CIVL 441: Transportation Engineering Labs-CURE-E Research Project

Analyze the pavement temperature using climate data from MERRA

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1. Project Description

Rutting and cracking, including fatigue cracking, thermal cracking, and longitudinal cracking, are common distresses in asphalt pavements, which significantly affect driving safety and pavement performance. ASCE ranked America's infrastructure as C- in 2021, up from a D+ in 2017 (ASCE 2021 Infrastructure Report Card). However, the road is still ranked as D. Pavement temperature is one of the contributing factors to causing aging and deterioration of pavement performance. In the era of climate change, the temperature rises, and more cities in the United States will experience extreme heat days in summer. This deteriorates the serviceability of highways and urban pavements and requires additional preservation and maintenance treatments.

Modeling and prediction of pavement temperature are cornerstones of understanding materials' aging and pavement structure responses. Pavement temperature could be modeled and predicted based on empirical models, analytical models, and numerical models (Chen et al. 2019). Han et al. (2011) used the finite difference method and Alavi et al. (2013) used the finite volume method to analyze and predict pavement temperature profiles based on climatic data, such as air temperature, solar radiation, wind speed, etc.

This laboratory course will implement course-based undergraduate research experiences (CUREs) and Entrepreneurial Mindset (EM) to allow students to explore the long-term pavement performance (LTPP) and climate database to develop numerical prediction models for pavement temperature. This CURE-E project is closely aligned with the national **Long-Term Infrastructure Performance (LTIP) Student Data Contest Analysis** that is organized by Federal Highway Administration (FHWA) (https://infopave.fhwa.dot.gov/Analysis/LtppDataContest). Current undergraduate and graduate students are eligible to prepare technical papers for the competition based on the research using InfoPave or InfoBridge data. The competition topics for pavement include

- "Evaluate a Question or Concern for a Region or State"
- "Visualization of Performance Data" and
- "Development of Models to Predict Future Condition Using the LTPP Pavement Condition and Traffic Data".

The national winners will receive award certificates and be sponsored to attend Transportation Research Board Conference in Washington D.C. The past winning projects and papers can be found at (https://infopave.fhwa.dot.gov/Analysis/LtppDataContest), e.g. 2018 winning paper: The use of LTPP SMP Data to Quantify Moisture Impacts on Fatigue Cracking in Flexible Pavements"; and 2017 winning paper: Using Data Analytics for Cost-Effective Prediction of Road Conditions: Case of the Pavement Condition Index.

More specifically, by completion of this CURE-E project, students will be able to:

- Extract climatic data and monitored pavement temperature data from the LTPP database

- Revise Python program for the finite volume method to calibrate the numerical model and analyze pavement temperature
- Run simulation to analyze pavement temperature in the past 40 years and conduct analysis on the impact of climate change on pavement temperature (Optional work)

Students are also expected to achieve the following student learning goals, including:

- Search and review relevant publications (journal papers and technical reports)
- Formulate open-ended research questions and hypothesis
- Perform numerical analysis to test research question and iterate hypothesis to draw conclusions
- Create informative and attractive graphs/videos for data visualization as EM skills
- Communicate effectively via technical writing and presentation of the research and project results and conclusions (ABET Student Learning Outcomes 6 and 3.

Why is CUREs-E? In past semesters, this lab course covers three modules of traffic analysis (speed, volume, accident), pavement design (geometric design and pavement structure design), and pavement materials (aggregate, asphalt binder, asphalt mixture). These labs were introduced using the lab manual ("cookbook") in a well-organized way. Students completed the tasks in a well set-up lab ("greenhouse") with limited active thinking and motivation. In this semester, these basic learning modules will still be covered, and the CURE-E research project will allow students to explore the research question that "How can we use climatic data to predict pavement temperature? And how will climate change affect pavement performance?" This will create a learning environment with discovery-based research and explore the open-ended problem.

What is CUREs-E? The "CURE" component is that undergraduate students will conduct authentic research in a course, which eliminates inequitable accessibility to traditional research experiences by engaging every student in a course to participate in the research project. The "E" component is an "Entrepreneurial Mindset" (EM) with curiosity, critical thinking, accepting ambiguity, creativity, persistence, iteration, and value creation.

Why am I benefited as a student in the CURE-E experience? Are you thinking to apply to a graduate school? Yes, then, this project will give a task of research experience in graduate school. You can include this work in your resume and application materials. Are you looking for industry jobs? Yes, then, the selected topic is hot and timely work relevant to the transportation industry, as the data visualization, machine learning, and prediction model for pavement distresses impact the policy and practice of pavement preservation and maintenance. For freelancers, you highly need the research and entrepreneurial mindset for your business. In 2017, 35% of all US workers were freelancers and this number will increase to 50% by 2027 (in 5 years from now).

2. Project Tasks, Assessments, and Schedule

To complete this project and earn 50 pts in this lab, the following tasks shall be completed based on a teamwork of a maximum of 2 students.

Google Drive
https://drive.google.com/drive/folders/18WfOVY9uEwjBqnQVq6hnxTly5LahgCtQ?usp=sharing

Task 1: Review relevant publications and install Python integrated development environment (IDE) (Week 5-9); Expected Working Hours: 6 hours

1.1 The following three publications are required to be read by each student. Papers can be accessed on BBL.

1. Han, R., Jin, X., & Glover, C. J. (2011). Modeling pavement temperature for use in binder oxidation models and pavement performance prediction. Journal of Materials in Civil Engineering, 23(4), 351-359.

2. Alavi, M. Z., Pouranian, M. R., & Hajj, E. Y. (2014). Prediction of asphalt pavement temperature profile with finite control volume method. Transportation Research Record, 2456(1), 96-106.

3. Chen, J., Wang, H., & Xie, P. (2019). Pavement temperature prediction: Theoretical models and critical affecting factors. Applied thermal engineering, 158, 113755.

When you read these articles, answer the following questions for each article by taking reading notes in Word or Google Doc:

(1) What are the research question(s), objective(s), and hypothesis of this article?

(2) What are the analysis method(s) used in this article?

(3) What are the main findings and conclusions from this article?

Please remember to rewrite and summarize to answer these questions and avoid "plagiarism".

After reading these three papers, **each student** is required to use "Google Scholar" to search and read at least 3 more journal papers and/or technical reports, which are relevant to *pavement temperature prediction and the impact of climate change on pavement infrastructure*. **If you work with another student in a team and turn in a group report, in total, you two have to review at least additional 6 journal papers and/or technical reports.**

1.2 Install Python integrated development environment (IDE)

You could choose one of the follow options to install Python IDE and use in this project:

- PyCharm: https://www.jetbrains.com/pycharm/; Installation details may refer to https://www.youtube.com/watch?v=_uQrJ0TkZlc
- Spyder: https://www.spyder-ide.org/
- Install Anaconda and use with Python: https://www.anaconda.com/products/individual

Assessment: project proposal (10 pts) due Week 10: each student/team is required to submit a mini literature review results (1-2 pages) by summarizing the publications that you and your teammate read, preliminary results you have, and project timeline. All publications used in the proposal shall be listed as "references" cited at the end of the proposal.

Extra Credits: In this task, a minimum of 6 publications (3 required reading and another 3 journal papers and technical reports) shall be included. Each student/team can earn 1 extra point by searching and critically reading every two more relevant publications that are listed as references. This extra credit policy is also applicable to the final project report so that during this project, you and other team members are encouraged to keep searching and reading more publications.

Task 2: Extract climate data, pavement structure information, and monitored pavement temperature from LTPP; Model calibration for the numerical model parameters by comparing numerical analysis results and test results of pavement temperature (Week 7-9); Expected Working Hours: 15 hours

2.1 Finite Volume Method and Algorithm to Analyze Pavement Temperature

The following derivation is based on these two publications;

1. Han, R., Jin, X., & Glover, C. J. (2011). Modeling pavement temperature for use in binder oxidation models and pavement performance prediction. Journal of Materials in Civil Engineering, 23(4), 351-359.

2. Alavi, M. Z., Pouranian, M. R., & Hajj, E. Y. (2014). Prediction of asphalt pavement temperature profile with finite control volume method. Transportation Research Record, 2456(1), 96-106.

Governing Equation:

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}(\alpha \frac{\partial T}{\partial z})$$

where $\alpha = \frac{k}{\rho c}$ is heat diffusivity (m^2/h); k is thermal conductivity (W/m/K); ρ is the density of material (kg/m^3); and c is the heat capacity (J/kg/K).

Finite volume method by integrating over the time and control volume (CV):

$$\int_{CV} \int_{t}^{t+\Delta t} \frac{\partial T}{\partial t} dt dV = \int_{t}^{t+\Delta t} \int_{CV} \frac{\partial}{\partial z}(\alpha \frac{\partial T}{\partial z}) \, dV dt$$

when α is constant and 1D problem with uniform mesh (dV=dz)

$$\int_{n}^{s} \int_{t}^{t+\Delta t} \frac{\partial T}{\partial t} dt dz = \int_{t}^{t+\Delta t} \int_{n}^{s} \alpha \frac{\partial}{\partial z}(\frac{\partial T}{\partial z}) \, dz dt$$

$$\int_{n}^{s} \int_{t}^{t+\Delta t} \partial T \, dz = \int_{t}^{t+\Delta t} \int_{n}^{s} \alpha \partial (\frac{\partial T}{\partial z}) \, dt$$

$$\int_{n}^{s} (T|_{t}^{t+\Delta t}) \, dz = \int_{t}^{t+\Delta t} [\alpha (\frac{\partial T}{\partial z})|_{n}^{s}] \, dt$$

$$\int_{n}^{s} (T_P^1 - T_P^0)\, dz = \int_{t}^{t+\Delta t} [\alpha \left(\frac{\partial T}{\partial z}\right)|_s - \alpha \left(\frac{\partial T}{\partial z}\right)|_n]\, dt$$

where T_P^1 is the temperature in Cell P at current timestep; T_P^0 is the temperature in Cell P at previous timestep.

$$(T_P^1 - T_P^0)\Delta z = \Delta t\{f\left[\frac{\alpha(T_S^1 - T_P^1)}{dz} - \frac{\alpha(T_P^1 - T_N^1)}{dz}\right] + (1-f)\left[\frac{\alpha(T_S^0 - T_P^0)}{dz} - \frac{\alpha(T_P^0 - T_N^0)}{dz}\right]\}$$

where f is a weighting factor between 0 and 1; when $f = 0$, it is explicit scheme and the timestep should be small enough to run simulation; when $f = 0.5$, it is Crank-Nicolson scheme, but it still needs small timestep. When $f = 1$, it is fully implicit scheme and commonly used.

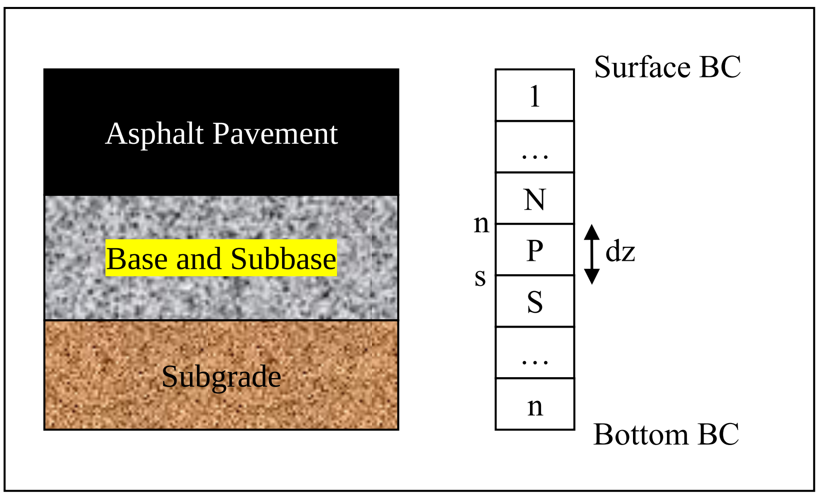
Thus,

$$(T_P^1 - T_P^0)\Delta z = \Delta t\left[\frac{\alpha(T_S^1 - T_P^1)}{dz} - \frac{\alpha(T_P^1 - T_N^1)}{dz}\right]$$

This equation will be applied to surface and bottom boundary condition with slight revision.

Revise:

$$T_P^1\left(\frac{\Delta z}{\Delta t} + \frac{\alpha}{dz} + \frac{\alpha}{dz}\right) = \frac{\alpha}{dz}T_S^1 + \frac{\alpha}{dz}T_N^1 + T_P^0\frac{\Delta z}{\Delta t}$$



The discretized equation is reformed for TriDiagonal-Matrix Algorithm (TDMA).

$$a_P T_P^1 = a_S T_S^1 + a_N T_N^1 + b$$

where $a_P = \left(\frac{\Delta z}{\Delta t} + \frac{\alpha}{dz} + \frac{\alpha}{dz}\right)$; $a_S = \frac{\alpha}{dz}$; $a_N = \frac{\alpha}{dz}$; $b = T_P^0\frac{\Delta z}{\Delta t}$

Further reform as:

$$a_i T_i = b_i T_{i+1} + c_i T_{i-1} + d_i$$

Likely, $a_i = a_P = \left(\frac{\Delta z}{\Delta t} + \frac{\alpha}{dz} + \frac{\alpha}{dz}\right)$; $b_i = a_S = \frac{\alpha}{dz}$; $c_i = a_N = \frac{\alpha}{dz}$; $d_i = b = T_P^0\frac{\Delta z}{\Delta t}$;

$T_i = T_P^1$; $T_{i+1} = T_S^1$; and $T_{i-1} = T_N^1$

The general TDMA for internal cells from cell 2 to n-1:

Assume $T_i = P_i T_{i+1} + Q_i$

Then, $T_{i-1} = P_{i-1} T_i + Q_{i-1}$

$$a_i T_i = b_i T_{i+1} + c_i T_{i-1} + d_i$$

$$a_i T_i = b_i T_{i+1} + c_i (P_{i-1} T_i + Q_{i-1}) + d_i$$

$$(a_i - c_i P_{i-1}) T_i = b_i T_{i+1} + c_i Q_{i-1} + d_i$$

$$T_i = \frac{b_i}{(a_i - c_i P_{i-1})} T_{i+1} + \frac{c_i Q_{i-1} + d_i}{(a_i - c_i P_{i-1})}$$

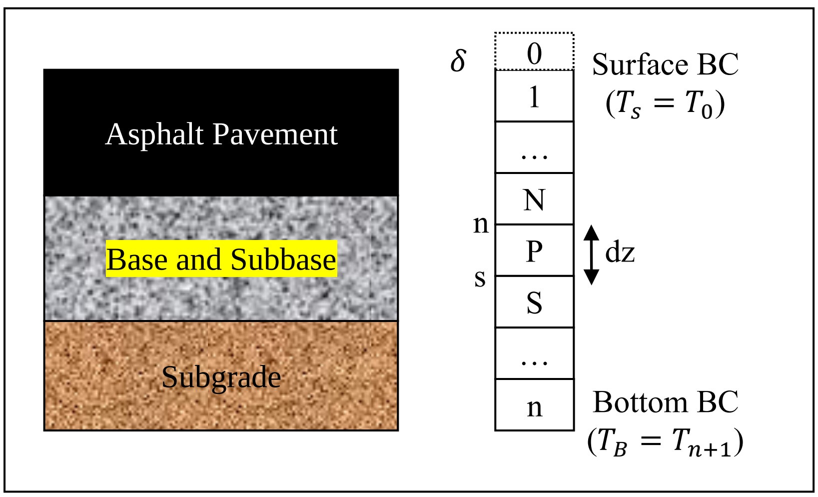
where $P_i = \frac{b_i}{(a_i - c_i P_{i-1})}$; $Q_i = \frac{c_i Q_{i-1} + d_i}{(a_i - c_i P_{i-1})}$

This is the general expression for internal cells, e.g. from 2 to n-1. For boundary conditions and at interface, we have:

Surface Boundary Condition

$$\delta(\rho c) \frac{\partial T_s}{\partial t} = q_{solar} + q_{radiation} - q_{convection} - q_{conduction}$$

where δ is thickness of the pavement surface at boundary, consider $\delta = 0$ (this work), or δ may be considered same as the thickness of first control volume. (Note: The unit of left-side and right-side is W/m^2).



So,

$$0 = q_{solar} + q_{radiation} - q_{convection} - q_{conduction}$$

where

- q_{solar} is the solar radiation heat flux; $q_{solar} = (1 - \tilde{\alpha}) Q_{solar}$; $\tilde{\alpha}$ is the albedo, varying from 0.15-0.35; Q_{solar} is the solar radiation incident (W/m^2), extracted from MERRA.
- $q_{radiation}$ is long-wave radiation heat flux.

$$q_{radiation} = q_{incoming} - q_{outgoing} = \varepsilon_a \sigma T_a^4 - \varepsilon \sigma T_s^4$$

where ε_a is the absorption coefficient of pavement surface; ε is emission coefficient of pavement surface; σ is the Stefan-Boltzman constant = 5.67×10^{-8} W/m^2/K^4; T_a is the air temperature (T_air), which is extracted from MERRA and converted to Kevin.

$$\varepsilon_a \sigma T_a^4 - \varepsilon \sigma T_s^4 = \varepsilon_a \sigma T_a^4 - \varepsilon \sigma T_a^4 + \varepsilon \sigma T_a^4 - \varepsilon \sigma T_s^4 = (\varepsilon_a - \varepsilon)\sigma T_a^4 + \varepsilon\sigma(T_a^4 - T_s^4)$$
$$= (\varepsilon_a - \varepsilon)\sigma T_a^4 + \varepsilon\sigma(T_a^2 - T_s^2)(T_a^2 + T_s^2)$$
$$= (\varepsilon_a - \varepsilon)\sigma T_a^4 + \varepsilon\sigma(T_a - T_s)(T_a + T_s)(T_a^2 + T_s^2)$$

Define $h_{radiation} = \varepsilon\sigma(T_a + T_s)(T_a^2 + T_s^2)$

Define $q_{rad\_diff} = (\varepsilon_a - \varepsilon)\sigma T_a^4$

Define $delta\_e = (\varepsilon_a - \varepsilon)$, which is negative and considers seasonal variation as parabolic curve; In Han et al. (2011), it investigates $(\varepsilon - \varepsilon_a)$, which varies from 0.05-0.2 and may be different between summer value and winter value.

$$q_{radiation} = delta\_e \times \sigma \times T_a^4 + h_{radiation}(T_a - T_s)$$

- ✓ $q_{convection}$ is convective heat flux; $q_{convection} = h_{conv}(T_s - T_a)$;

$$h_{conv} = 698.24 * 1.4 * (0.00144 * \left\{abs\frac{T_s + T_a}{2}\right\}^{0.3} (U^{0.5}) + 0.00097 * [abs(T_s - T_a)])^{0.3}$$

where U is the wind speed (m/s), which is extracted from MERRA. Since h_{conv} includes T_s, and T_s cannot be explicitly expressed, iteration is needed to find T_s. In addition, linearization of surface BC is discussed below.

- ✓ $q_{conduction}$ is the conductive heat flux; $q_{conduction} = -k\frac{\partial T_s}{\partial z}|_{surface} = -k\frac{(T_1 - T_s)}{d_z/2}$
  Note: if δ, the thickness of boundary is considered as d_z, $-k\frac{\partial T_s}{\partial z}|_{surface} = -k\frac{(T_1 - T_s)}{d_z}$

Combine these together:

$$(1-\tilde{\alpha})Q_{solar} + delta_e \times \sigma \times T_a^4 + h_{radiation}(T_a - T_s) - h_{conv}(T_s - T_a) - (-k\frac{(T_1 - T_s)}{d_z/2})=0$$

$$(1-\tilde{\alpha})Q_{solar} + delta_e \times \sigma \times T_a^4 + (h_{radiation} + h_{conv})(T_a - T_s) + k\frac{(T_1 - T_s)}{d_z/2} = 0$$

$$(1-\tilde{\alpha})Q_{solar} + delta_e \times \sigma \times T_a^4 + (h_{radiation} + h_{conv})T_a + k\frac{T_1}{d_z/2}$$
$$= T_s\left(h_{radiation} + h_{conv} + \frac{k}{d_z/2}\right)$$

Finally,

$$T_s = \frac{(1-\tilde{\alpha})Q_{solar} + delta_e \times \sigma \times T_a^4 + (h_{radiation} + h_{conv})T_a + k\frac{T_1}{d_z/2}}{h_{radiation} + h_{conv} + \frac{k}{d_z/2}}$$

Expression in the Python Code: $T_s = \frac{q_{solar}+(h_{radiation}+h_{conv})T_a+q_{rad_{diff}}+k\frac{T_1}{d_z/2}}{h_{radiation}+h_{conv}+\frac{k}{d_z/2}}$

At surface and Cell Number (P) = 1, its north neighbor is $T_s = T_0$, and the gradient distance is $\frac{dz}{2}$

Recall:

$$(T_P^1 - T_P^0)\Delta z = \Delta t\left[\frac{\alpha(T_S^1 - T_P^1)}{dz} - \frac{\alpha(T_P^1 - T_N^1)}{dz}\right]$$

$$(T_1^1 - T_1^0)\Delta z = \Delta t\left[\frac{\alpha(T_2^1 - T_1^1)}{dz} - \frac{\alpha(T_1^1 - T_0^1)}{(\frac{dz}{2})}\right]$$

$$T_1^1\left(\frac{\Delta z}{\Delta t} + \frac{\alpha}{dz} + \frac{\alpha}{\frac{dz}{2}}\right) = \left(\frac{\alpha}{dz}\right)T_2^1 + 0 + (\frac{\Delta z}{\Delta t}T_1^0 + \frac{\alpha}{\frac{dz}{2}}T_0^1)$$

$$T_0^1 = T_s = \frac{q_{solar} + (h_{radiation} + h_{conv})T_a + q_{rad_{diff}}}{h_{radiation} + h_{conv} + \frac{k}{d_z/2}} + \frac{(\frac{k}{d_z/2})}{h_{radiation} + h_{conv} + \frac{k}{d_z/2}}T_1$$

$$T_1^1\left(\frac{\Delta z}{\Delta t} + \frac{\alpha}{dz} + \frac{\alpha}{\frac{dz}{2}}\right)$$
$$= \left(\frac{\alpha}{dz}\right)T_2^1 + 0 + (\frac{\Delta z}{\Delta t}T_1^0 + \frac{\alpha}{\frac{dz}{2}}[\frac{q_{solar} + (h_{radiation} + h_{conv})T_a + q_{rad_{diff}}}{h_{radiation} + h_{conv} + \frac{k}{d_z/2}}$$
$$+ \frac{(\frac{k}{d_z/2})}{h_{radiation} + h_{conv} + \frac{k}{d_z/2}}T_1])$$

$$T_1^1\left[\frac{\Delta z}{\Delta t} + \frac{\alpha}{dz} + \frac{\alpha}{\frac{dz}{2}} - \frac{\alpha}{\frac{dz}{2}}\left(\frac{\left(\frac{k}{\frac{d_z}{2}}\right)}{h_{radiation} + h_{conv} + \frac{k}{\frac{d_z}{2}}}\right)\right]$$
$$= \left(\frac{\alpha}{dz}\right)T_2^1 + 0 + (\frac{\Delta z}{\Delta t}T_1^0 + \frac{\alpha}{\frac{dz}{2}}[\frac{q_{solar} + (h_{radiation} + h_{conv})T_a + q_{rad_{diff}}}{h_{radiation} + h_{conv} + \frac{k}{\frac{d_z}{2}}}]$$

Thus, a[1] = $\frac{\Delta z}{\Delta t} + \frac{\alpha}{dz} + \frac{\alpha}{\frac{dz}{2}} - \frac{\alpha}{\frac{dz}{2}}\left(\frac{\left(\frac{k}{\frac{dz}{2}}\right)}{h_{radation}+h_{conv}+\frac{k}{\frac{dz}{2}}}\right)$

b[1] =$\left(\frac{\alpha}{dz}\right)$

c[1] =0

d[1] = $(\frac{\Delta z}{\Delta t}T_1^0 + \frac{\alpha}{\frac{dz}{2}}[\frac{q_{solar}+(h_{radation}+h_{conv})T_a+q_{rad_{diff}}}{h_{radation}+h_{conv}+\frac{k}{\frac{dz}{2}}}]$

Recall: $P_i = \frac{b_i}{(a_i-c_iP_{i-1})}; Q_i = \frac{c_iQ_{i-1}+d_i}{(a_i-c_iP_{i-1})}$

$P_1 = \frac{b_1}{a_1}; Q_1 = \frac{d_1}{(a_1)}$

The forward substitution is to find P[n] and Q[n]

Bottom Boundary Condition (at the Subgrade layer)

$$\frac{\partial T}{\partial z}|_{3m} = constant = -2.3$$

$$\frac{T_B - T_n}{(\frac{d_z}{2})} = -2.3$$

$$T_B = T_n + \left(\frac{d_z}{2}\right)(-2.3)$$

where $T_B = T_{n+1}$ is the temperature at Bottom Boundary. By including temperatures at surface and boundary, the total number of temperature values in the matrix is n+2.

At bottome and Cell Number (P) = n, its south neighbor is T_B, and the gradient distance is $\frac{dz}{2}$

Recall:

$$(T_P^1 - T_P^0)\Delta z = \Delta t\left[\frac{\alpha(T_S^1 - T_P^1)}{dz} - \frac{\alpha(T_P^1 - T_N^1)}{dz}\right]$$

$$(T_n^1 - T_n^0)\Delta z = \Delta t\left[\frac{\alpha(T_B^1 - T_n^1)}{dz/2} - \frac{\alpha(T_n^1 - T_{n-1}^1)}{dz}\right]$$

$$T_n^1\left(\frac{\Delta z}{\Delta t} + \frac{\alpha}{\frac{dz}{2}} + \frac{\alpha}{dz}\right) = 0 + \frac{\alpha}{dz}T_{n-1}^1 + (\frac{\alpha}{\frac{dz}{2}}T_B^1 + \frac{\Delta z}{\Delta t}T_n^0)$$

$$T_n^1\left(\frac{\Delta z}{\Delta t}+\frac{\alpha}{\frac{dz}{2}}+\frac{\alpha}{dz}\right)=0+\frac{\alpha}{dz}T_{n-1}^1+\left[\frac{\alpha}{\frac{dz}{2}}\left(T_n+\left(\frac{d_z}{2}\right)(-2.3)\right)\right]+\frac{\Delta z}{\Delta t}T_n^0$$

$$T_n^1\left(\frac{\Delta z}{\Delta t}+\frac{\alpha}{\frac{dz}{2}}+\frac{\alpha}{dz}-\frac{\alpha}{\frac{dz}{2}}\right)=0+\frac{\alpha}{dz}T_{n-1}^1+[(\alpha)(-2.3)+\frac{\Delta z}{\Delta t}T_n^0]$$

Thus, a[n] = $\left(\frac{\Delta z}{\Delta t}+\frac{\alpha}{\frac{dz}{2}}+\frac{\alpha}{dz}-\frac{\alpha}{\frac{dz}{2}}\right)$

b[n] = 0

c[n] = $\frac{\alpha}{dz}$

d[n] = $(\alpha)(-2.3)+\frac{\Delta z}{\Delta t}T_n^0$

since b[n] = 0

Recall: $P_i=\frac{b_i}{(a_i-c_iP_{i-1})}$; $Q_i=\frac{c_iQ_{i-1}+d_i}{(a_i-c_iP_{i-1})}$

$P_n=0$; $Q_i=\frac{c_iQ_{i-1}+d_i}{(a_i-c_iP_{i-1})}$

$$T_i=P_iT_{i+1}+Q_i$$

$$T_n=Q_n$$

The backward substitution is to find T[n] first and T[n-1], to T[1]

I also defined a temporary temperature matrix T_star, which is used for iteration.

For each step, do iteration and check convergence to find surface temperature implicitly.

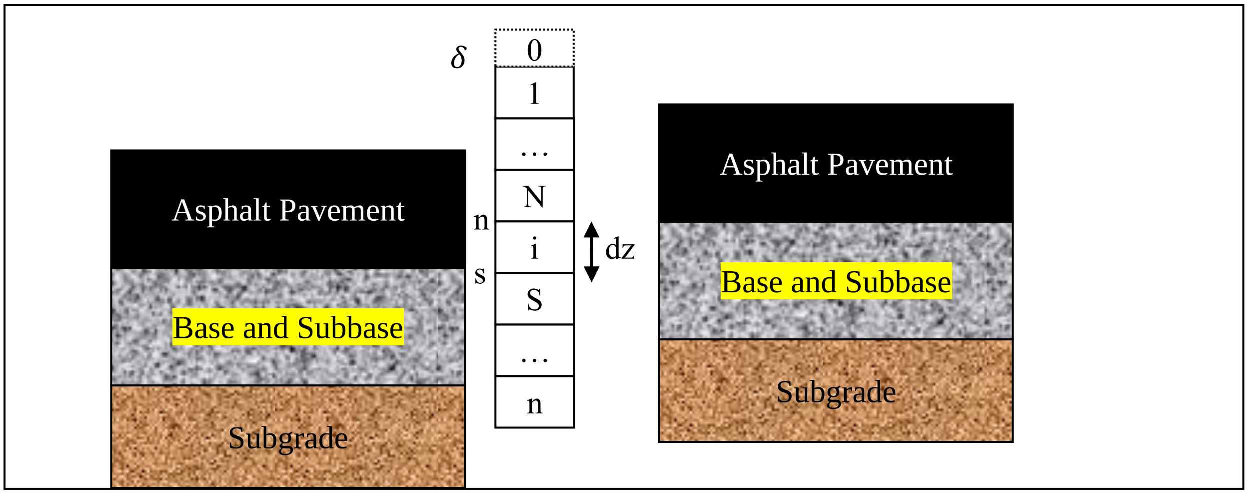
At interface between asphalt layer and base, base and subbase, subbase and subgrade

See 1-Dimensional Steady Conduction file. Consider energy balance

$$\alpha_n=\frac{2\alpha_N\alpha_P}{\alpha_N+\alpha_P}$$

$$\alpha_s=\frac{2\alpha_S\alpha_P}{\alpha_S+\alpha_P}$$

e.g. between asphalt and base, for the last cell (i) in asphalt layer, the south neighbor is base, so α_s is calculated as above and used to calculate b[i]. The north neighbor is still asphalt, so c[i] is calculated based on $\alpha_{asphalt}$. While, for the first cell in base, the north neighbor is asphalt and α_n is calculated as above to find c[]. The south neighbor is base and b[] is not affect.



2.2 Data Extraction (Seasonal Monitoring Program**)**

2.2.1 Download Pavement Test Temperature

- ✓ Go to LTPP InfoPave: https://infopave.fhwa.dot.gov/
- ✓ Click "DATA" and in General, Select "Section", choose e.g. "10-0102", click "apply"
- ✓ Click "Climate" and Check "Show Advanced Data Classification"
- ✓ Navigate to "SMP (Seasonal Monitoring Program)", "Seasonal Monitored Sub-Surface Parameters (Moisture, Temperature, Freeze)", then click "Temperature", and "Add to Selection", and "Add to Bucket"
- ✓ Click "Go to Data Bucket", Type your Email Address, Export File Format is "Microsoft Excel", Unit System "Metric", and Type Security Check. Click "Submit for Data Extraction"
- ✓ Now, you will wait and check the email to download data.

After downloading the pavement monitored temperature, explore the data as:

- ✓ Save the data as *LTPP Section-Raw*, e.g. "10-0102-Raw"
- ✓ Open the excel file, Navigate to SMP_MRCTEMP_AUTO_HOUR, Click "Data-Sort" based on "Therm_NO" , SMP_DATE, and TEMPERATURE_TIME.
    - o Explore the measured temperature data; Review the SMP_DATE range, e.g. for 10-0102 section, the temperature test for thermo_no 1 and construction number 1 is from 11/18/1995-05/09/1996. For construction number 2, the time window is 08/09/1999-10/07/1999. This information will be used to extract climate data timeframe. For thermo_NO 3, 11/18/1995-09/21/1996, and 09/22/1996-09/18/1999. Based on that, we will extract climatic data from 11/18/1995-09/21/1996 for Construction No.1;
    - o Pay close attention to the Construction NO, as it will affect pavement structure input.

2.2.2 Pavement Structure Data

- ✓ Go back to Data and Choose Section; Click "Go To…" and Choose "Pavement Cross-Section Viewer"
- ✓ Collect thickness information

- ✓ For construction No 1:
  - Total thickness for Asphalt Concrete (AC) = 1.3”+3” = 4.3” (Convert to meter = 0.109m, three decimals),
  - Base = 11.8” = 0.300m,
  - Subbase =39” = 0.991m; (If there is no subbase, input = 0 m)
- ✓ For Construction No 2:
  - Total thickness for Asphalt Concrete (AC) = 1.2”+1.3”+3” = 5.5” (Convert to meter = 0.139 m, three decimals),
  - Base = 11.8” = 0.300m,
  - Subbase =39” = 0.991m;
- ✓ Go to… “Section Summary Report”, choose “Metric”, Expand “LTPP Section History and Pavement Structure”, double check the Layer Information for Thickness. (The layer thickness might be slightly adjusted)

2.2.3 Extract MERRA Climate Data

- ✓ Review the SMP_DATE range, e.g. for 10-0102 section, the temperature test for thermo_no 1 and construction number 1 is from 11/18/1995-05/09/1996. For construction number 2, the time window is 08/09/1999-10/07/1999. This information will be used to extract climate data timeframe. For thermo_NO 3, 11/18/1995-09/21/1996, and 09/22/1996-09/18/1999.
- ✓ Based on that, we will extract climatic data from 11/18/1995-09/21/1996 for Construction No.1; 09/22/1996-12/31/1999 for construction No.2. (You may focus on Construction No.1 Data for this project if it covers a whole year)
- ✓ Extract MERRA Climate Data including Temperature, Wind, and Solar
- ✓ Go to…Data Section and Download
- ✓ Click “Climate” and check “Show Advanced Data Classification”
- ✓ Click “+” sign to expand MERRA-Temperature and check “Hourly”, Click “Add to Selection”; Data Range “11/18/1995-09/21/1996”; “Add to Data Bucket”, “Go to Data Bucket”, email, metrics, security check, Submit for Data Extraction
- ✓ Continue to Select Data, repeat for wind-hourly (wind velocity), and solar-hourly (Shortwave Surface)
- ✓ Download Temperature, Wind, and Solar. Rename these files as *LTPP Section-Temp/Wind/Solar* and move them to the target folder.
- ✓ For environmental data, pay attention to the DATE_TIME, which shall be sorted based on date as well as time. *Sometimes, I found the time is not sorted from lowest value to highest value. Thus, I would copy the DATE_TIME column and sort them again.*
  - Copy DATE_TIME, show the pasted column based on Time
  - Sort column B and column C

2.3 Run Simulation, Post-Processing, and Adjust Seasonal Parameter for Calibration

2.3.1 Modify Python Code and Run Simulation

The python code for temperature analysis (TEMPY) is provided; you are so welcome to revise, improve, and change the code when needed. The following instruction shows the step-by-step on how to use the code for the analysis.

You will need install packages, e.g. openpyxl, numpy, matplotlib, and sklearn to run the program. I installed the package via the Pycharm using ‘pip install XXX’

- ✓ Change LTPP-Section to the Code, e.g. 10-0102
- ✓ According to *LTPP-Section-Raw* file, extract and manually input the depth of available thermocouples, e.g. 0.006m for thermocouple 1 based on Sheet “SMP_MRCTEMP_DEPTHS”
- ✓ Change the thickness_AC, thickness_Base, and thickness_subbase according to the pavement structure in 2.2.2. The total thickness is assumed to be 3 meters.
- ✓ Change the env_data_path, where you move the MERRA data to the designated folder. *Change the names of temperature, wind, and solar if needed (Pay attend to upper and lower letters)*
- ✓ Note: Please run the code first and check the plot of test temperature and simulation temperature along the date as x-axis. There might be a need to shift the test temperature by 1 to 3 hours to allow the matching between the peak of test temperature and simulation temperature. The default value is 0. (This might be adjusted later on)
- ✓ Use the default delta_e_1 = -0.15 and delta_e_6 = -0.05 (This might be adjusted later on)
- ✓ Check T_surf is calling air-temperature in column 4 of Temp data file. Make sure the correct column is used. Double Check Q_solar is calling correct column in Solar data file for Shortwave Surface, T_air as the air temperature in Temperature Data File, and v-wind is the wind speed in the Wind data file.
- ✓ The density, thermal conductivity, and heat capacity might be changed, or use the default value

Now, it is time to run the simulation!

2.3.2 Post-Processing

It is aware that the malfunction of thermocouple so that some test data are missing. The post-process is conducted to compare tested results and simulation results, and then adjust the seasonal parameters to find the best fitting materials parameters to run simulation for long-term pavement temperature. The Python code can complete post-processing automatically by plotting the test temperature and simulation temperature. Also, the regression between test temperature and simulation temperature, coefficient of determination (R^2), and mean absolute error are calculated, which will be used to adjust seasonal parameters and materials parameters.

2.3.3 Seasonal Parameter Adjustment for Calibration

Adjust seasonal parameter **(delta_e_1 and delta_e_6)** and/or fine-tune material property, e.g. k and/or cp, could increase the accuracy of prediction. Based on the initial trial of simulation results, you could change delta_e, (may be k, and/or cp) to find the better matching between the test temperature and simulation temperature. In general,

- ✓ If both the maximum and minimum temperatures from the simulation are lower than those from the test, the delta_e_1 for January (winter) and/or delta_e_6 for June (Summer) could be increased, e.g. delta_e_6 from -0.05 to -0.02, as delta_e is a negative number defined in this code. Vice Versa, if simulation results are higher than test results, decrease the delta_e_1 and/or delta_e_6.

- ✓ If the amplitudes of the maximum and minimum temperatures from the simulation are smaller than those from test, k could be decreased and/or the cp could be decreased within the suggested ranges. (*Increase k will lower the surface temperature and increase the bottom temperature (amplitude becomes smaller, less temperature gradient in layer; temperature variation decreases as cp increases*).

2.4 Section Assignments (see attachment)

Please summarize results in the Excel table of CURE-E FA 22-Assignment! See example.

Based on the literature review, extracted data, and model calibration, a progress seminar is organized on Week 10, each student/team will prepare a progress presentation and present it to other students/teams by discussing the proposed research topic, literature review results, data extraction, database, and preliminary findings and outcomes.

Assessment: progress presentation (10 pts) due Week 10: each student/team is required to submit a project progress presentation (at least 5 slides) by including (1) project background and literature review results, (2) data extraction and preliminary database, (3) analysis methods, and preliminary findings and outcomes.

Extra Credits: during the progress seminar, each student can earn 1 extra point by asking one question to other students/teams. Each student can earn a maximum of 3 pts by asking 3 questions during the progress seminar. This extra credit policy is also applicable to the presentation in the final project seminar.

Task 3: Investiage Climate Change on Pavement Temperature based on the Past 40-year climatic data (1980-2020) (Week 11-14); Expected Working Hours: 16 hours (Optional Work with 15 pts extra credit)

Webinar: Past Climates inform our future

https://players.brightcove.net/679256133001/NkgrDczuol_default/index.html?videoId=6313660008112

For students who would like to investigate the impact of climate change on pavement temperature, you could conduct numerical analysis of pavement temperature for one pavement section based on the past 40-year climatic data. If two students work together, the team shall report two pavement sections. You can extract the maximum, minimum, and mean pavement temperature in each year. You are going to explore a graphical method to plot pavement temperature chronologically and statistically. Such plots could provide informative visualization. The Excel can be used for the basic plot. The advanced plot method is suggested using spirals, see the example https://www.dataquest.io/blog/climate-temperature-spirals-python/. In addition, you will draw the conclusion on the fluctuation of pavement temperature in the past 40 years, e.g. the mean temperature is increasing, decreasing, or more fluctuating? More frequent extreme high or low pavement temperature?

Please revise the Python code accordingly to complete this task.

Task 4 Final Assessment: Each student/team is required to present their project by preparing Powerpoint slides (15 pts) and submit a 2-page final report (15 pts) on Week 16. **You need to upload your section folder with all required files (see example) and summarize results in the Excel table of CURE-E FA 22-Assignment to earn points on final report and final presentation!!!** The grading rubric of the final report is the same as the lab letter report. The grading rubric of the project presentation is shown as:

Final Project Presentation	**Points**	**Your Grade**
1. Introduction for project background	3.0	
2. Data extract and methods	3.0	
3. Results and Findings	3.0	
4. Data Visualization and Discussions	3.0	
5. References	3.0	
Total:	15.0	