Cold Region Pavement Performances

Why pavements fail or perform poorly?

Climate Changes

Bound and unbound layers → inadequate design or poor materials

Geotechnical failures → many times catastrophic

Frost Heave

Subgrade baring capacity failures

Pavement structure
Cold Region Pavement Performances

- Pavement performances: functional and structural performances
  - Functional performances: the ride quality, surface texture
  - Structural performances: the structural capacity / load-bearing capacity (deflection, layer thickness, and material properties).

- Cold region pavement performances:
  - Subject to intense loading by climate and environmental factors
  - Deterioration mechanisms based on materials:
    - Asphalt-bound materials
    - Unbound layers and subgrade soils
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• Deterioration mechanisms:

**Asphalt-bound materials:**
- Thermal contraction or fracture
- Fatigue
- Crack deterioration
- Rutting
- Aging
- Pavement disintegration caused by action of water, salt, and frost within the asphalt-bound layer
- Potholes

**Unbound layers and subgrade soils:**
- Differential volume change caused by frost heave
- Bearing capacity loss during spring thaw
- Frost destructuration of sensitive clays
- Thaw consolidation of frozen soils in permafrost regions

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**Cold Region Pavement Performances**

----Thermal cracking of asphalt concrete

• Temperature in the climate decreases → asphalt contracts and shrinks → cracks form (perpendicular/transverse to the pavement’s centerline).
• Cracks parallel to the direction of the road start to form.
• Generally initiated in the asphalt bound layer, but can also be initiated in the underlying *frozen* layers.

How is thermal cracking developed? “Cold” and “Constraint”

\[
\text{Thermal stress} = \text{tensile strength of the pavement}
\]
(temperature and loading time dependent)

Sources: https://www.pavementinteractive.org/reference-desk/pavement-management/pavement-distresses/
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---Thermal cracking of asphalt concrete

- **Two types of thermal cracking:**
  - Low-temperature cracking*: below -16°C to -35°C
  - Thermal fatigue cracking: diurnal temperature cycling

*most typical form in cold regions

\[
\sigma_{\text{thermal}} = \alpha \int_{T_1}^{T_2} S dT,
\]

\( \alpha \): linear thermal contraction coefficient, \( S \): temperature and loading time dependent stiffness of the asphalt concrete, \( T_1, T_2 \): initial and final temperature.

\[
\sigma_{\text{thermal}}(t) = \int_0^t E(t - \xi) \frac{\partial \varepsilon(\xi)}{\partial \xi} d\xi, \varepsilon(\xi) = \alpha(T) \Delta T
\]

\( \alpha \): thermal contraction coefficient as a function of temperature, \( \varepsilon \): thermal strain, \( t \): time.


Typical results from a TSRST

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---Thermal cracking of asphalt concrete

- **Factors affecting low-temperature cracking**
  - **Material factors**: asphalt binder, aggregate type
  - **Environmental factors**: temperature, rate of cooling, pavement age
  - **Pavement structure geometry**: HMA thickness, shear strength between the HMA layer and base course, subgrade type
  - **Construction flaws

Table 3-1 Textbook (pg. 61)
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How to assess/predict thermal cracking?

• Two approaches:
  • Based on cracking temperature alone
  • Predict the crack spacing by statistically derived models or by a mechanistic approach

Statistically derived model (Hajek, 1971):

\[
I = 30.3974 + (6.7966 - 0.8741 \cdot h + 1.3388 \cdot a)\log(0.1S_{bit}) - 2.1516 \cdot d - 1.2496 \cdot m + 0.06026 \cdot S_{bit}\log(d)
\]

Number of cracks per 152m section of two-lane roadway! Crack Spacing = 152 / I

Where, I: cracking index, $S_{bit}$: stiffness modulus of the original asphalt binder, a: age of pavement in years, m: winter design temperature($^\circ$C), d: dimensionless code for subgrade, h: thickness of bituminous layers (inch).

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How to assess/predict thermal cracking?

• Mechanistic model (Zubeck and Vinson, 1996 and 2007):

\[
F_{failure} = P_{ts}(T, t)WD = (yD \tan \phi + c)Wx
\]

\[
\text{Spacing}_{\text{min}} = \frac{P_{ts}(T, t) \cdot D}{yD \tan \phi + c}
\]

\[
\text{Spacing}_{\text{max}} \approx 2\text{Spacing}_{\text{min}}
\]

Why maximum spacing is twice the minimum spacing (approximately)?
Cold Region Pavement Performances

---Thermal cracking of asphalt concrete

What are the disadvantages of thermal cracking in pavements?

- Thermal cracking of asphalt concrete
  - Decreasing the riding quality
  - Allow water and deicing agents to penetrate the pavement structure causing frost-related problems
  - Difficulty to prevent the cracks from reflecting through a new overlay

Source: https://www.fhwa.dot.gov/hfl/partnerships/asphalt/ppt.cfm

Remedial solutions for low-temperature cracking

- Material factors: use low fracture temperatures and high fracture strengths
  - Compromise between temperatures and traffic volume
  - High-traffic pavements: polymer-modified asphalts; low-traffic pavements: soft asphalt binder
- Geometry factors: increase the thickness of the HMA layer
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---Fatigue cracking/Alligator cracking

- **Fatigue cracking/alligator cracking:**
  - Fracture phenomenon caused by a *repeated* application of tensile strains that are *less than* the strength of the material
  - Microscopic flaws grow under repeated loading, visible flaws or cracks develop, propagate
  - Moisture and drainage condition in underlying layers have significant effects on fatigue cracking in HMA layers, especially in cold regions

**How is fatigue cracking developed in pavements?**

- Increase in loading
- Inadequate structural design
- Poor construction
- Decrease in pavement load supporting characteristics
  - *A loss of base, subbase or subgrade support from poor drainage*
  - *Stripping on the bottom of the HMA layer*
Cold Region Pavement Performances

---Fatigue cracking/Alligator cracking

What are the disadvantages of fatigue cracking in pavements?

- Roughness
- Moisture infiltration into the base and subgrade, eventually results in potholes and pavement disintegration if not treated
- Indicator of structural failure

Source: https://www.pavementinteractive.org/reference-desk/pavement-management/pavement-distresses/fatigue-cracking/

How to assess/predict fatigue cracking?

- Expressed as relationships between initial stress or strain and the number of load repetitions to failure

\[ N_f = f_1 \left( \frac{1}{\epsilon_f} \right)^{f_2} \left( \frac{1}{E_1} \right)^{f_3} \]  

(Huang 2004; Monismith et al. 1985)

Where \( N_f \): allowable number of load repetitions to prevent fatigue cracking, \( \epsilon_f \): tensile strain at the bottom of asphalt layer, \( E_1 \): elastic modulus of asphalt layer, \( f_1, f_2, f_3 \): constants determined from lab fatigue test.

\[ N_f = A \cdot 0.00432 \cdot C \cdot \left( \frac{1}{\epsilon_f} \right)^{3.291} \frac{1}{E_1}^{0.854} \]  

(Huang 2004)

Where \( A \): factor to correlate with field performance observations, \( C \): volumetric correction factor, \( E \): dynamic modulus, \( \epsilon_f \): air void content %, \( V_{beff} \): effective binder volume %.
Cold Region Pavement Performances
----Fatigue cracking/Alligator cracking

• **Factors affecting fatigue cracking**
  - **Mode of loading**: constant stress or constant strain
    - **Constant stress**: thick pavement > 150mm
    - **Constant strain**: thin pavement < 50mm
  - **Mixture variables**: asphalt content, air void content, ....
    - asphalt content increase ↔ decrease in mix stiffness
    - air void content increase ↔ decrease in lab fatigue life
  - **Temperature**
    - increasing temperature ↔ decreased stiffness

  *Thick pavement: Decreased fatigue life
   Thin pavement: increased fatigue life*

  A mix targeted at 5% asphalt and 5% air voids will suffer:
  - 30% reduction in fatigue life if the air void content exceeds its target by 1%;
  - 12% reduction if the asphalt content is shy of its target by 1%.


• **Remedial solutions**
  - **Material selection** depending on the thickness of the HMA layer:
    - Thick pavements (>150mm) — stiff HMA; thin pavements (<50mm) — soft HMA
  - Improve drainage
  - Proper quality control during construction
  - Determine the root cause of failure
    - Small, localized -- loss of subgrade support: remove the cracked pavement area, dig out and replace the area of poor subgrade
    - Large areas -- general structural failure: place an HMA overlay

Sources:
Cold Region Pavement Performances

--- crack deterioration

- Pavement deterioration is accelerated with the presence of cracks (either developed from thermal or traffic loading reasons)

A crack appears

- Ineffective load transfer
- Stress distribution pattern affected
- Water infiltrating into granular base through the crack

Excessive deflection of surface at the crack

Development of spalling, formation of secondary cracks, accumulation of differential permanent deformation

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--- crack deterioration

- Remedial solutions (two categories)
  - Sealing the crack early after crack initiation
    - Prevents water and incompressible materials entering
    - Reducing further deterioration of the crack
    - Openings between 6mm and 12mm
  - Sealing the crack at certain level of deterioration without important structural damage to the pavement
    - Removal of existing damaged area & filling with HMA
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--- rutting of asphalt concrete

- **Rutting:** surface depression in the wheel path, and possible uplift (shearing) along the sides of the rut
- **Problems:** affect lateral maneuverability, hydroplaning, decrease the structural capacity

Sources: https://civilblog.org/2015/09/18/10-different-types-of-failures-of-flexible-pavement/
https://resources.tireamerica.com/research/hydroplaning-why-it-happens-and-how-you-can-avoid-it

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Cold Region Pavement Performances

--- rutting of asphalt concrete

- **Sources of rutting:**
  - In asphalt layer:
    - Permanent deformation
    - Wear by studded tires
  - In unbound structural layer:
    - Bearing capacity loss
  - In subgrade:
    - Bearing capacity loss

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rutting of asphalt concrete

• Rutting due to permanent deformation
  • Permanent deformation: Road construction materials are not ideally elastic so they will accumulate irrecoverable deformation under every load application.
    • Initial densification: air voids reduce and the volume of HMA decrease
    • Plastic flow: after the air voids drop below a limit, volume does not change anymore and plastic flow starts—mixture flows from the wheel paths to the small upheavals beside the wheel path.

Factors affecting permanent deformation
  • Material properties: aggregate, binder stiffness
    • Fine, angular aggregates
    • Stiffer binder, grade performance table (Superpave)

Performance Grading “PG 58-22”: 58°C, -22°C

• Mix design: binder content, air void content, VMA, compaction method
• In-service conditions: temperature, state of stress/strain, load repetitions, moisture
Cold Region Pavement Performances

rutting of asphalt concrete

- Rutting due to permanent deformation
  - Prediction of the amount of rutting in the HMA layer
    - Layer-strain predictive methodology and closed form viscoelastic analysis
      - \[ \Delta p = \sum_{i=1}^{n} \left( \frac{\epsilon_i}{\epsilon_r} \right) \Delta z_i \]
        - Where \( \Delta p \): total rut depth; \( \epsilon_i \): average plastic strain in the \( i \)th sublayer; \( \Delta z_i \): thickness of the \( i \)th sublayer, \( n \): total number of the sublayers.

- Other statistically derived model:
  - \[ \log \left( \frac{\epsilon_p}{\epsilon_r} \right) = -4.80661 + 2.58155 \cdot \log T + 0.429561 \cdot \log N \]
    - (Originally by Leahy, modified by Ayres)
    - Where \( \epsilon_p \): plastic strain, \( \epsilon_r \): elastic strain, \( N \): number of equivalent load cycles, \( T \): temperature in °F
Cold Region Pavement Performances

--- rutting of asphalt concrete

- **Rutting due to studded tire wear**
  - Studded tires are used to increase traction on snowy and icy roads; high usage percentage of 89% to 96% during winter months in Finland
  - Studs remove particles from the pavement surface, after a large number of stud passages ruts start to form.
    - *Stud fractures the exposed aggregates or mastic*
    - *Scratching effect detaches the fractured particle*
  - How to differentiated from permanent deformation: rough surfaces with exposed aggregates; single narrow depression without adjacent upheavals

Factors affecting pavement wear

- *Traffic volume and the percentage of vehicles using studs*
- *Pavement surface conditions, and road geometry (lane width, intersections, crown slope, vertical grade, etc.)*
- *Pavement materials: aggregate is the most important material factor (abrasion resistance, content of coarse aggregate, mix design)*
- *Environment: duration of wet surface, duration of traction sanding*...
Cold Region Pavement Performances

---- rutting of asphalt concrete

- Rutting due to studded tire wear
  - Remedial solutions
    - Use of less aggressive studs, strictly enforcing seasonal tire usage
    - Wear-resistance pavements
      - Use of abrasion-resistant aggregates
      - Use of SMA mixtures

*Textbook Table 3-6 (pg. 79)*

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Cold Region Pavement Performances

---- aging of asphalt concrete

- Aging of asphalt concrete: oxygen reacts with its constituent molecules resulting in a stiffer, more viscous, brittle material.
- Negative effects: increased tendency toward cracking, moisture damage, pothole, wearing by studded tires.
- Factors affecting aging: binder properties, air void content, layer thickness, climate

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--- aging of asphalt concrete

• **Assessment of aging:**
  - **Evaporation/Volatilization:** loss of volatile components, mainly during mixing
  - **Oxidation:** irreversible chemical reaction
  - **Physical hardening:** reversible, by heating or agitation
  - **Exudation:** oily components exude from asphalt cements into aggregate

• **Significant aging period:** during hot-plant mixing during first few months in service

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Cold Region Pavement Performances

--- aging of asphalt concrete

• **Remedial solutions:**
  - Selection of asphalt cement and aggregate
  - Controlling the mixing temperatures in the hot mix plant
  - Using dense-graded mixtures, using high asphalt contents
  - Applying surface dressings (rejuvenators) as the pavement ages

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Cold Region Pavement Performances

--- pavement disintegration

- Breakup and loss of individual pieces of HMA
- In form of raveling, stripping, and potholes
  - **Raveling**: disintegration of the HMA from the top downward, as aggregate particles become loose due to loss of bond between the asphalt binder and aggregate
  - **Stripping**: weakening or eventual loss of the adhesion bond in the presence of moisture between aggregate surface and asphalt binder, typically begins from the bottom of the HMA layer and progress upward
  - **Potholes**: circular or elongated cavities resulting from a localized disintegration of the pavement surface.

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**Raveling**

- Problems: Loose debris on the pavement, roughness, water collecting in the raveled locations resulting in vehicle hydroplaning, loss of skid resistance
- Causes:
  - *Coating of fine dust on aggregate surface*
  - *Insufficient amount of fines*
  - *Low in-place density*
  - *Deficient asphalt content*
  - *Excessively aged asphalt binder*

[Source](https://www.pavementinteractive.org/reference-desk/pavement-management/pavement-distresses/raveling/)
Cold Region Pavement Performances

--- pavement disintegration

**Raveling**
- Remedial solutions:
  - Optimum amount of fines and asphalt content
  - Avoid excessive asphalt aging, inadequate compaction, and mix segregation during construction
- Repair:
  - Small, localized areas of raveling: Remove the raveled pavement and patch
  - Large raveled areas indicative of general HMA failure: remove the damaged pavement and overlay

https://www.pavementinteractive.org/reference-desk/pavement-management/pavement-distresses/raveling/

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**Stripping**
- **Problems**: Decreased structural support, rutting, shoving/corrugations, raveling, or cracking (fatigue and longitudinal)
- **Causes**: moisture, mineralogy and chemical composition of the aggregate
- **Mechanisms**: detachment, displacement, spontaneous emulsification, pore pressure, hydraulic scouring

https://www.pavementinteractive.org/reference-desk/testing/asphalt-tests/moisture-susceptibility/
Cold Region Pavement Performances

---- pavement disintegration

• **Stripping**
  - Remedial solutions:
    • *Prevent moisture damage, keep moisture out of the pavement*
    • *Incompatible materials, antistripping agents*
    • *Pretreatments of aggregate during production*
    • *Proper field compaction, avoid segregation*
    • *Maintenance of rut filling, crack sealing, pothole filling*
  - Repair:
    • Stripped pavement needs to be removed and replaced after correction of any subsurface drainage issues.

Source: [https://www.pavementinteractive.org/reference-desk/testing/asphalt-tests/moisture-susceptibility/](https://www.pavementinteractive.org/reference-desk/testing/asphalt-tests/moisture-susceptibility/)

Cold Region Pavement Performances

---- pavement disintegration

• **Potholes---Extreme manifestation of distress**  NOT a type of distress!
  - Three conditions: a breach, water, traffic action
  - Problems: roughness (serious vehicular damage can result from driving across potholes at higher speeds), moisture infiltration
  - Causes (a break in pavement surface):
    • *Pavement cracking*
    • *Pavement disintegration*
    • *Deteriorated construction joints*
    • *Usually related with water*

Cold Region Pavement Performances

---- pavement disintegration

- **Development of Potholes**
  - Cracks allow water to infiltrate higher strains (from traffic and frost heave) at the crack further deterioration/partial disintegration
  - Moving wheel loading intense hydrostatic pressure forcing upward movement of adjacent pavement remove broken pieces tires directly acting on water erosion

- **Potholes**
  - Remedial solutions:
    - Pavement drainage to remove water
    - Effective maintenance strategies performed on pavement breach before disintegration occurs: crack sealing, resurfacing shortly after distress observed
  - Repair:
    - Cutting around the affected area
    - Removal materials in the hole
    - Compact bottom of the hole
    - Coating walls of hole with tack coat
    - Filling the hole

https://www.pavementinteractive.org/reference-desk/pavement-management/pavement-distresses/potholes/
Summary

- Pavement performances: functional and structural
  - Thermal cracking
  - Fatigue cracking
  - Crack deterioration
  - Rutting
  - Aging
  - Pavement disintegration

Thanks for attention!