanogenerator concrete (Fig. 2a) [14]. The research team envisions using this conductive concrete as a basis for the proposed self-heating pavement with surface-mounted heating elements, as shown in Fig. 2b. To create the heating elements, The research team will modify the conductive concrete chemically and mechanically to "partially" fill the grooves created during the diamond grinding and grooving process. Alternative heating elements, such as polymeric materials (e.g., silicone rubber heating elements) or self-heating paint/tapes that can withstand harsh environmental conditions will also be explored. The design for the electrical and heating resistance of the elements will be critical in achieving the desired heating performance. The electrically insulated electrodes can be connected to any source of electrical energy, including solar grids (Fig. 2b).

Proposed Work:

The objectives of this project will be realized through the completion of the following tasks:

Task A – Review of the State-of-the-Art of Self-heating Pavement Research

In this task, we will conduct a comprehensive literature review to identify recent advancements in fabrication techniques for self-heating conductive concrete systems. This review will cover various aspects reported in the literature for successful implementation of self-heating conductive concrete, including mix designs, electrode types and configurations, energy requirements, voltage and current selection, installation methods, construction procedures, and electrical safety tests. Additionally, we will investigate polymeric heating elements that can withstand harsh environmental conditions.

Task B – Characterization and Optimization of the Heating Performance of the Conductive Elements

Self-heating electrically conductive concrete systems rely on resistive heating, the process by which electric current passing through an electrically resistive material generates heat. To achieve the desired heating performance, tuning the electrical resistivity is crucial. Conductive cement composites with an electrical resistivity of 10-60 Ω·cm can provide acceptable heating performance [1, 15]. Different types of conductive additive materials, such as graphite, carbon fiber, steel fiber, and steel shavings, can be added to normal concrete to adjust its electrical conductivity. Yehia et al. [13] and Yehia and Tuan [16] reported several drawbacks when using steel shavings in a concrete mixture, thus carbon and graphite products are likely the best additives for improving electrical conductivity and the associated heating rate.

We have recently developed a conductive cement mixture by adding 2% graphite into the basic mixture of Type I Portland cement. Two-by-two-inch (5.08× 5.08 cm) cement cubes were cast, and aluminum and copper electrodes with different diameters were embedded inside the specimens to measure the electrical resistance, as shown in Fig. 3a. The electrical resistance of the fabricated conductive concrete is about 50 Ω.cm [14].

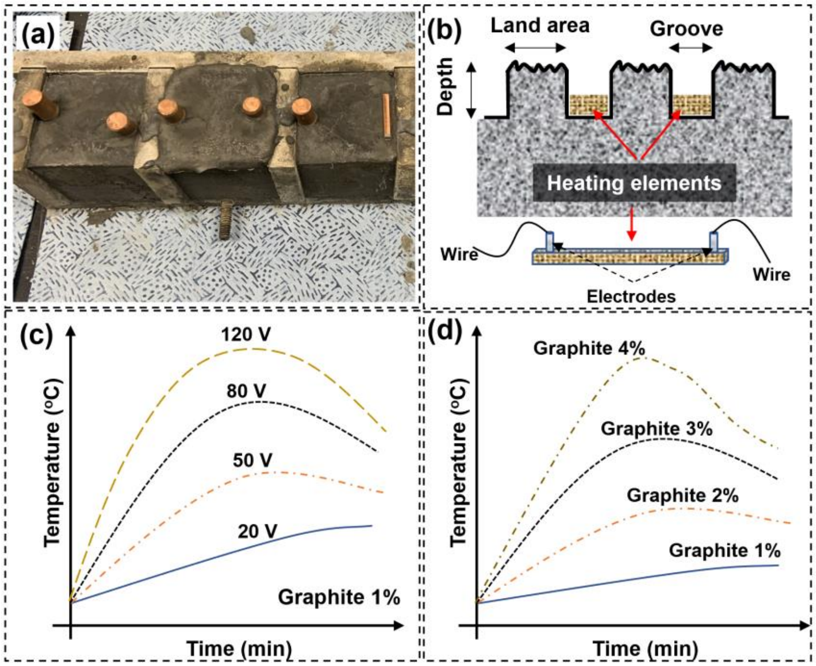

Fig. 3. (a) Two-inch-by-two-inch cement cubes added with graphite powder and different electrodes for electrical resistance measurement, as reported in [14]. (b) The envisioned placement of the heating element inside the grooves created during the diamond grinding or grooving process. The figure shows diamond grinding and grooving terminology, as reported in FHWA [17]. (c) Typical plots showing the increase in the temperature of the heating element at various voltage inputs for a fixed graphite percentage. (d) Typical plots showing the increase in the temperature of the heating element for a fixed voltage input and varying graphite percentages.

This task will focus on determining the minimum graphite percentage needed to allow proper flow of electricity in the cement mixture. The mixture will partially fill the grooves created during the diamond grinding and grooving processes and serve as a gap-filling heating element strip/bar (Fig. 3b).

The “maximum” groove and depth dimensions recommended by FHWA [17,19] for diamond grinding and grooving design are shown in Table 1. To maintain the grooves' functionality while restoring ride quality and reducing hydroplaning, heating element flat bars should occupy the minimum depth possible. Thus, our goal will be to find a minimum thickness for the heating elements first, which can later be used to determine the total groove depth according to the specifications. Various heating element flat bars with different graphite percentages, geometries, and sizes will be fabricated and tested to find a mix design with desired workability, mixability, and conductivity.

Table 1. Maximum dimensions recommended for diamond grinding and grooving design [17,19]

Parameter	Diamond grinding	Diamond grooving
Groove	0.12 inch (3 mm)	0.125 inch (3 mm)
Depth	0.08 inch (2 mm)	0.25 inch (6 mm)

We will fabricate 24-inch-long heating element flat bars with various depths to be consistent with the dimensions of the slabs which will be tested in Task C. Depending on the design and insulation requirements, we will develop strategies to cover the top surface of the heating element. For example, we can use grout, a thin layer of normal concrete, or an electrically isolative epoxy coating for this purpose. Since the electrical performance of such elements depends on their geometry as well, we should fabricate and test various heating element flat bars with different graphite percentages, geometries, and sizes. The graphite content will range from 1%-4% to find a mix design with desired workability and conductivity.

The research team will use electrically insulated electrodes (e.g., heavy-duty cables laid out into the transverse and longitudinal joints) to establish a voltage gradient throughout the heating elements. As an alternative approach, the team will consider using insulated stainless-steel electrodes as they are extremely corrosion-resistant and effectively conduct electrical current into the concrete layers [1]. Various electrode geometries and sizes will be tested to determine which configuration provides the best thermal performance when coupled with heating element flat bars. Self-heating tests of cementitious composites will be performed with different input voltages ranging from 20 to 120 VAC. An infrared thermal camera will monitor the rate of temperature increase, and a clamp-on multimeter will measure the electrical current. We expect to generate design curves similar to plots schematically shown in Figs. 3c,d.

Additionally, we will investigate the use of polymeric materials such as silicone rubber as heating elements. However, durability under various traffic and environmental conditions is a concern for polymeric materials. Printing on the surface expands the proposed technology's utility for any roadway surface.

Task C – Design and Fabrication of Self-heating Concrete Slabs with Surface-Mounted Heating Elements and Field Demonstration

The primary objective of this task is to apply the knowledge gained in Task B to design, fabricate, and evaluate concrete slabs with surface-mounted heating elements. We will use the dimensions (12 inch × 12 inch × 4.5 inch “or” 24 inch × 24 inch × 4.5 inch) and mix designs recommended in [1,18]. The samples will be cured for 24 hours at 20°C and 95% relative humidity, and then demolded and kept in the same conditions for 28 days.

We will use these dimensions for the experimental study. Parallel grooves will be cut into the slab surface with diamond saw blades, as shown in Fig. 4a. We plan to fabricate twelve slabs: three samples with 2 mm groove depth, representing diamond grinding, and three samples with 6 mm grooves, representing diamond grooving. If our research during Task B results in designing a polymeric mixture, we will fabricate an additional six slabs. Three of these slabs will be used for studying heating polymeric elements for 6 mm grooves, and the remaining three slabs will be used to study whether we can paint the desired slab surface with heating polymeric epoxy paints through a patterned stencil mask. The patterning schemes will be determined during the study and based on latex paint-based patterning approaches (e.g. [20]). In this case, the paint performance will be evaluated with paint laboratory control tests, including composition, consistency, and drying time tests [21].

We will first test the self-heating capability of all samples at room temperature by considering various input voltages ranging from 20 to 120 V. Temperatures will be monitored using an infrared thermal camera along the specimen's surface (e.g., Fig. 4b), and the electrical current will be measured to obtain the power density (P=V×I). The power sources will be secured, due to safety concerns. Next, the specimens will be put into the freezer for 24 hours, so that their temperature can approximately reach −10 to −15 °C, and their self-heating capability at low temperatures will be evaluated. The temperature increase rate will be continuously monitored and plotted against time. We will also calculate the energy conversion efficiency by measuring the electrical energy and converted thermal energy. Another important design consideration is the bonding between the heating elements and the concrete substrate. To assess this property, low-cycle fatigue testing will be carried out on random samples, and the point loads applied to the center of the samples will be incrementally increased to understand the level of deformations causing debonding. We will consider using the thermal camera to detect the damaged elements.

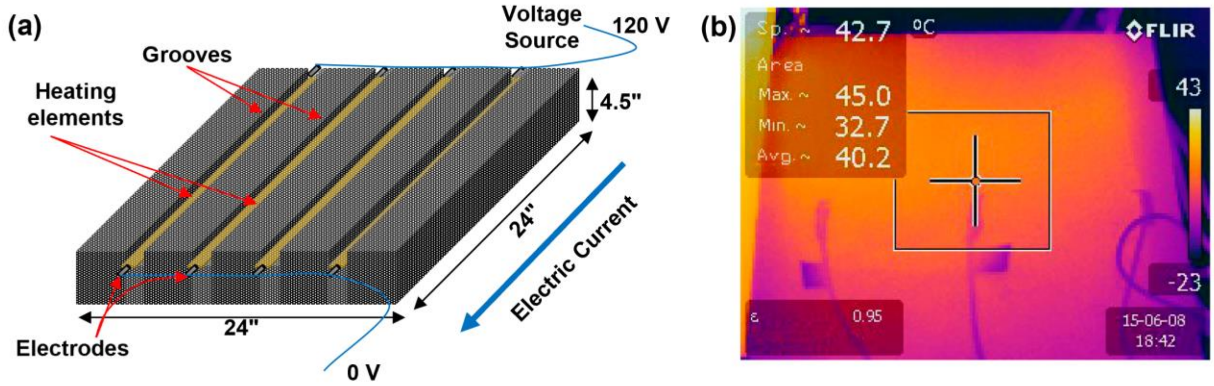

Fig. 4. (a) Schematic of specimen geometry and setup for testing the self-heating performance. The number of groves will vary depending on the design requirement. (b) Typical infrared camera images showing the specimen temperature, as reported in [22].

Upon successful execution of the steps described above, we will then study a small-scale field demonstration. To this aim, a test slab, approximately 6 ft. by 6 ft., will be constructed on Pitt campus. Test strips will be built by IRISE members or at a batch plant site. The test slab will be equipped with the self-heating technology, and it will be tested during the snow season in the second year.

The results of Tasks B and C will yield optimal mixture designs for cementitious and polymeric heating elements that can be integrated into pavement systems. The temperature-voltage-graphite percentage curves and power density plots will serve as useful tools for designing various self-heating pavement systems using the proposed technology. These research findings will facilitate the large-scale fabrication and testing of the proposed system on designated corridors in Pennsylvania in the near future.

Task D: Development of Recommendations

In this task, we will develop recommendations for addressing the technical challenges involved in manufacturing self-heating pavement systems with surface-mounted heating elements, as well as addressing the associated power density, and controlling the system using programmed PLC modules. We will also provide details about the implementation and constructability of the technology. It is possible to automate this process using a set of nozzles with small heads attached to the grooving equipment. In this process, the heating element paste/polymer will be extruded from the nozzles and laid down inside the grooves automatically immediately after the saw grooves the pavement surface. One of our main motivations for this research is to develop a surface-mounted system that offers easy access to the elements for repairing purposes in case of failure. In the final report, we will present procedures for detecting and repairing the failed elements, and potential risks associated with groove overflow and the water running off to the side of the road. We will also conduct a cost-benefit analysis, examine power consumption, and explore the possibility of integrating the system with solar grids as a power source. Our findings will be categorized based on equipment, material, and design requirements, and will provide guidance for future research. Our work will contribute to the development of new design codes and standardized approaches in this field.

Task E: Final Report

A draft final report will be prepared and distributed to IRISE Steering Committee representatives. The report will include a state-of-the-art review of self-heating conductive concrete systems fabrication techniques, and recommendations for the implementation of surface-mounted heating elements in different pavement systems. Final recommendations will be further drafted in the form of suggested revisions to PennDOT publications and/or provisions. A progress review meeting with IRISE Steering Committee representatives, including the PennDOT team, will be held 22 months from the Notice to Proceed date. The draft final report will be delivered 23 months after the Notice to Proceed date, and the final report (reflecting comments) will be delivered 24 months after the Notice to Proceed date (end of project).

Deliverables:

- Task A – A literature review summary, to be discussed at a progress review meeting with IRISE Steering Committee representatives, including PennDOT representatives and technical advisor from PennDOT, 3 months from the Notice to Proceed date.
- Task B – A technical memorandum summarizing the optimal designs for self-heating elements, to be discussed at a progress review meeting with IRISE Steering Committee

representatives, including PennDOT representatives and technical advisor from PennDOT, 12 months from the Notice to Proceed date.

- Task C – A technical memorandum summarizing the laboratory testing of the of self-heating concrete slabs with surface-mounted heating elements, to be discussed at a progress review meeting with IRISE Steering Committee representatives, including PennDOT representatives and technical advisor from PennDOT, 22 months from the Notice to Proceed date.
- Task D – The draft list of recommendations, which will be included in the draft final report and discussed with IRISE Steering Committee representatives, including the PennDOT team and technical advisor from PennDOT, as described in Task E.
- Task E – The draft final report the final report (reflecting comments), due 23 and 24 months after the Notice to Proceed date, respectively.

Upon completion, deliverables will be submitted to PennDOT.

In addition to the deliverables listed above, it is also anticipated that the findings of this research will be published and presented at key technical conferences (e.g., TRB, ASCE Structural Congress, among others) and in journal publications. The publications must be approved by the technical panel member(s) and technical advisor from PennDOT before being presented or published.

References

1. Malakooti, A., Sadati, S., Ceylan, H., Kim, S., Cetin, K. S., Taylor, P. C., ... & Theh, W. S. (2021). Self-Heating Electrically Conductive Concrete Demonstration Project (No. IHRB Project TR-724).
2. Ceylan, H., K. Gopalakrishnan, S. Kim, and W. Cord. 2014. Heated Transportation Infrastructure Systems: Existing and Emerging Technologies. 12th International Symposium on Concrete Roads, September 23–26, Prague, Czech Republic.
3. PennDOT, Winter Operations. Online Report. Last accessed on 4/18/23. https://www.penndot.pa.gov/TravelInPA/Winter/Pages/Winter-Operations.aspx
4. Bolen, W. P. 2020. Salt. U.S. Geological Survey Mineral Commodity Summaries, pp. 138–139.
5. Jamil, A., S. Riaz, M. Ashraf, and M. R. Foolad. 2011. Gene Expression Profiling of Plants Under Salt Stress. Critical Reviews in Plant Sciences, Vol. 30, No. 5, pp. 435–458.
6. FHWA. 2017. FHWA Road Weather Management, How Do Weather Events Impact Roads? Federal Highway Administration. https://ops.fhwa.dot.gov/weather/q1_roadimpact.htm.
7. Habibzadeh-Bigdarvish, O., X. Yu, G. Lei, T. Li, and A. J. Puppala. 2019. Life-Cycle Cost-Benefit Analysis of Bridge Deck De-Icing Using Geothermal Heat Pump System: A Case Study of North Texas. Sustainable Cities and Society, Vol. 47, Article no. 101492, pp. 1–13.
8. Thurston, R. E., G. Culver, and J. W. Lund. 1995. Pavement Snow Melting in Klamath Falls - Rehabilitation of the ODOT Well. Geo-Heat Center Quarterly Bulletin, Vol. 16, No. 2.
9. Farnam, Y., M. Krafcik, L. Liston, T. Washington, K. Erk, B. Tao, and J. Weiss. 2016. Evaluating the Use of Phase Change Materials in Concrete Pavement to Melt Ice and Snow. Journal of Materials in Civil Engineering, Vol. 28, No. 4, Article no. 04015161.
10. Xi, Y. and P. J. Olsgard. 2000. Effects of De-Icing Agents (Magnesium Chloride and Sodium Chloride) on Corrosion of Truck Components. Colorado Department of Transportation Research Branch, Denver, CO.
11. Arabzadeh, A., H. Ceylan, S. Kim, K. Gopalakrishnan, A. Sassani, S. Sundararajan, and P. C. Taylor. 2017b. Superhydrophobic Coatings on Portland Cement Concrete Surfaces. Construction and Building Materials, Vol. 141, pp. 393–401.
12. Malakooti, A., W. S. Theh, S. Sadati, H. Ceylan, S. Kim, M. Mina, K. Cetin, and P. C. Taylor. 2020. Design and Full-Scale Implementation of the Largest Operational Electrically Conductive Concrete Heated Pavement System. Construction and Building Materials, Vol. 255, Article no. 119229, pp. 1–11.
13. Yehia, S., Tuan, C. Y., Ferdon, D., & Chen, B. (2000). Conductive concrete overlay for bridge deck deicing: mixture proportioning, optimization, and properties. ACI Materials Journal, 97(2), 172-181.
14. Barri K., Zhang Q., Kline J., Taylor B., Lu W., Luo J., Sun Z., Taylor B.E., Sachs S., Khazanovich L., Wang, Z.L., Alavi A.H., 2023. Multifunctional nanogenerator-integrated metamaterial concrete systems for smart civil infrastructure. Advanced Materials, Article 17643876.
15. Tang Z., Li Z., Qian J., Wang K. Experimental study on deicing performance of carbon fiber reinforced conductive concrete. J. Mater. Sci. Technol. 2005;21:113–117.

16. Yehia, S.; Tuan, C. Conductive concrete overlay for bridge deck deicing. Am. Concr. Inst. Mater. J. 1999, 3, 382–390.
17. Federal Highway Administration and the Foundation for Pavement Preservation, 2005. Pavement Preservation Checklist Series, No 7, Diamond Grinding of Portland Cement Concrete Pavements, Publication No. FHWA-IF-03-040, August 2005.
18. Sassani, A., H. Ceylan, S. Kim, K. Gopalakrishnan, A. Arabzadeh, and P. C. Taylor. 2017. Influence of Mix Design Variables on Engineering Properties of Carbon Fiber-Modified Electrically Conductive Concrete. Construction and Building Materials, Vol. 152, pp. 168–181.
19. Federal Highway Administration, 2004. Pavement preservation design and construction of quality preventive maintenance treatments, National Highway Institute Course 131103, November 2004.
20. Singh, P., Mutzel, C., MacNaughton, S., & Sonkusale, S. (2013). In-situ large area fabrication of metamaterials on arbitrary substrates using paint process. Progress In Electromagnetics Research, 141, 117-133.
21. Vannoy, W. G. (1952). Traffic Paint Tests. Highway Research Board Bulletin, (57).
22. Galao, O., Bañón, L., Baeza, F. J., Carmona, J., & Garcés, P. (2016). Highly conductive carbon fiber reinforced concrete for icing prevention and curing. Materials, 9(4), 281.

Budget Notes

Key Personnel:

Principal Investigator:
Amir H. Alavi, PhD
Assistant Professor
University of Pittsburgh
Swanson School of Engineering
Department of Civil & Environmental Engineering
3700 O'Hara Street
209 Benedum Hall Pittsburgh, PA 15261-2294 USA
Telephone: 412 648-4385| Fax: 412-624-0135
E-mail: alavi@pitt.edu

Co-Principal Investigator:
Lev Khazanovich, PhD
Anthony Gill Chair Professor
University of Pittsburgh
Swanson School of Engineering
Department of Civil & Environmental Engineering
3700 O'Hara Street
706 Benedum Hall Pittsburgh, PA 15261-2294 USA
Telephone: 412 624-9047 | Fax: 412-624-0135
E-mail: lev.k@pitt.edu

Other Personnel:
Graduate student
TBD
University of Pittsburgh
Department of Civil and Environmental Engineering

Non-Personnel:
Supplies:

$5,800 is requested for the supplies below:

1. Cement
2. Carbon nanotubes
3. Graphite
4. Aggregate
5. Conductive Polymers
6. Insulation Material
7. Temperature Sensors
8. Control System (including power supplier)
9. Wires

Schedule:

	Year 1				**Year 2**			
	Q1	**Q2**	**Q3**	**Q4**	**Q1**	**Q2**	**Q3**	**Q4**
Task A: Self-heating pavement research literature review	🟧							
Task B: Characterization of the heating performance of the conductive elements		🟧	🟧	🟧	🟧			
Task C: Design and fabrication of self-heating concrete slabs & Field demonstration			🟧	🟧	🟧	🟧	🟧	
Task D: Development of Recommendations						🟧	🟧	
Task E: Final Report							🟧	🟧

Proposed Person-Hours by Task:

Team Member	**Task A**	**Task B**	**Task C**	**Task D**	**Task E**	**Total**
Key Project Team Members, Estimated Hours Per Task						
Dr. Amir Alavi, PI	50	60	75	20	40	245
Dr. Lev Khazanovich	-	-	40	20	22	82
Other Project Team Members, Estimated Hours Per Task						
Graduate student (TBD)	200	590	590	200	220	1800
Hourly Student (Undergrad)	-	40	50	-	-	90

Budget: The total project cost is $191,492.68

		UPitt FY 24 (PennDOT FY 23)	UPitt FY 25 (PennDOT FY 24)	UPitt FY 26 (PennDOT FY 25)	Total
Personnel					
Amir Alavi	PI	4,672.20	8,470.90	4,889.95	18,033.05
Lev Khazanovich	Faculty 2	-	5,496.80	5,859.42	11,356.22
	Faculty 3	-	-	-	-
	Post Doc	-	-	-	-
TBN	Grad Student 1	12,276.00	32,079.00	12,209.40	56,564.40
	Grad Student 2	-	-	-	-
TBN	Hourly Student 1	123.00	886.20	128.60	1,137.80
	Hourly Student 2	-	-	-	-
Total Personnel		17,071.20	46,932.90	23,087.37	87,091.47
Fringe Benefits					
Amir Alavi	PI	1,537.15	2,786.92	1,608.79	5,932.86
Lev Khazanovich	Faculty 2	-	1,808.44	1,927.74	3,736.18
	Faculty 3	-	-	-	-
	Post Doc	-	-	-	-
TBN	Grad Student 1	6,138.00	16,039.50	6,104.70	28,282.20
	Grad Student 2	-	-	-	
TBN	Hourly Student 1	9.47	68.23	9.90	87.60
	Hourly Student 2	-	-	-	-
Total Fringe Benefits		7,684.62	20,703.09	9,651.13	38,038.84
Total Salaries & Fringe		24,755.82	67,635.99	32,738.50	125,130.31
Travel:		-	-	-	-
Supplies:		2,200.00	3,600.00	-	5,800.00
Professional Services		-	-	-	-
University Service Centers		-	-	-	-
Total Direct Costs		26,955.82	71,235.99	32,738.50	130,930.31
Indirect Cost Base		20,817.82	55,196.49	26,633.80	102,648.11
Overhead		12,282.51	32,565.92	15,713.94	60,562.37
TOTAL Fund Request		**39,238.33**	**103,801.91**	**48,452.44**	**191,492.68**

Acknowledged By:

Dr. Amir Alavi
Principal Investigator