A Mechanistically and Risk Based Design Method for Concrete Pavements

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Structural performance of concrete pavements

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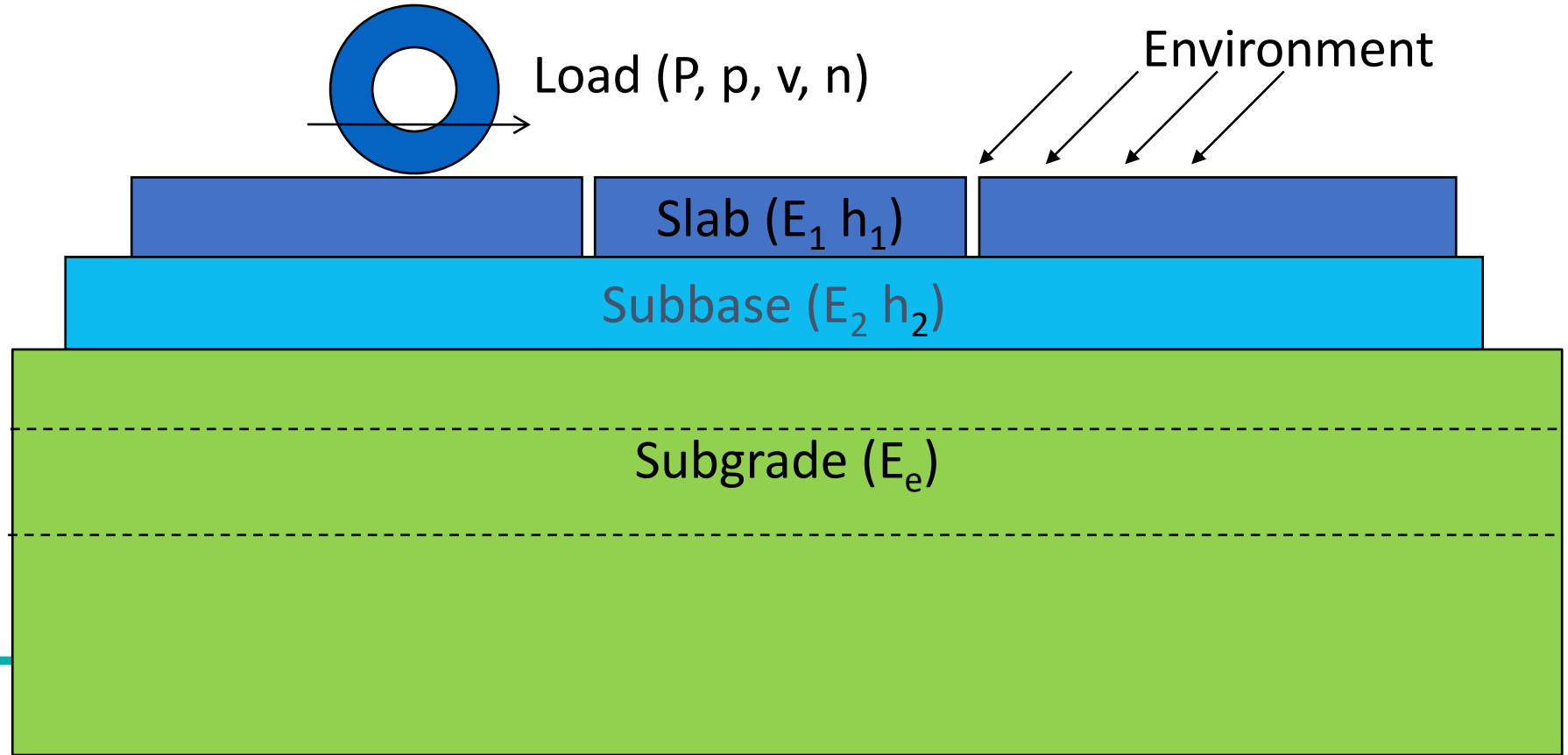
Newly paved concrete strip

Slab shrinks and cracks at intervals:



The concrete slab protects the subgrade against surface loading

- Surface load in terms of magnitude P, pressure p, speed v & number of loads n over time (fatigue)
- Stiffness of subgrade E_e dependent on layer thicknesses, soil type, moisture changes & stability
- Slab “stiffness” dependent on slab thickness & stiffness modulus of the concrete
- Environment (temp. & moisture) affects the slab movement, joint width etc.
- Big variations in the above: big risk of failure

Pavement Behaviour & Distress

- Concrete in strips shrinks & cracks
- Stress at cracks/joints due to wheel loading depends on load transfer to adjoining slabs
- Higher deflections occur at cracks/joints
- Water enters, reduce subbase stiffness & fines move (erosion and pumping)
- Temp. difference in slab creates curl & voids
- Loss in slab support increases stress: cracks
- Cracked slabs with pumping & faulting (shattered & faulted) need to be repaired

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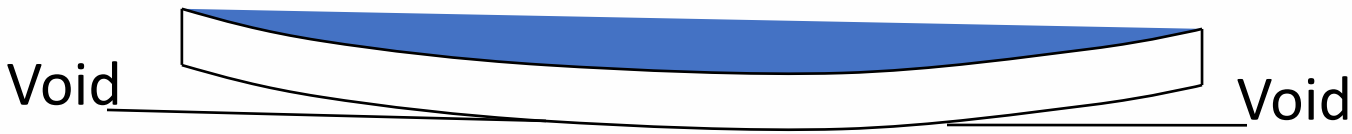
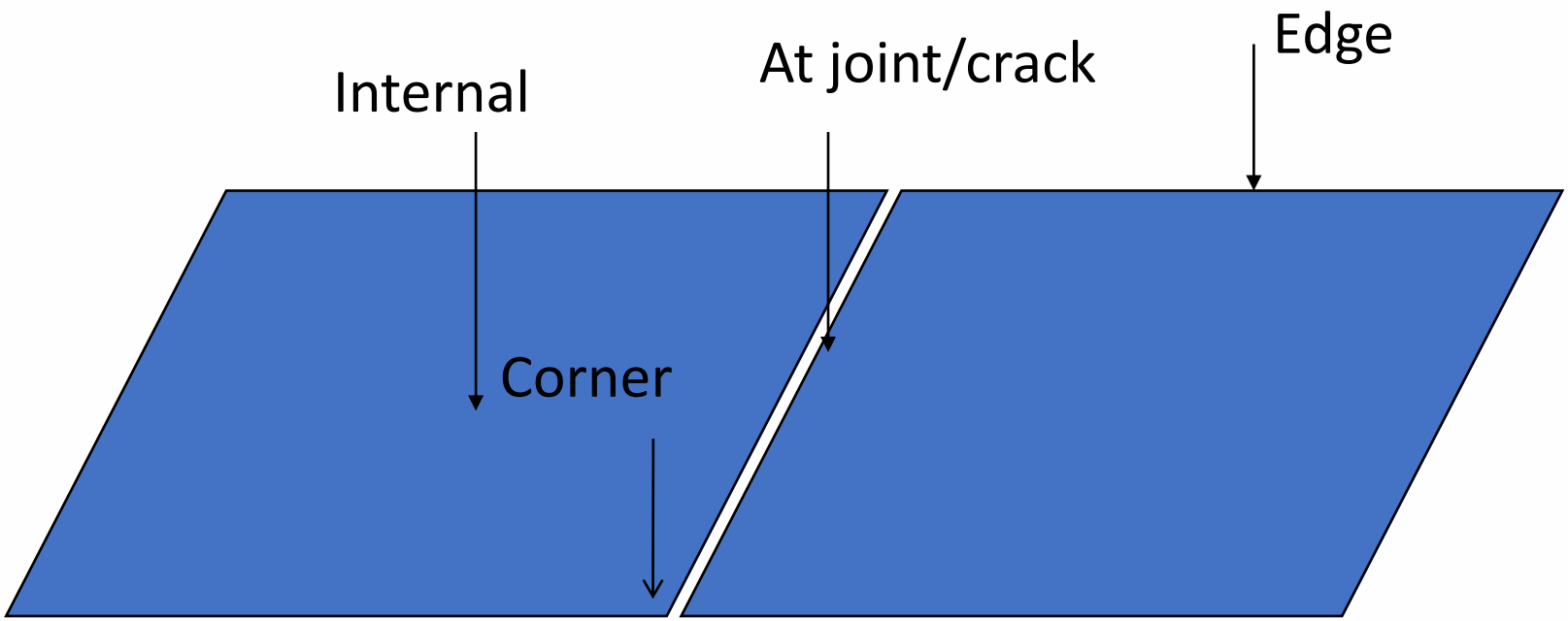
Environmental effect on slab

Shrink due to drying out and lower temp.
Expand due to wetting and higher temp.

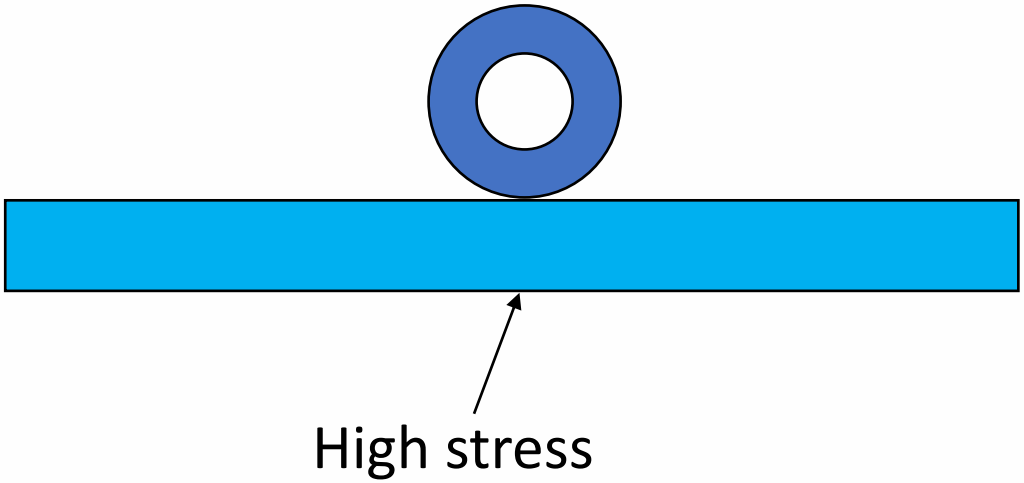


Curl: shrinks more at top

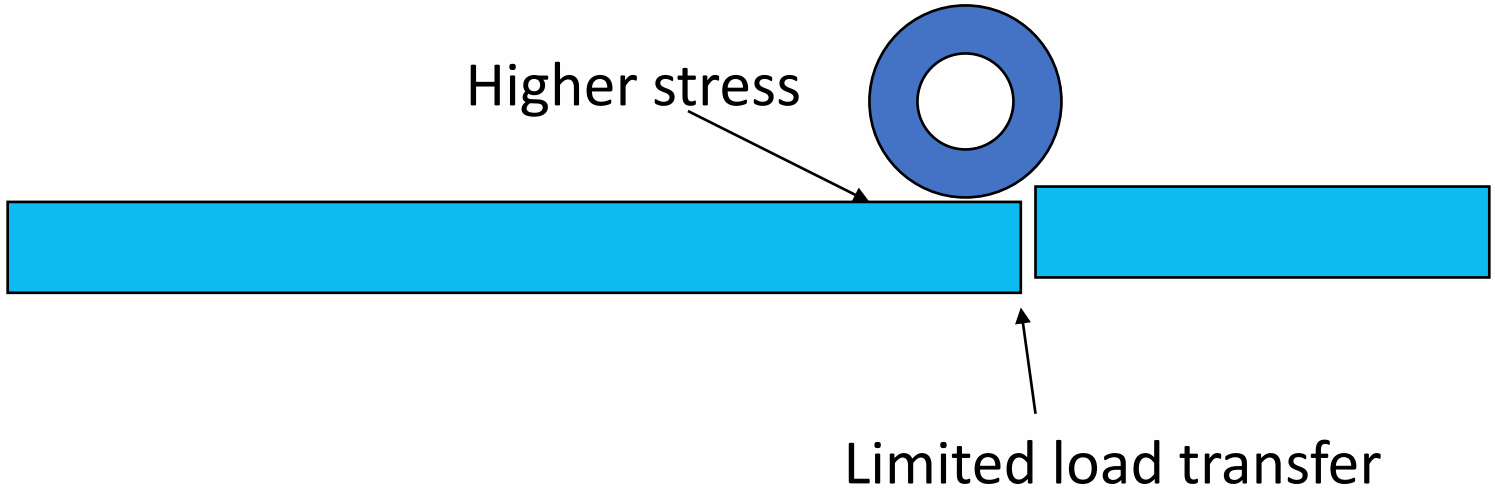
Surface Loading



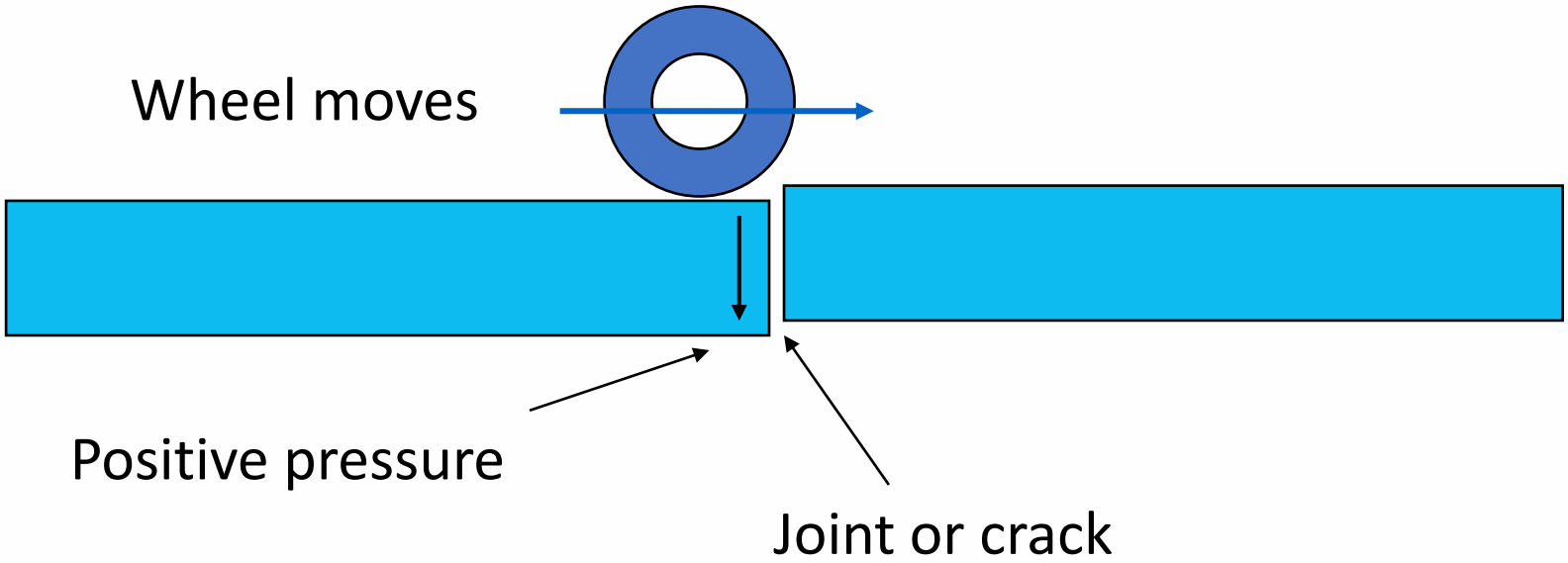
Internal loading



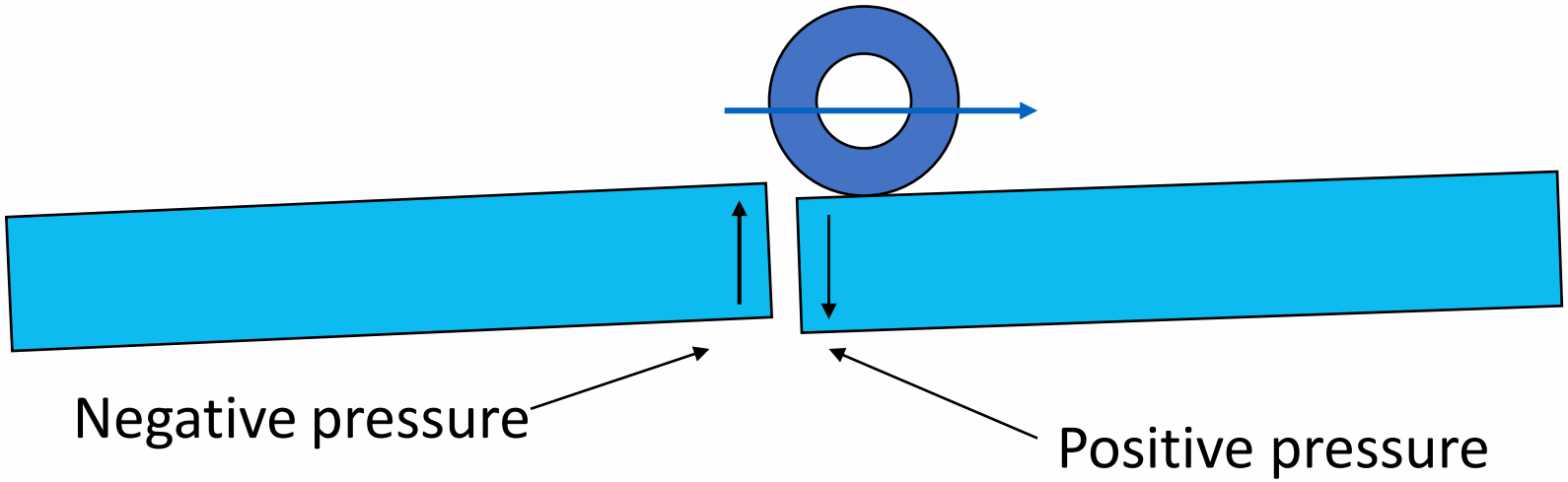
Loading at joint, crack or edge



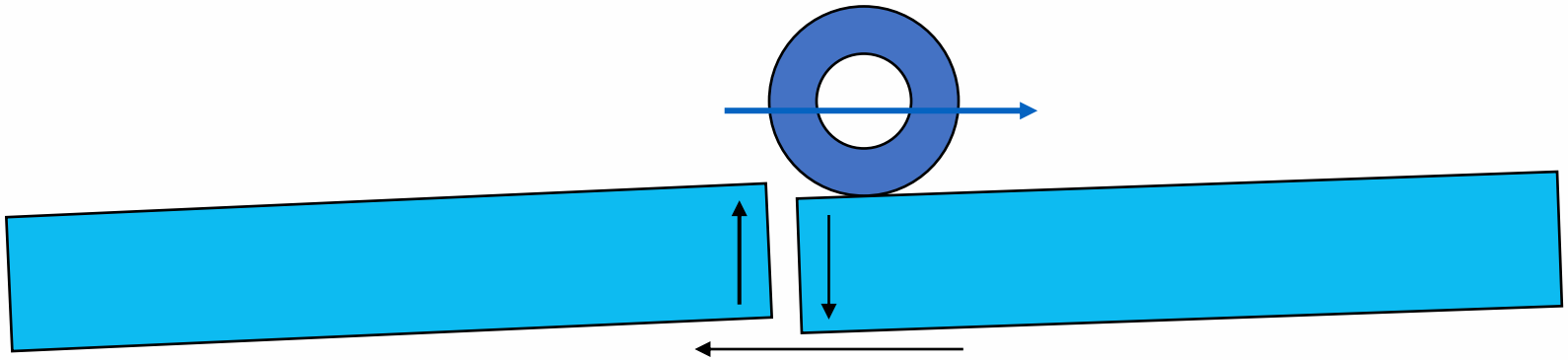
Wheel approaches joint or crack



Wheel crosses joint or crack

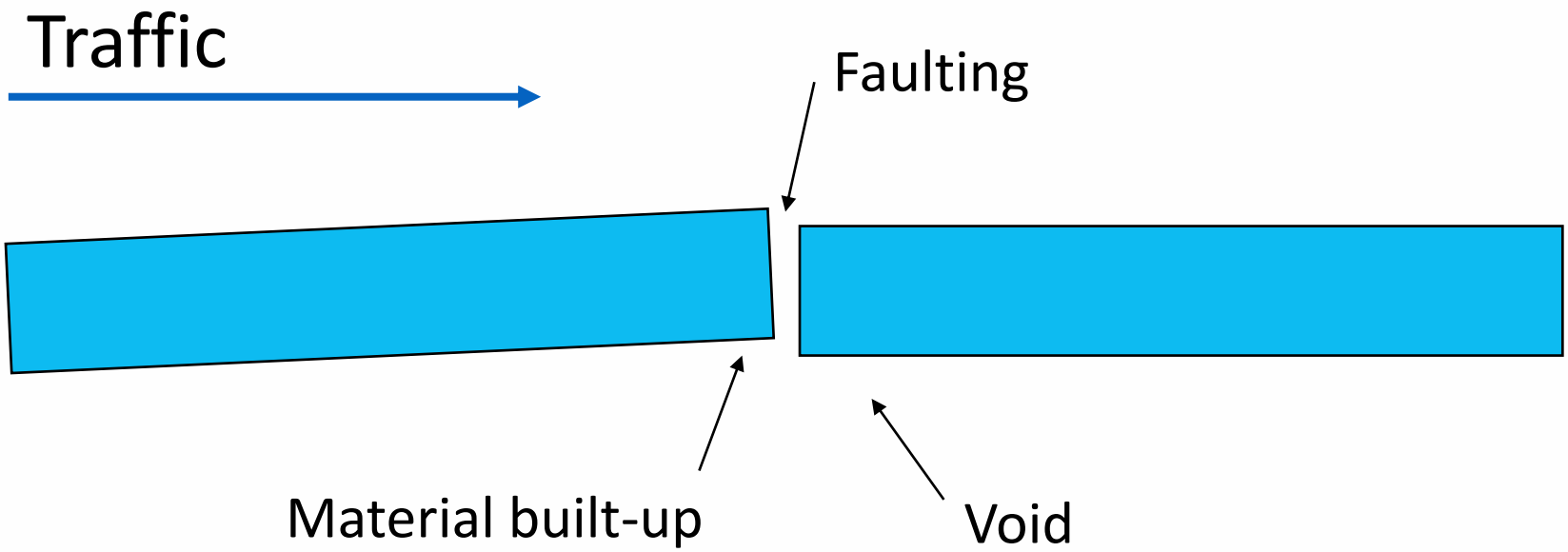


“Erosion” occurs

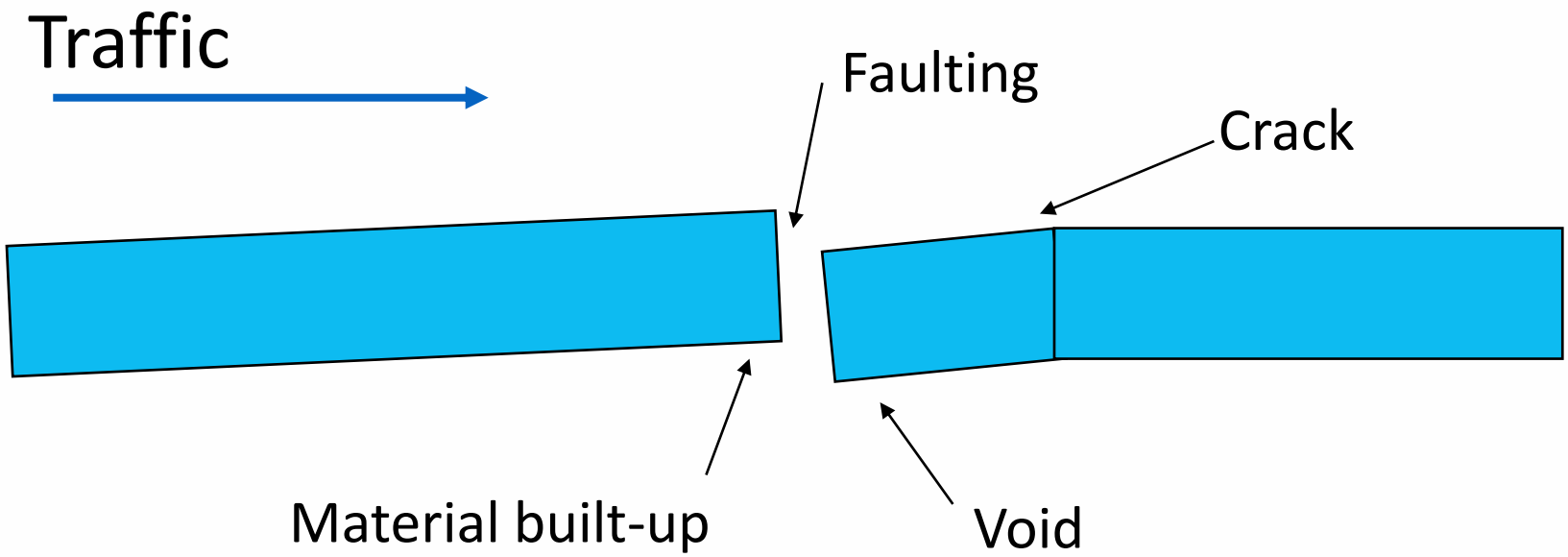


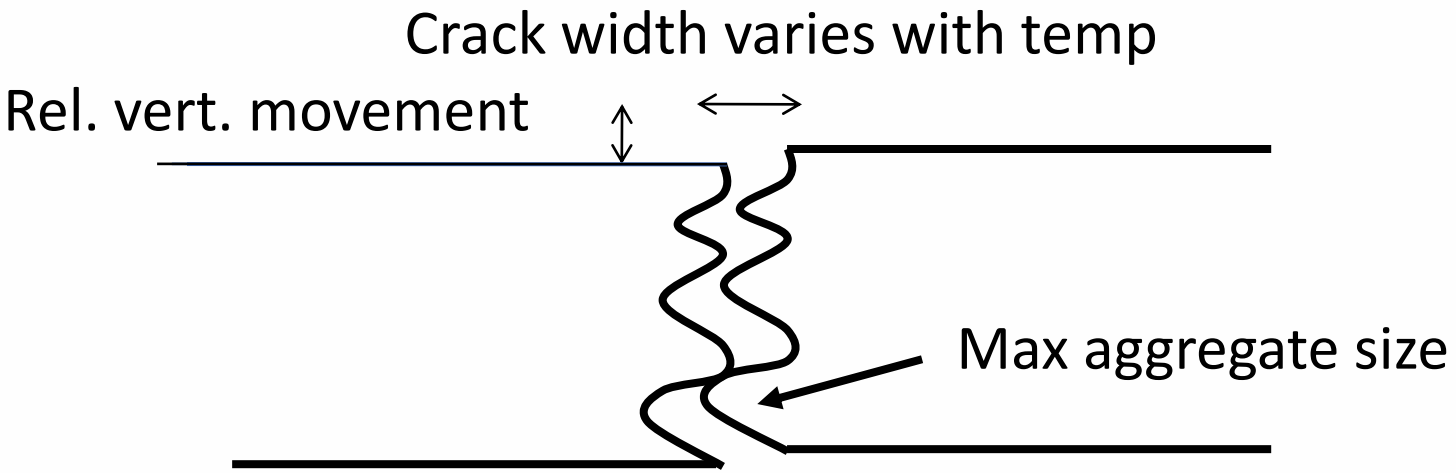
Water & subbase material moves

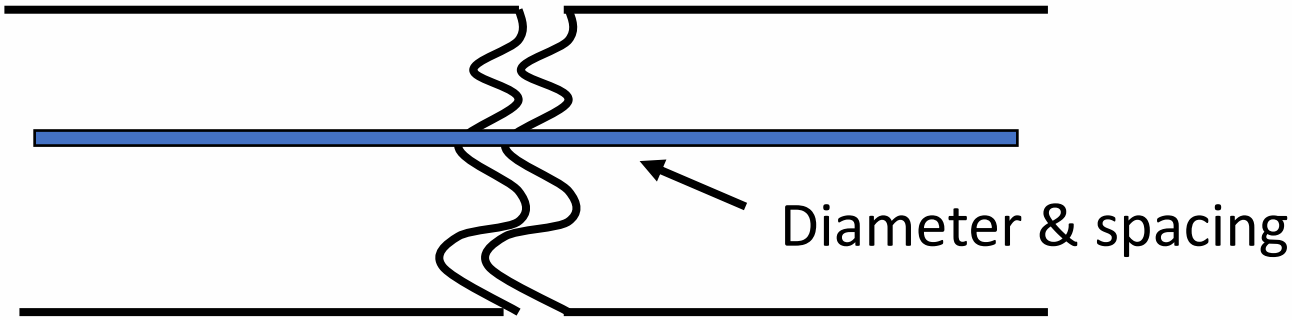
Faulting develops with time



Higher stress develops




Crack width varies with temp
Rel. vert. movement
Max aggregate size


Diameter & spacing

Jointed Concrete Pavements

- Plain jointed (J)
- Dowel jointed (D)
- Jointed reinforced (Europe)

Continuously Reinforced Concrete Pavements

- Continuously reinforced (CRCP, CR)
- Ultra-thin continuously reinforced (UT)

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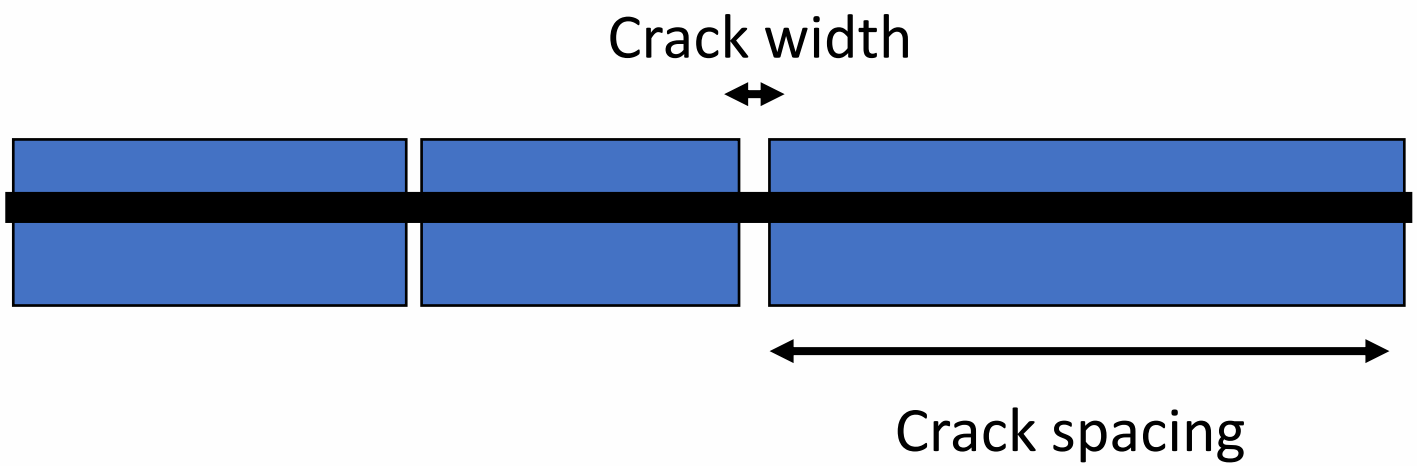
Continuously reinforced

Balance between % steel & concrete strength



Summary: Performance of Pavements

- Concrete in strips shrinks & cracks
- Stress at cracks/joints due to wheel loading depends on load transferred to next slab
- Higher deflections occur at cracks/joints
- Water enters, reduce subbase stiffness & fines move (erosion and pumping)
- Temp. difference in slab creates changes in crack width, curl & voids
- Loss in slab support increases stress: cracks
- Cracked slabs with pumping & faulting need to be repaired (shattered)

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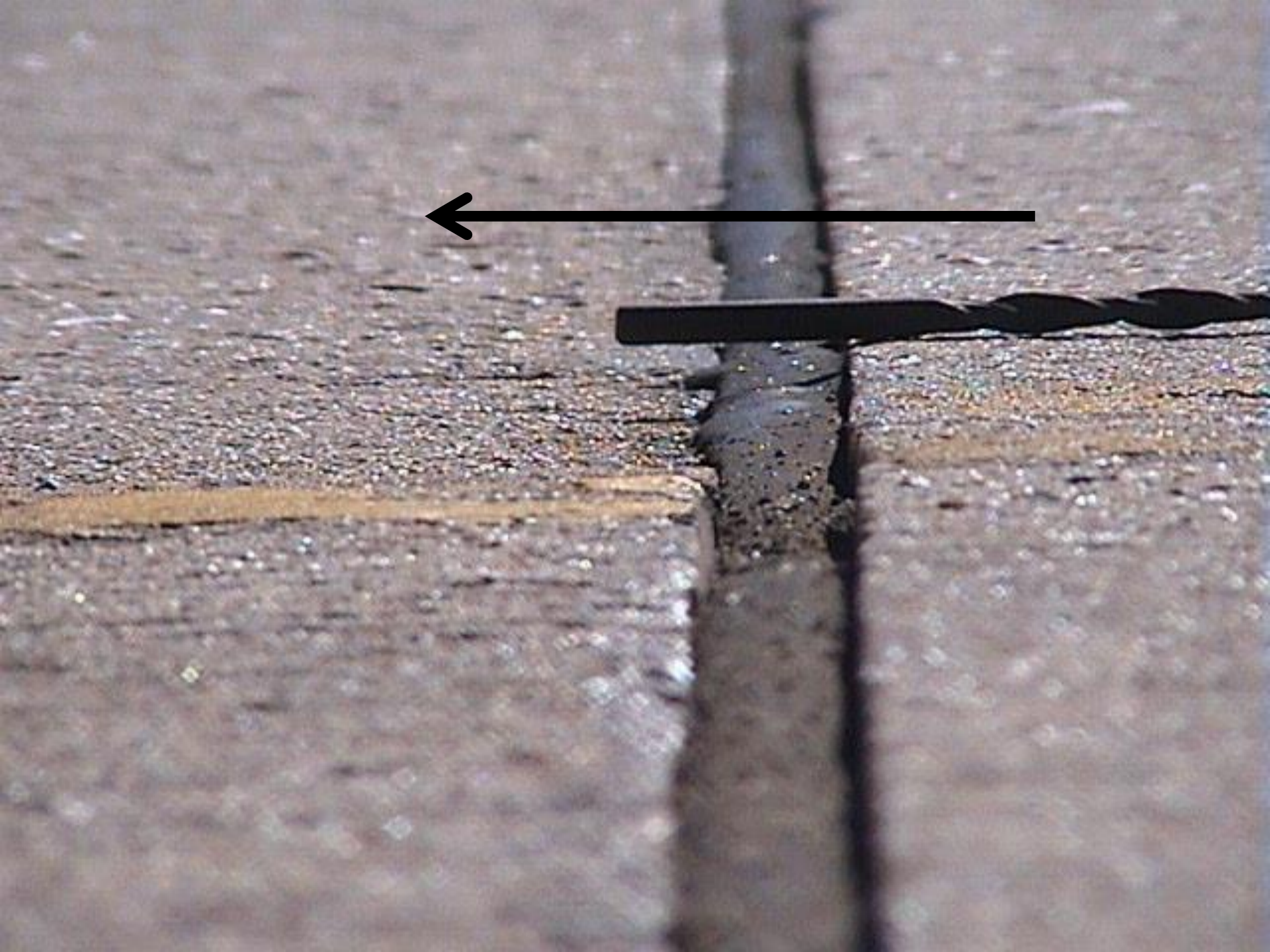
STOP



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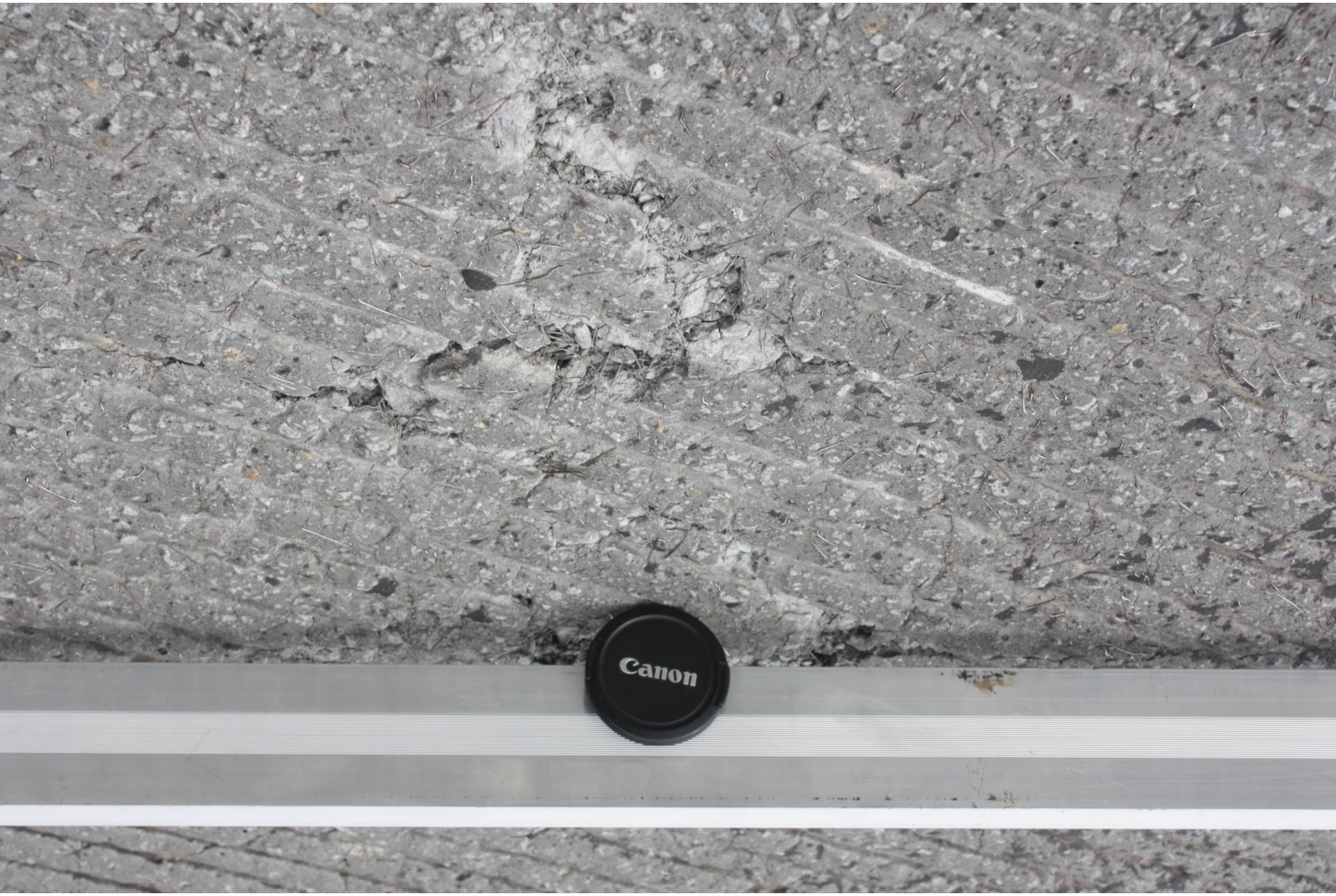
Canon

Design Methods for Concrete Pavements

The following methods primarily used for road and street design, are to be discussed:

- M10 (1990 to 2005)
- cncPAVE (1999 to present)

Design method:
M10

M10 Design Manual

- Axle group loading
- Stiffness moduli used for slab support layers
- Nomograph to get equivalent support stiffness
- Nomograph to determine relative vertical movement at joint/crack (load transfer)
- Nomograph to obtain slab thickness
- Guidance on specifications

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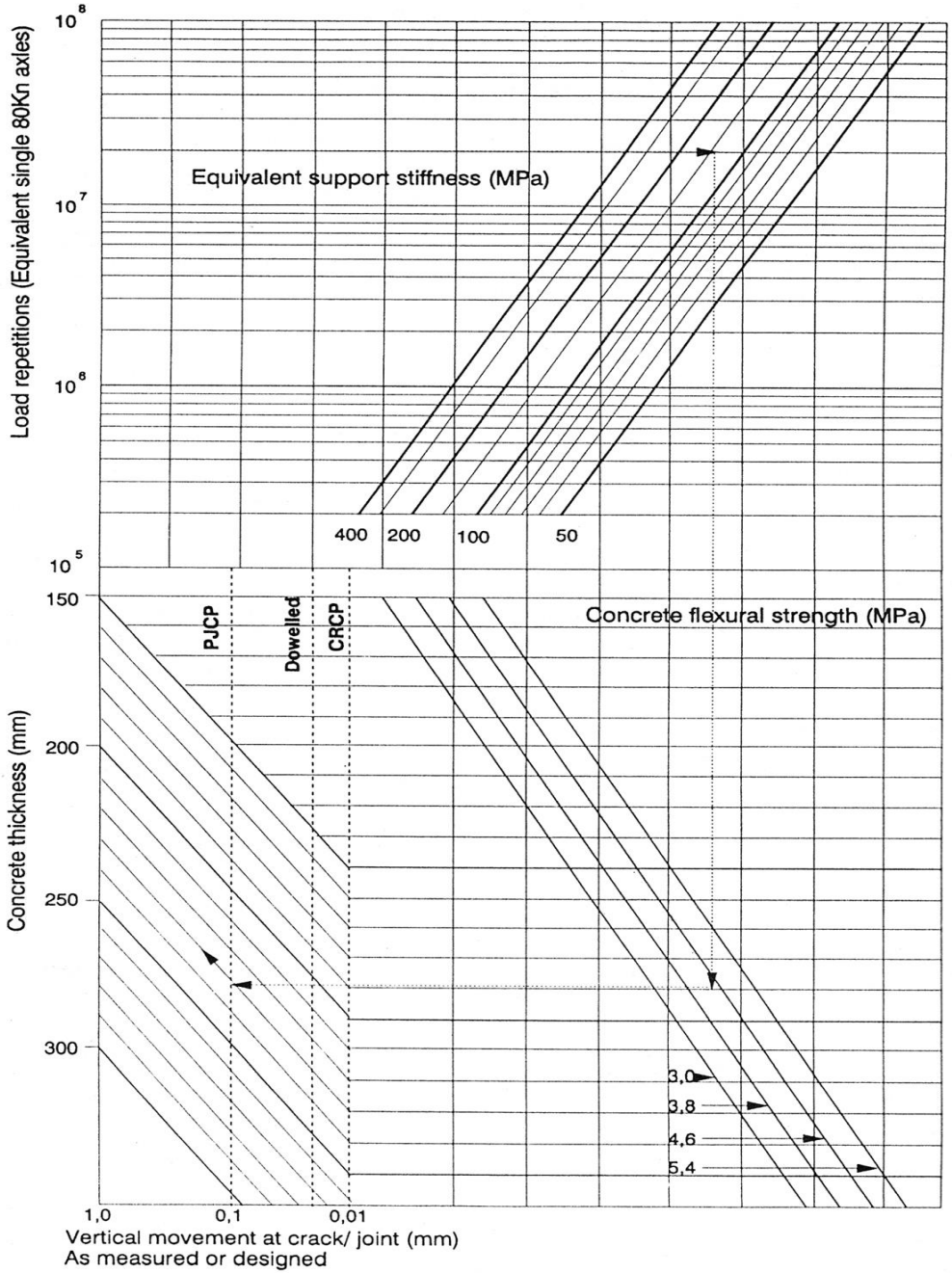

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Design method: cncPave

Basic Principles

The cncPAVE program is based on mechanistic principles :

- Input parameters: Variables & constants
- Calculate max. stress in pavement & its behaviour (deflections, relative vert. movement at cracks) under loading
- Predict performance
- Calculate life cycle costs

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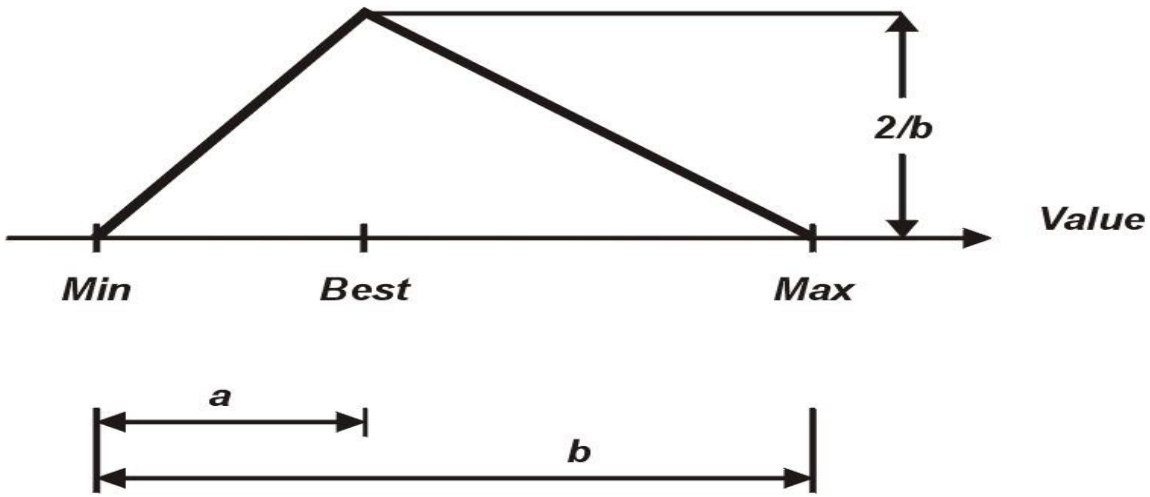
Variation of Input Parameters



$$\text{mean} = (a + b)/3$$
$$\text{variance} = (a^2 - ab + b^2)/18$$

Stress and Performance

$$Stress = f\left(C, \frac{P}{h_1^{\,2}} \sqrt[4]{\frac{Ec}{Ee}}\right)$$

$$\textbf{Life N} = \textbf{a}\left(\frac{\text{stress}}{\text{strength}}\right)^{b}$$

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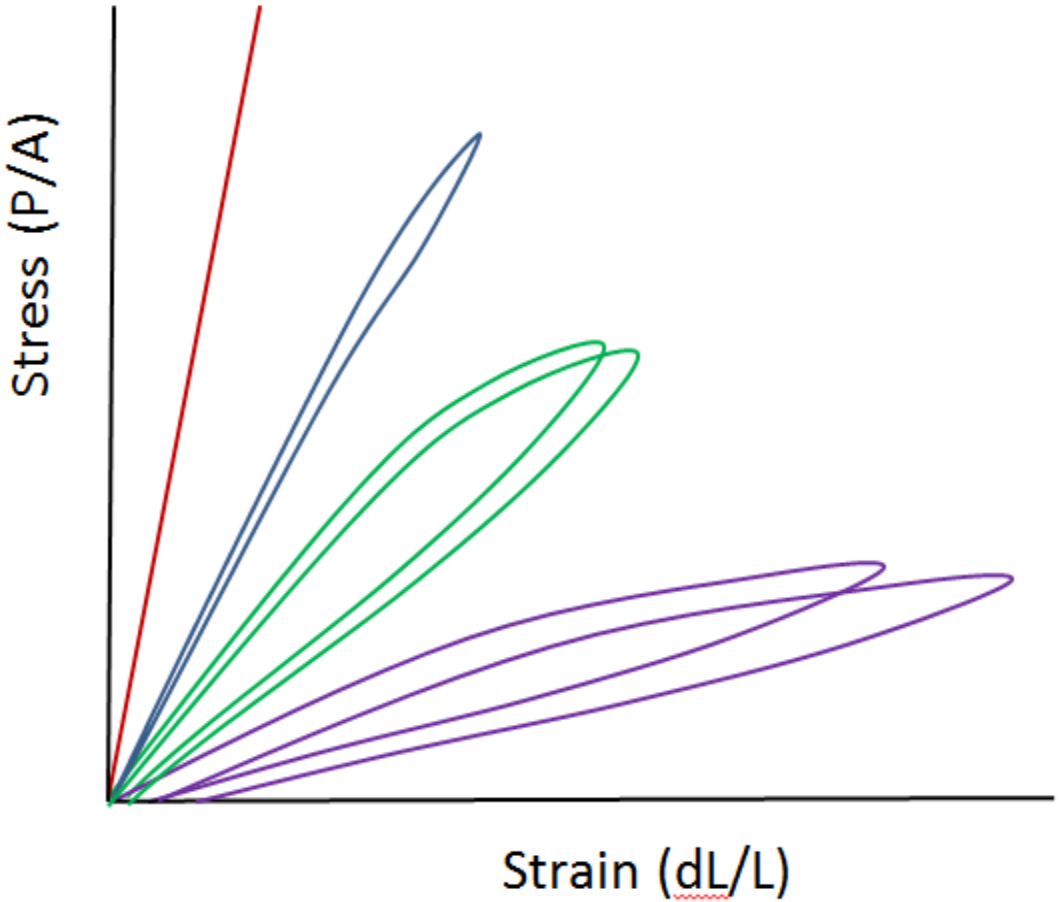
Stiffness E (Stress/Strain)



Calculating the Stress

Sub-models were developed separately for:

- load transfer through aggregate interlock and dowel action (C)
- combination of sub-layers to form equivalent subgrade stiffness (Ee)
- curling & the development of voids
- effect of different loads and surface pressures (P, p)

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Load transfer: C

$$C = (0.04d_y)^{0.43}$$

d_y for aggregate = f (crack width, aggregate size)

d_y for steel = f (dowel action of steel)

C = 0.16 for interior loading

C = 0.55 for edge loading

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Load transfer by Aggregate: Ca

dy = f {L, n, Weath, sh, T, Agg}

L = Joint/crack spacing

n = load applications (time)

Weath = rainfall + humidity

sh = initial shrinkage of concrete

T = variation in temperature

Agg = aggregate size

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Crack or Joint Spacing : L

For CRC: L = f {dia, ITS, spac, bond, sh, n}

For Jointed: L = transverse joint spacing

dia = diameter of steel

ITS = concrete tensile strength

spac = spacing of steel bars

C1, a, b, e = constants & power coefficients

sh = shrinkage

bond = bond between slab and subbase

n = load application

Shrinkage: sh

sh = f {wat, h, f, aggc, cem, t, hum, T }

h = slab thickness
f = flexural strength
wat = water content
aggc = coarse aggregate content
cem = cement content
hum = humidity
t = time
T = temperature

Load transfer by Steel: Cs

dy = f {P, n, spac, E, dia }

P = wheel load

n = number of load applications

spac = spacing of steel

E = concrete stiffness

dia = diameter of steel

Slab Support

- Convert the stiffness of the sub layers into a two-layer system:
  subbase (E_2) & subgrade (E_e)
- Voids below slab due to curling & subbase erosion

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Equivalent Slab Support: Ee

$$Ee = E_5\,[E_3/E_5]^{h3}.[E_4/E_5]^{h4}$$

E = stiffness values of different layers

h3 = thickness of layer 3

h4 = thickness of layer 4

Slab Curl

Curl = f {bond, E1, T, sh, E2, L, h, Weath}

bond = bond between slab & subbase

E1 = slab stiffness

T = variation in temperature

sh = shrinkage of concrete

E2 = subbase stiffness

L = joint/crack spacing

h = slab thickness

Weath = rainfall & humidity

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Void under Slab

Void = f {Curl, y, Weath, Drain, C, E_2, Ero}

y = deflection at joint/crack

Drain = draining capability of pavement

C = load transfer constant of joint/crack

E_2 = subbase stiffness

Ero = erosion characteristics of subbase

Weath = environmental influence (rain & humidity)

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Slab Stress at Joint/crack (Ss)

$Ss = f\{P, p, v, h, C, E_c, h_2, E_2, bond, E_e, Void\}$

P, p = wheel load & tyre pressure

v = speed of loading

h = slab thickness

E_c = slab stiffness (function of flexural strength)

C = load transfer coefficient

h_2, E_2 = subbase thickness & stiffness

Bond = bond between slab and subbase

Void = void between subbase and slab

E_e = subgrade (below subbase) stiffness

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Deflection of the Slab: y

$Ss = f\{P, v, edg, h, C, E_c, h_2, E_2, E_e, Void\}$

P = wheel load & tyre pressure

v = speed of loading

edg = percentage edge loading

h = slab thickness

E_c = slab stiffness (function of flexural strength)

C = load transfer coefficient

h_2, E_2 = subbase thickness & stiffness

Void = void between subbase and slab

E_e = subgrade (below subbase) stiffness

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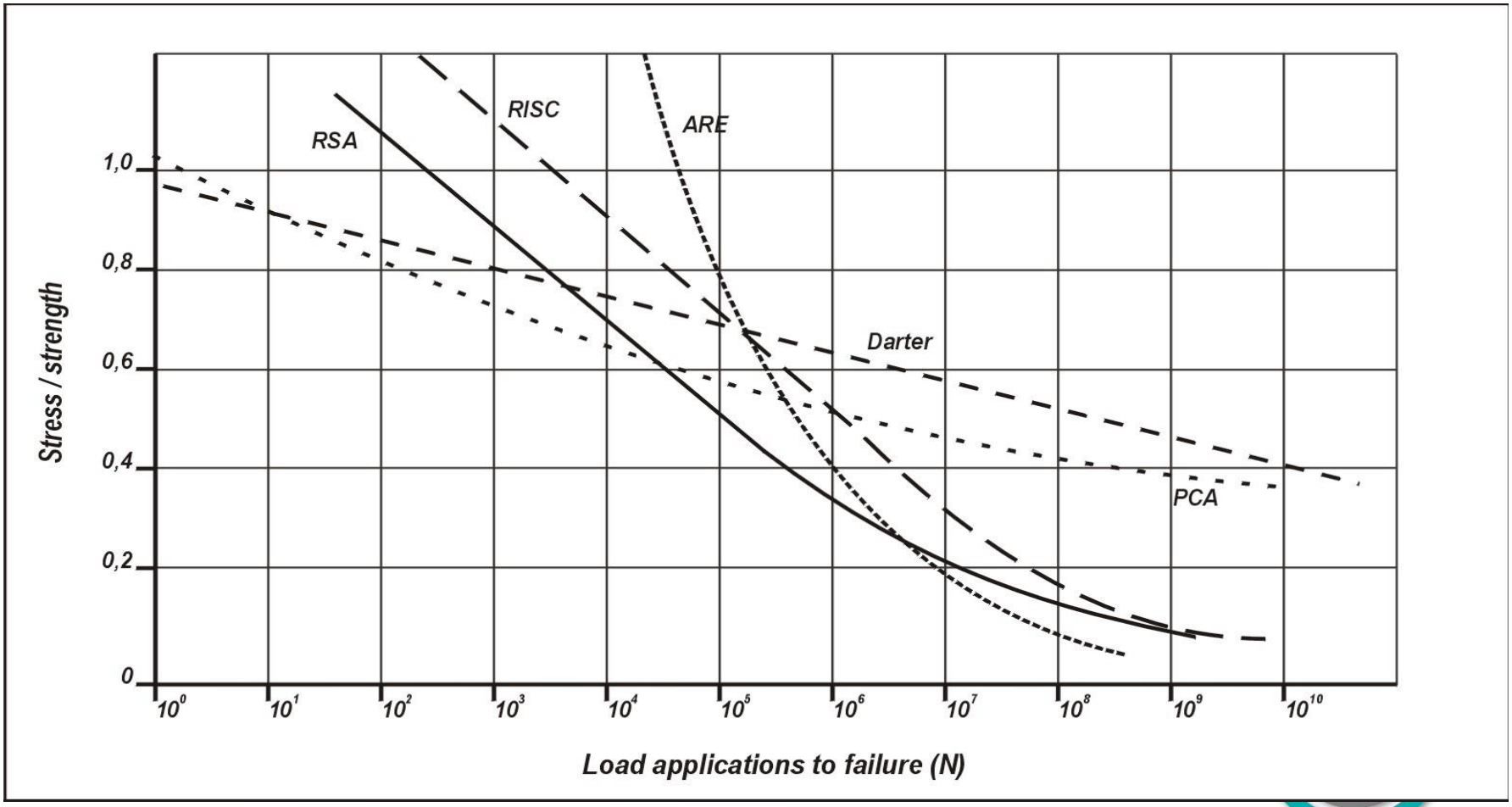
Structural Performance

$$\textbf{Life N} = \textbf{a}\left(\frac{\text{stress}}{\text{strength}}\right)^{b}$$

Structural Performance



Structural Performance

- N is the number of loads that the pavement can take
- n is the number of loads applied
- Failure whenever n>N

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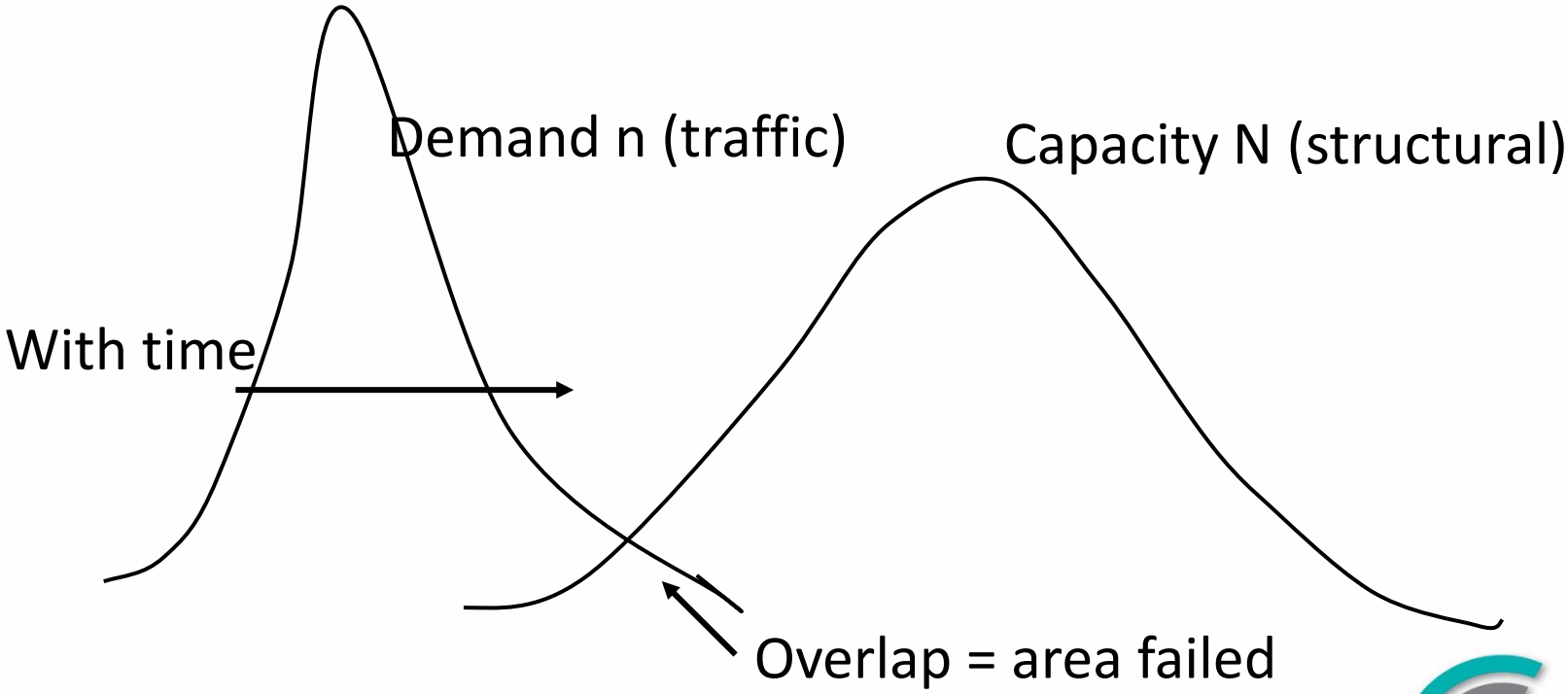
FAILED WHERE n > N



% Shattered Slabs

% SH= % (n/Nc >1) + % (n/Np >1)

n = traffic loading

Np = no of loads to unacceptable pumping

Nc = no of loads to unacceptable cracking

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Pumping (erosion)

$N_{Pumping}$ = f {drain, Weath, ero, y, C}

drain = drainage of the pavement

Ero = erosion characteristics of subbase

Weath = environmental influence (rain & humidity

y = deflection at joint/crack

C = load transfer constant

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Summary

Performance (shattered slabs) depend on:

- Loading (number of loads, magnitude of loads, surface pressure & speed of loading)
- Stiffness of the slab which includes the load transferred at joints or cracks
- Slab thickness and flexural strength
- Stiffness & erosion of the subbase
- Stiffness of the lower layers
- Environment
- Variation in the above parameters (Construction?)

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Summary (continue)

Pumping, erosion, voids and faulting a function of:

- Deflection at joint/crack under traffic loading
- Erodibility of the slab support
- Permeability of the joints & cracks to surface water and pavement capability to drain it
- Environmental factors eg. rainfall, humidity

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Conclusion

A shattered slabs is only a function of a loss in slab support and overstressing of the slab under traffic loading UNLESS environmental factors during and after construction resulted in unwanted early cracking.

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Calculations using cncPave

Repetitive Calculations

- Random selection of a value within the distribution for each variable
- Calculate Np, Nc, Nf
- The percentage of cases where n exceeds N, represents area of pavement distressed

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Life Cycle Costing

- Analysis period normally 40 years
- Period (time) to first rehabilitation also determines the acceptable standards for area shattered, faulted and pumping (20 years)
- Compare types of concrete pavements: performance and life cycle costs
- Road user's cost (riding surface, maintenance, rehabilitation, time)?

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Typical Designs (for same sub- layers)

Type

- Jointed (J)
- Dowel jointed (D)
- Cont. reinforced (CR)
- UT (thin CR + fibre)
- UT (thin CR no fibre)

Thickness / E80's

- 240mm for 33 million
- 215mm for 33 million
- 200mm for 33 million
- 55mm for 43 million
- 50mm for 0.7 million

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Typical Designs (continue)

Type

- Jointed (J)
- Dowel jointed (D)
- Cont. reinf. (CR)
- UT (thin CR + fibre)
- UT (thin CR no fibre)

Reinforcement

- None
- 32mm @ 300mm at joints
- 16mm @ 160mm spacing
- 5.6mm @ 50mm + 80kg steel fiber
- 5.6mm @ 200mm spacing

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Demonstration of cncPAVE