Airport pavement infrastructure in the context of climate change

INSTITUTE FOR SUSTAINABLE AVIATION

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The Vulnerability of Air Transport to Weather and Climate Change

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What is Airport Pavement?

Pavement is:

A major airport asset which allows aircraft to taxi, take-off, land and park

30% of airport construction cost and **up to 50% of annual airport infrastructure maintenance cost**

Must be capable of:

- ✓ Satisfying bearing strength capabilities to accommodate an analyzed aircraft mix (Vertical)
- ✓ Providing sufficient friction characteristics to maintain aircraft under control in critical phases (horizontal)

Airport pavements are critical infrastructure for cities across the globe. Runways, taxiways, and aprons consume large amounts of land, are ***expensive*** *to build, have* ***high performance requirements****, and demand* ***significant maintenance and rehabilitation investment*** *over their lifecycle. Consequently, sound design, construction, maintenance, and management practices founded on cutting-edge technology and research is essential.*

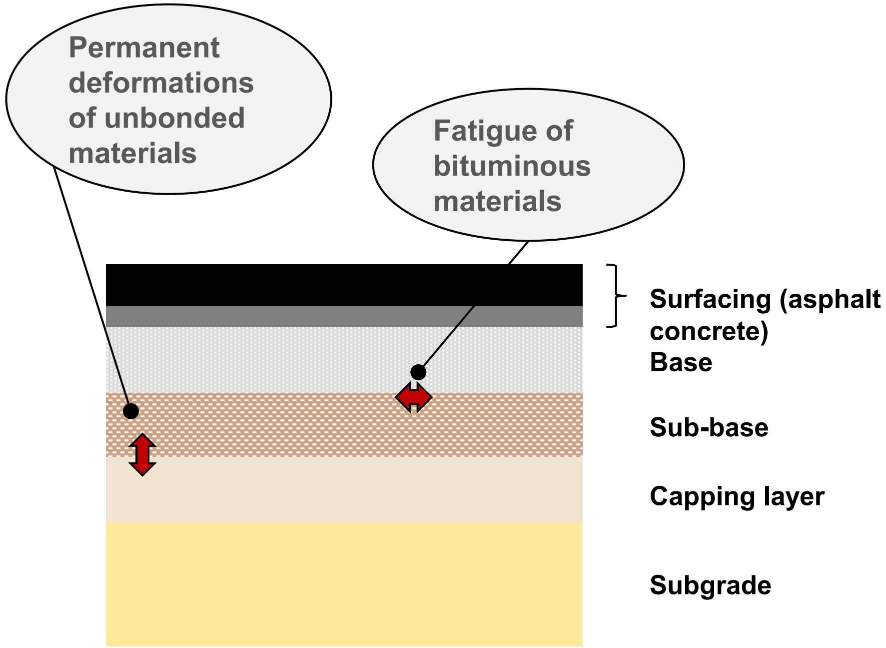
WHAT WE DON’T WANT

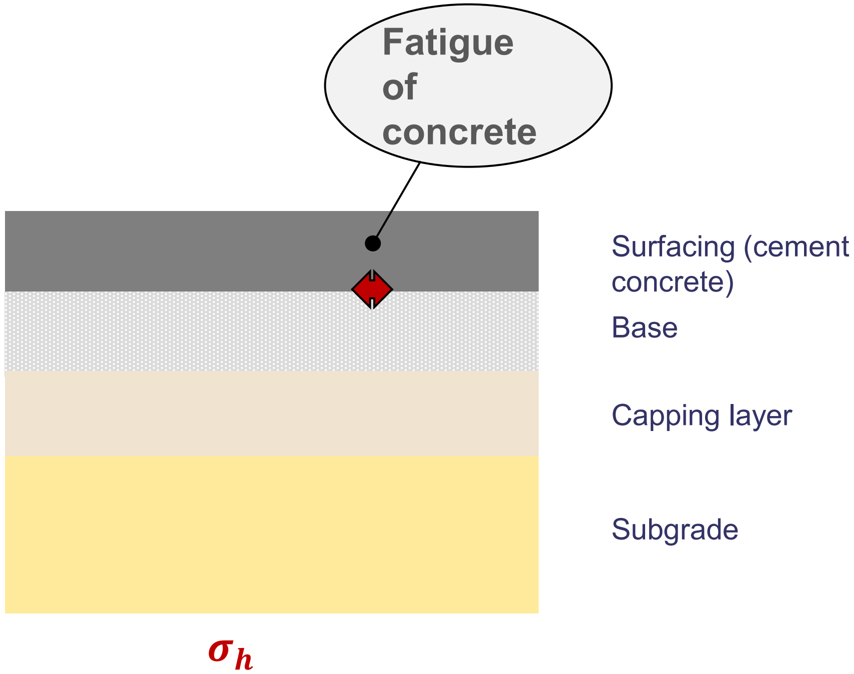
The runway is long enough, but is it strong enough?

Careful trip planning must always include determining the weight bearing strength of airport pavements as it is done for Takeoff/landing performance.

“It is better to anticipate problems rather than to find recovery solution once the problem occurs”

What Type of Pavements?





Flexible Pavements:

- ✓ 70 % Runways
- ✓ 50% Taxiways
- ✓ 10% Parking / Apron Stands

Rigid Pavements:

- ✓ 30 % Runways
- ✓ 50% Taxiways
- ✓ 90% Parking / Apron Stands

PAVEMENT DESIGN AND ANALYSIS - PRINCIPLE

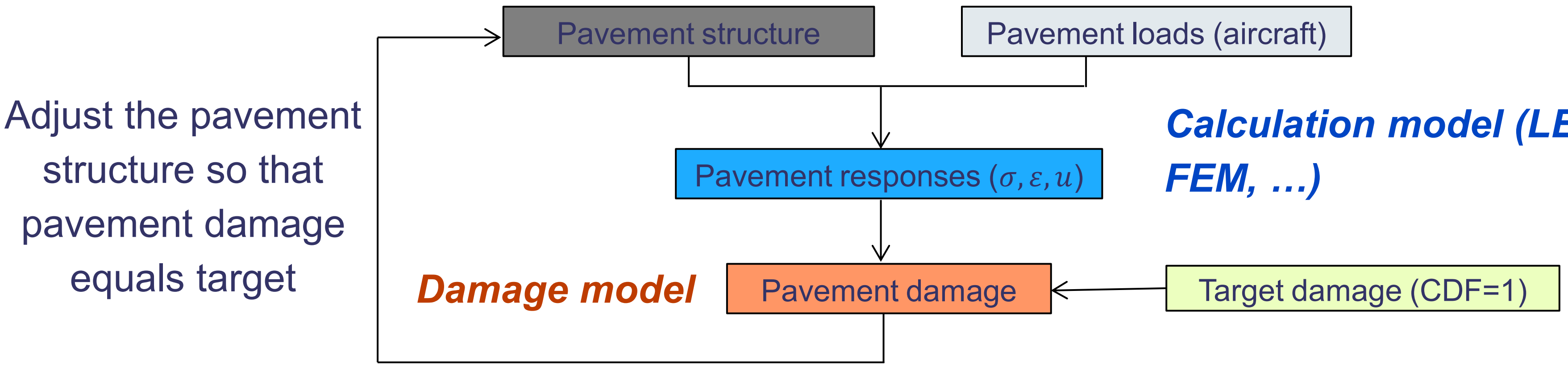
- Rational pavement design procedures involve the following steps:
  - Compute the pavement responses (stresses σ, strains ε, displacements u) to aircraft loads

⇨ this relies on a **calculation model** (e.g. Linear Elastic Analysis LEA, Finite Element Model FEM, …)

  - Determine the pavement damage induced by the pavement responses

⇨ this relies on a **damage model** that relates pavement response to pavement damage

  - Adjust the pavement structure until a target damage (conventionally CDF = 1) is reached



Adjust the pavement structure so that pavement damage equals target

Pavement structure

Pavement loads (aircraft)

Pavement responses (σ, ε, u)

Calculation model (LEA, FEM, …)

Damage model

Pavement damage

Target damage (CDF=1)

Tangible Climate Impacts

Climate change effects are no longer theoretical; they are tangible and observed globally.

Extreme Events: Recent heatwaves (e.g., Summer 2022 in Europe) have stressed airport operations.

Magnitude Matters: Focus is shifting from average temperatures to the frequency and intensity of extreme phenomena.

Precipitation: Intensified rainfall vs. severe droughts affecting underlying pavement layers.

Strategic Engineering Objectives

In-Service Assets

Manage risks for existing pavements, plan reinforcements, and adapt drainage systems to higher precipitation intensity and frequency

New Infrastructure

Incorporate updated temperature data and risk coefficients into initial design phases.

Resilience Planning

Proactive maintenance to ensure long-term bearing capacity and safety standards.

Identified Potential Effects

Flexible Pavements

Rutting risk, mechanical design sensitivity, thermal cracking, and interface debonding.

Rigid Pavements

Impact on load transfer conditions and slab curling/warping due to thermal gradients.

All Pavements

Subgrade bearing capacity fluctuations and soil swelling/shrinkage issues.

…And for all Water / Moisture penetration within pavement layers or interfaces!

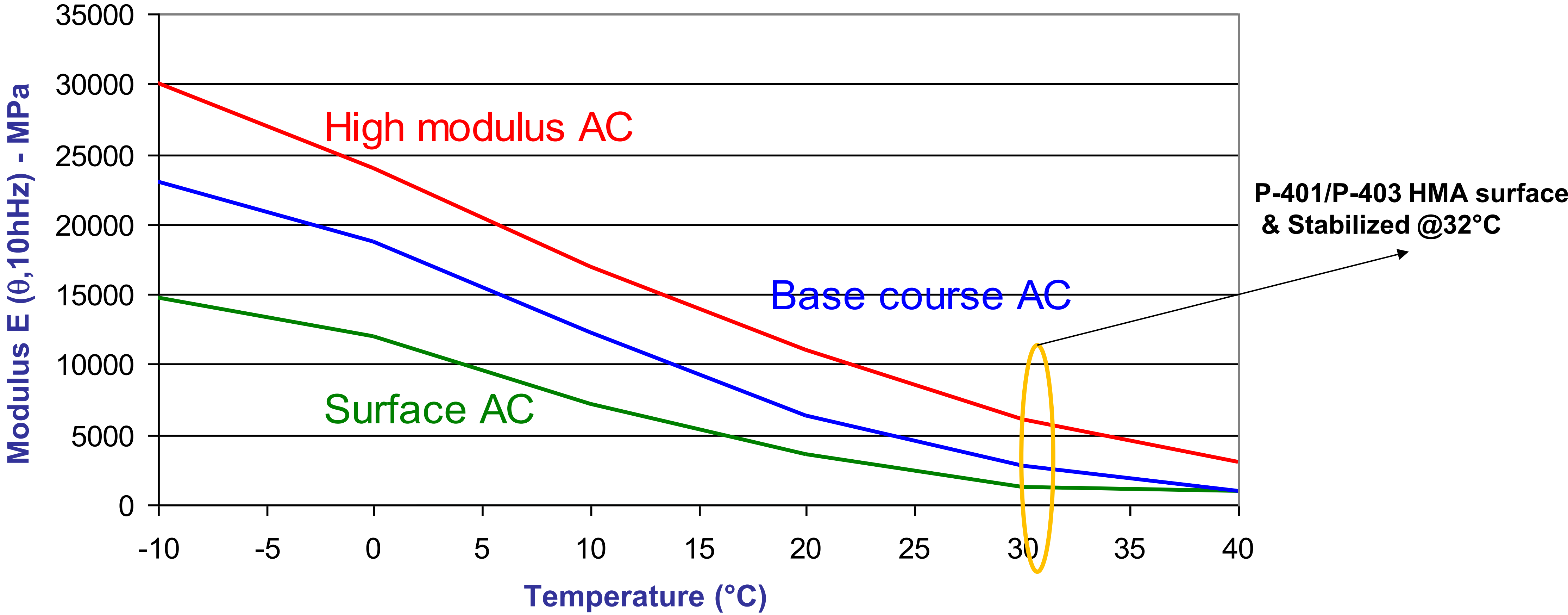
Flexible Pavements

Sensitivity of Bituminous Materials

…and Indirectly to Subgrade

INFLUENCING PARAMETERS

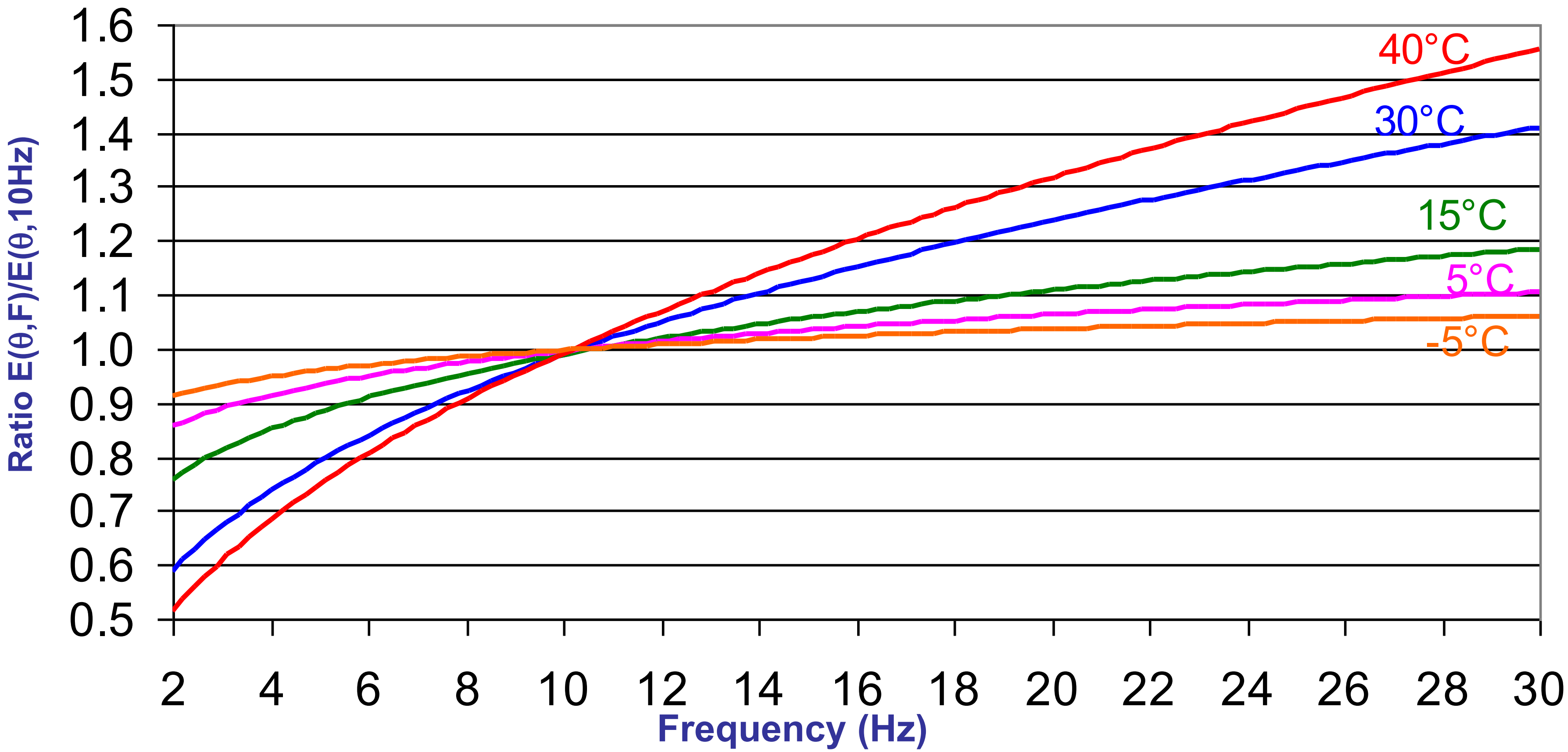
- **FLEXIBLE PAVEMENTS: E Modulus = f(Temperature)**



Temperature effect : correlation from complex module (master curves) laboratory test synthesis

INFLUENCING PARAMETERS

- **FLEXIBLE PAVEMENTS : E Modulus = f(frequency)**



Frequency effect : correlation from complex module laboratory test synthesis

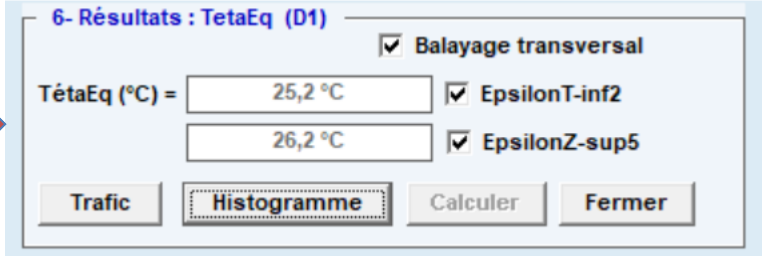
Equivalent T° vs. Aerodrome Reference Temperature

- **FLEXIBLE PAVEMENTS**

- **Equivalent Temperature**: In practice, the “equivalent temperature” (Teq) concept is «the constant temperature which would lead to the same bituminous materials damage than the summation of all elementary damages calculated considering the real temperature in the bituminous material at each aircraft passage».

Test Teta Eq		
Period	2023	
Temperature Histogram		
T1(øC)	T2(øC)	%Trafic
0	5	5
5	10	20
10	15	8
15	25	12
25	35	40
35	40	15

Average = 21,5°C



6- Résultats : TetaEq (D1)

☑ Balayage transversal

TétaEq (°C) = 25,2 °C ☑ EpsilonT-inf2

26,2 °C ☑ EpsilonZ-sup5

- Design at 25,2°C (AC – E modulus adjustment)
- Design at 26,2°C (AC – E modulus adjustment)

Final design is the most conservative

Small Bending Radius Rutting

Asphalt binder softens at high temperatures, behaving as a viscous fluid with decreased creep resistance.

Risk Areas: Critical for slow-moving or static traffic (aprons, thresholds and low speed taxi).

Current Methods: Surface courses are often selected empirically rather than designed.

Adaptation: Use specialized bituminous materials or hydraulic surface courses (e.g., Ultra-thin white topping).

Mechanical Design Challenges

Failure Criteria

1. Bituminous Fatigue: Repeated tensile strain at layer bottom.
2. Subgrade Deformation: Repeated compressive stress at subgrade top.

E_i

The Role of Climate

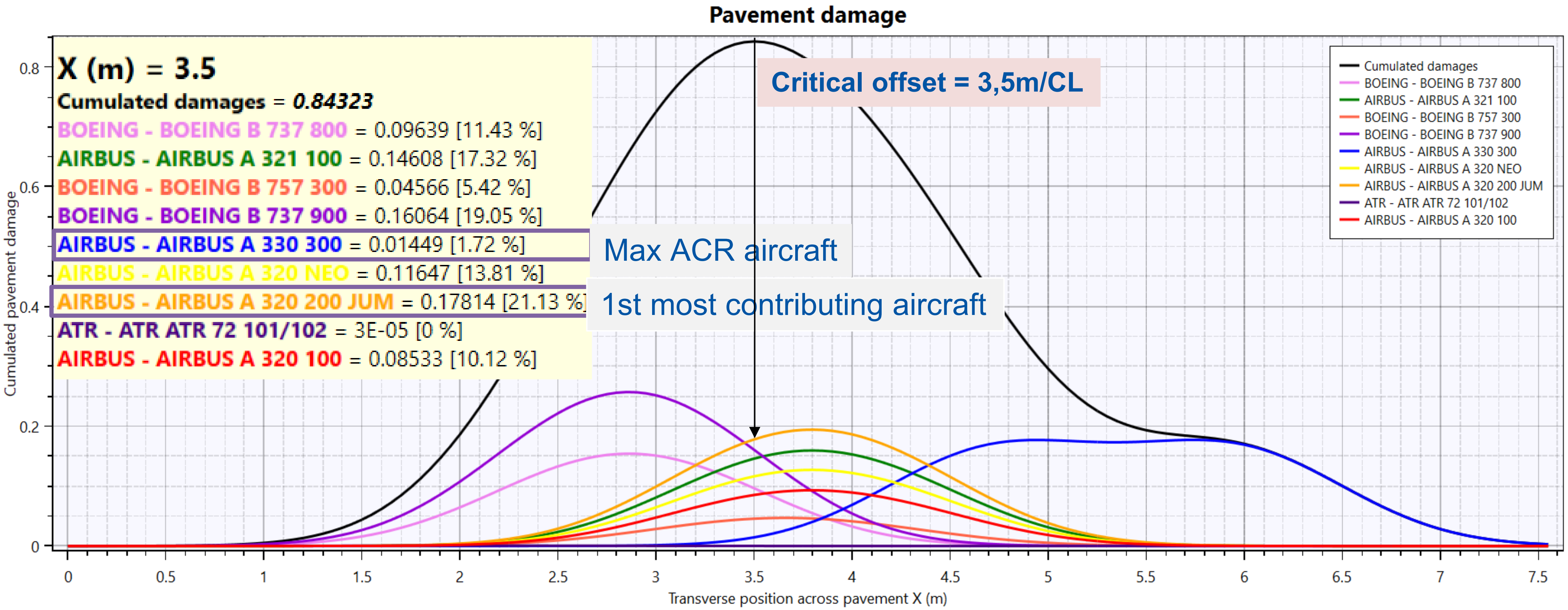
Elastic moduli (E) decrease with temperature, significantly increasing calculated strains and damages.

Cumulative Damage Factor (CDF) - 1

Universal Damage Model Does not exist, it depends on:

- The damage **criterion**
- The **elementary damage law** associated with the criterion
- The consideration of **multi-axle loads** (tandem wheels)
- The handling of **aircraft lateral wander**

Cumulative Damage Factor (CDF) - 2



X (m) = 3.5

Cumulated damages = ***0.84323***

BOEING - BOEING B 737 800 = 0.09639 [11.43 %]

AIRBUS - AIRBUS A 321 100 = 0.14608 [17.32 %]

BOEING - BOEING B 757 300 = 0.04566 [5.42 %]

BOEING - BOEING B 737 900 = 0.16064 [19.05 %]

AIRBUS - AIRBUS A 330 300 = 0.01449 [1.72 %]

AIRBUS - AIRBUS A 320 NEO = 0.11647 [13.81 %]

AIRBUS - AIRBUS A 320 200 JUM = 0.17814 [21.13 %]

ATR - ATR ATR 72 101/102 = 3E-05 [0 %]

AIRBUS - AIRBUS A 320 100 = 0.08533 [10.12 %]

Critical offset = 3,5m/CL

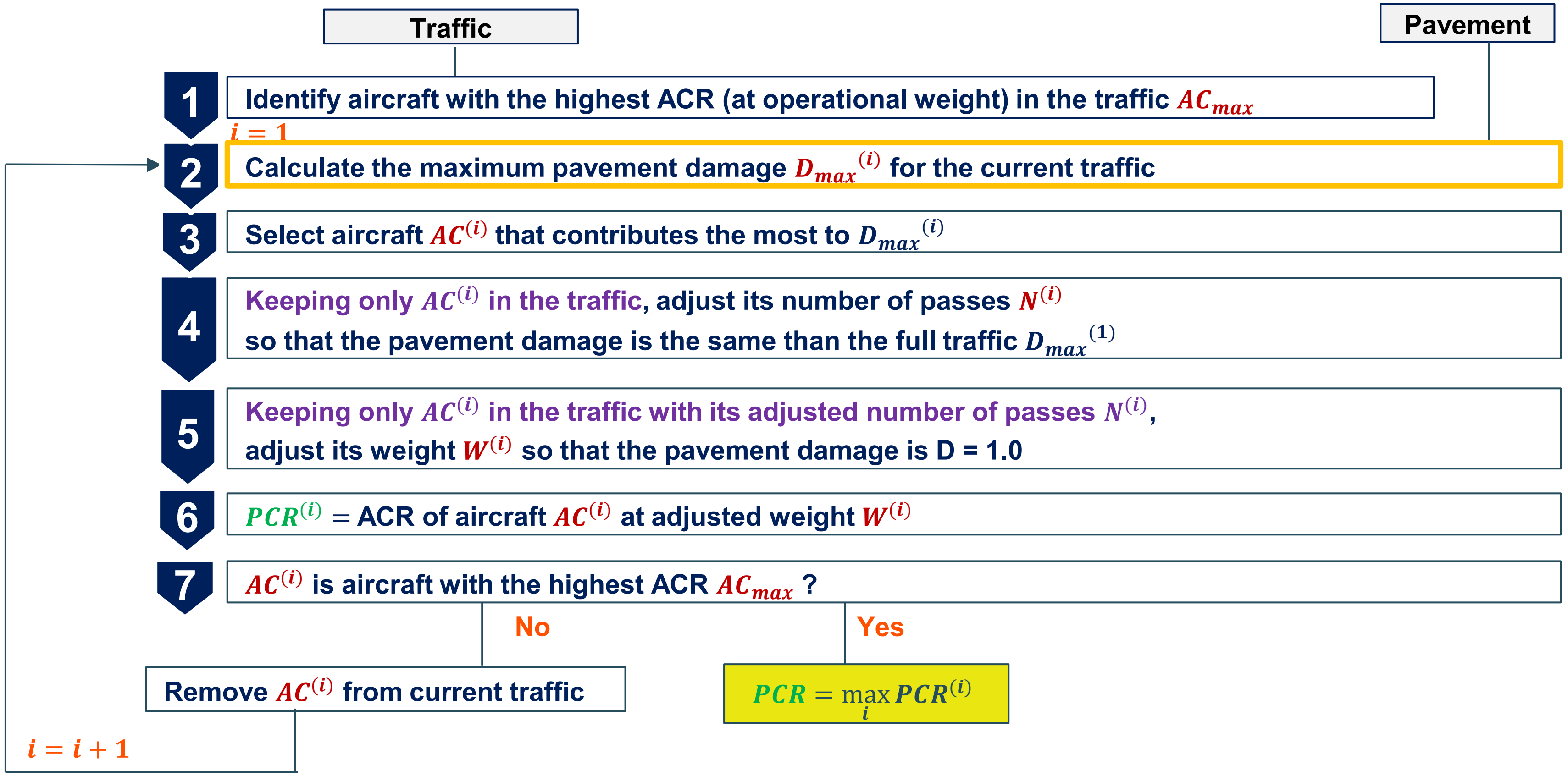
Max ACR aircraft

1st most contributing aircraft

PCR: 690/F/C

PCR determination

$D_{max.}$?



Traffic

Pavement

1 Identify aircraft with the highest ACR (at operational weight) in the traffic AC_{max}

$i = 1$

2 Calculate the maximum pavement damage ${D_{max}}^{(i)}$ for the current traffic

3 Select aircraft $AC^{(i)}$ that contributes the most to ${D_{max}}^{(i)}$

4 Keeping only $AC^{(i)}$ in the traffic, adjust its number of passes $N^{(i)}$ so that the pavement damage is the same than the full traffic ${D_{max}}^{(1)}$

Make aircraft equivalent to the full traffic

5 Keeping only $AC^{(i)}$ in the traffic with its adjusted number of passes $N^{(i)}$, adjust its weight $W^{(i)}$ so that the pavement damage is D = 1.0

Make equivalent aircraft compatible with the pavement

6 $PCR^{(i)}$ = ACR of aircraft $AC^{(i)}$ at adjusted weight $W^{(i)}$

7 $AC^{(i)}$ is aircraft with the highest ACR AC_{max} ?

No

Remove $AC^{(i)}$ from current traffic

$i = i + 1$

Yes

$PCR = \max_i PCR^{(i)}$

Computer programs: ALIZE, FAARFIELD, APSD, PCR 1.0 etc...

Cumulative Damage Factor (CDF) - 3

Inconsistent parameters for Design evaluation or PCR calculation – Examples:

Design Parameters	CDF	PCR (F/C/W/T)	Delta (%)	Structural life (Years)
Consistent with pavement design*	**0.84**	**690**	**Ref.**	**23.8**
Wandering with P-to-C ratio (1)	1.02	650	-5.8	19.6
FAA subgrade failure model (2)	0.43	710	2.9	46.5
(1) AND (2)=(3)	1.17	650	-5.8	17.1
T°(Corrected E) = 30°C (4)	2.41	500	-27.5	8.3
Frequency (speed) = 10Hz (100km/h) (5)	0.7	730	+5.8	28.6
(4) AND (5)=(6)	1.91	540	-21.7	10.5
(3) AND (6)=7	16.9	470	-31.9	1.2

*HMA@15°C/3Hz

Lateral wandering, standard deviation and subgrade failure model as per French practice

Thermal Cracking & Interface Bonding

Interface Debonding

Increased temperature lowers interface stiffness, accelerating fatigue and initiating cracks from the interface rather than the base.

Thermal Fatigue

Enhanced day-night temperature variations amplify heat shrinkage, initiating cracks that allow water ingress and subgrade degradation.

Asphalt Blistering

Water trapped into the AC may produce Blistering at the surface (then FODs) at high temperature due to vapor pressure

Rigid Pavements

Thermal Expansion & Slab Support

Load Transfer Conditions

Thermal Expansion

Increased mean slab temperature improves load transfer by promoting concrete expansion and joint contraction.

Stress Concentrations

Extreme day-night variations can damage load transfer systems (dowels, sinusoidal joints) at high-stress areas.

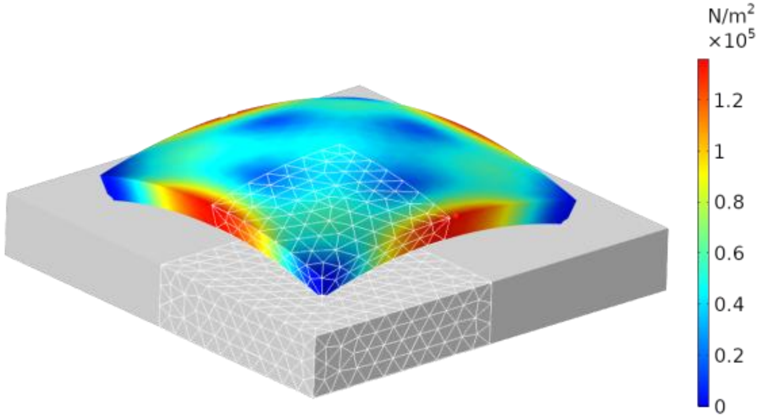
Slab Curling & Support Conditions

Vertical thermal gradients create differential expansion between the top and bottom of the concrete slab.

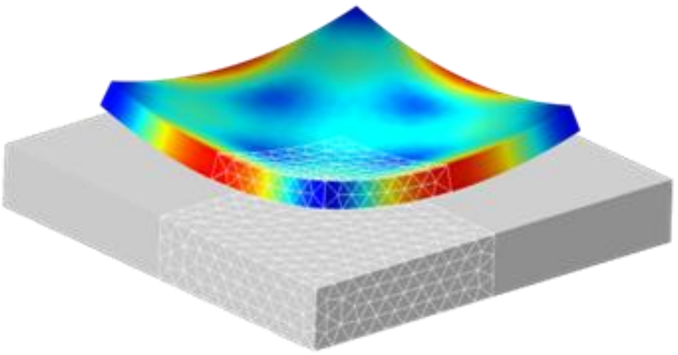
Day (Downward): Support shifts to slab corners

Night (Upward): Support shifts to slab center

Curling stresses can match traffic stresses in magnitude. Enhanced vertical gradients increase the risk of harmful thermal-mechanical combinations.



Downward (Day)$T_{Surface}>T_{bottom}$



Upward (Night)$T_{Surface}<T_{bottom}$

Thermal Expansion- Examples

Hungary - 12 July 2024 18:55

Hanover, 07/27/2018

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Subgrade Bearing Capacity

Moisture content directly dictates subgrade stability. Climate change threatens this through:

Rainfall Intensity: Increased frequency of extreme precipitation saturation layers.

Structural Risk: Water ingress through thermal cracks decreases resilient modulus.

Mitigation: Prioritize design and maintenance of drainage systems.

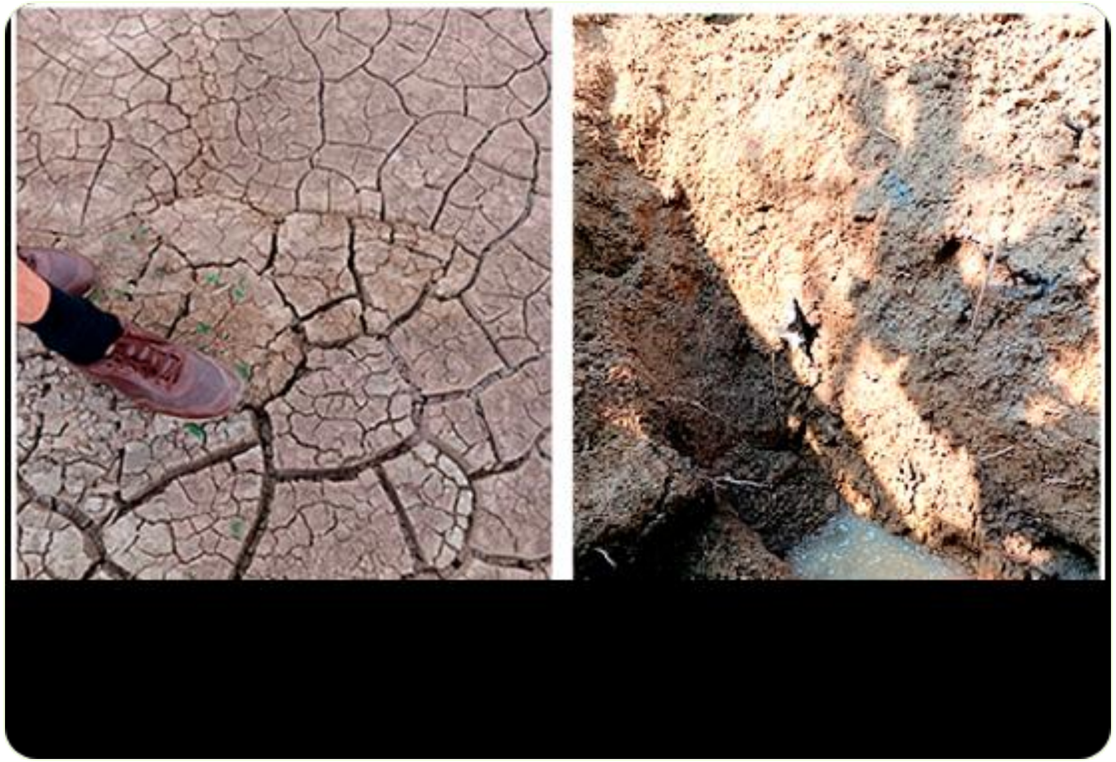
Swelling & Shrinkage Phenomena

A major concern for clayey subgrades exposed to drought-rainfall cycles.

Drought Effects: Accelerated shrinkage leads to differential settlement.

Rainy Alternation: Promotes harmful swelling.

Prevention: Soil testing (Methylene Blue Content), purging clayey areas, and using water-insensitive materials



Proposed Measures & Adaptation

- **Materials:** Adopt polymer-modified binders or hydraulic surface courses for static zones.
- **Design Evolution:** Transition to probabilistic methods incorporating future thermal profiles.
- **Equivalent Temperature** instead of using the Aerodrome Reference Temperature
- **Maintenance:** Rigorous care of drainage networks and joint sealing
- **Instrumentation:** Monitor in-service pavements with embedded temperature sensors

Pavements are primarily sensitive to aircraft loads, temperature, and moisture conditions. While these effects are well-documented, the combination of climate change and continuously rising air traffic is shifting the paradigm. This highlights the critical need for a global transition toward mechanistic-empirical design methods, moving away from purely empirical approaches that remain overly prevalent

Q&A

Thank you for your attention