Active Design in Road Building

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Rutting and unevenness in roads have been a problem in many thousand years

Road building

Investment cost	New technique 3 % per year or 15 % in 5 years	System costs 5%	Unnecessary costs 10 %	Error costs 10 %

Investigation from Chalmers University of Technology

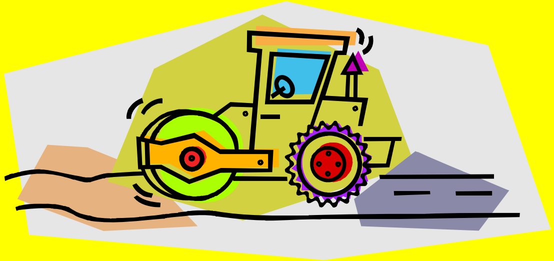
saving POTENTIAL (inside 5 years) 40 %!

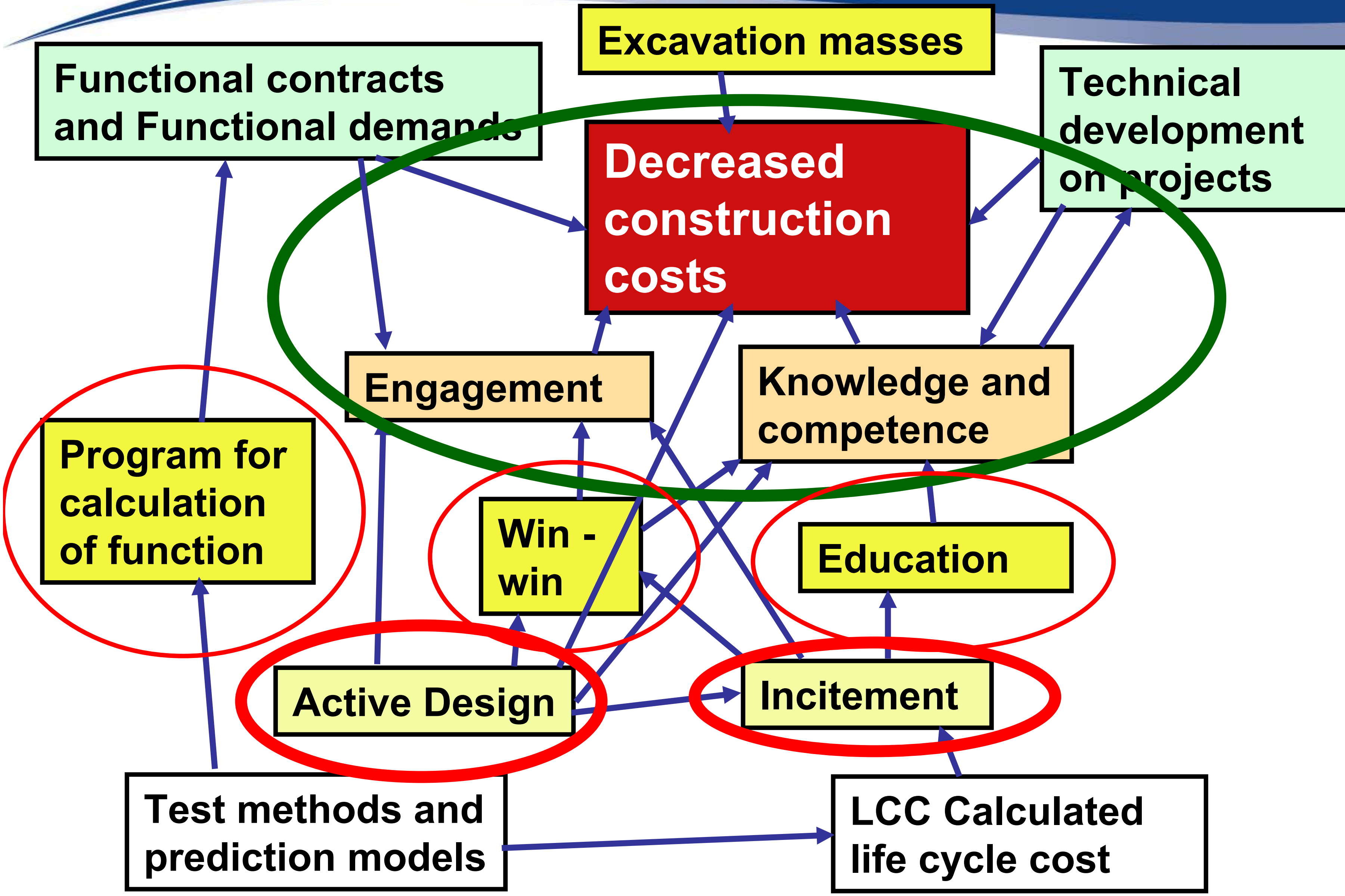
Implementation of new technique

Research

Where are the resources here?

Real design and construction of roads




Excavation masses
Functional contracts and Functional demands
Decreased construction costs
Technical development on projects
Engagement
Knowledge and competence
Program for calculation of function
Win - win
Education
Active Design
Incitement
Test methods and prediction models
LCC Calculated life cycle cost

IMPLEMENTATION MEASURES

Necessary measures in order to succeed with implementation of research results

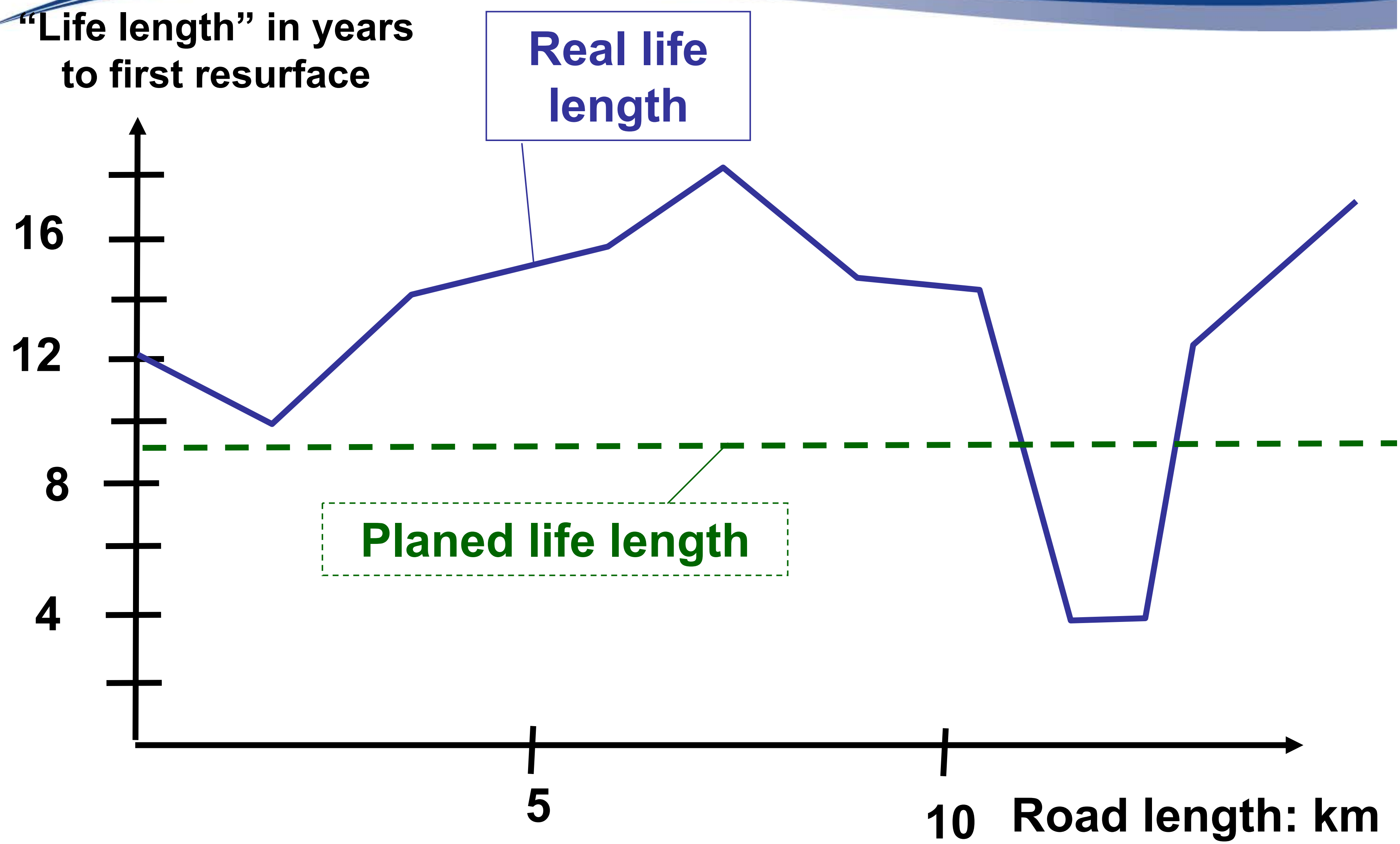
Training course in road design and practical road building: 30 consultants and contractors

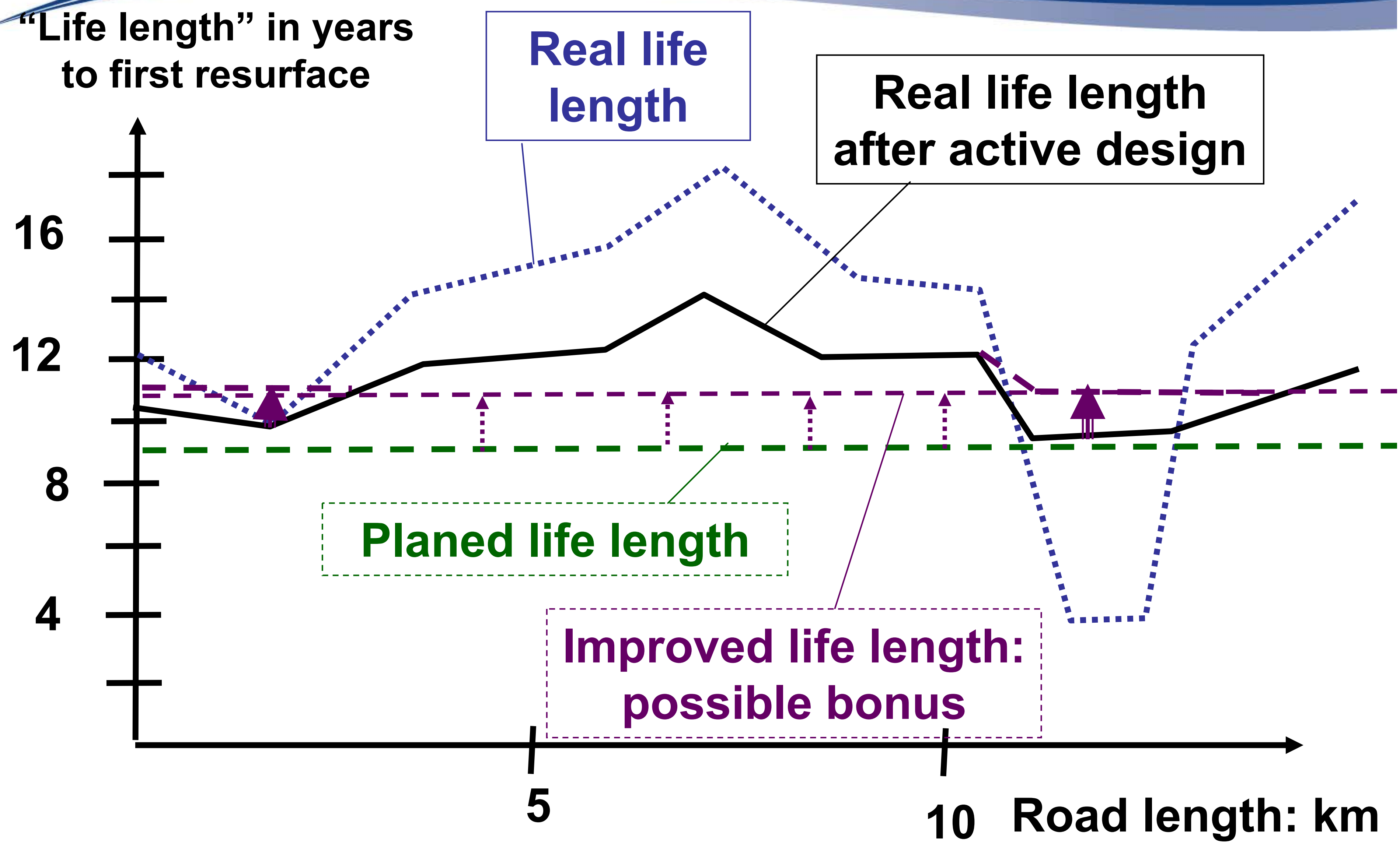
Measuring methods used: Triaxial test, Plate loading and Instrumented roller compactor

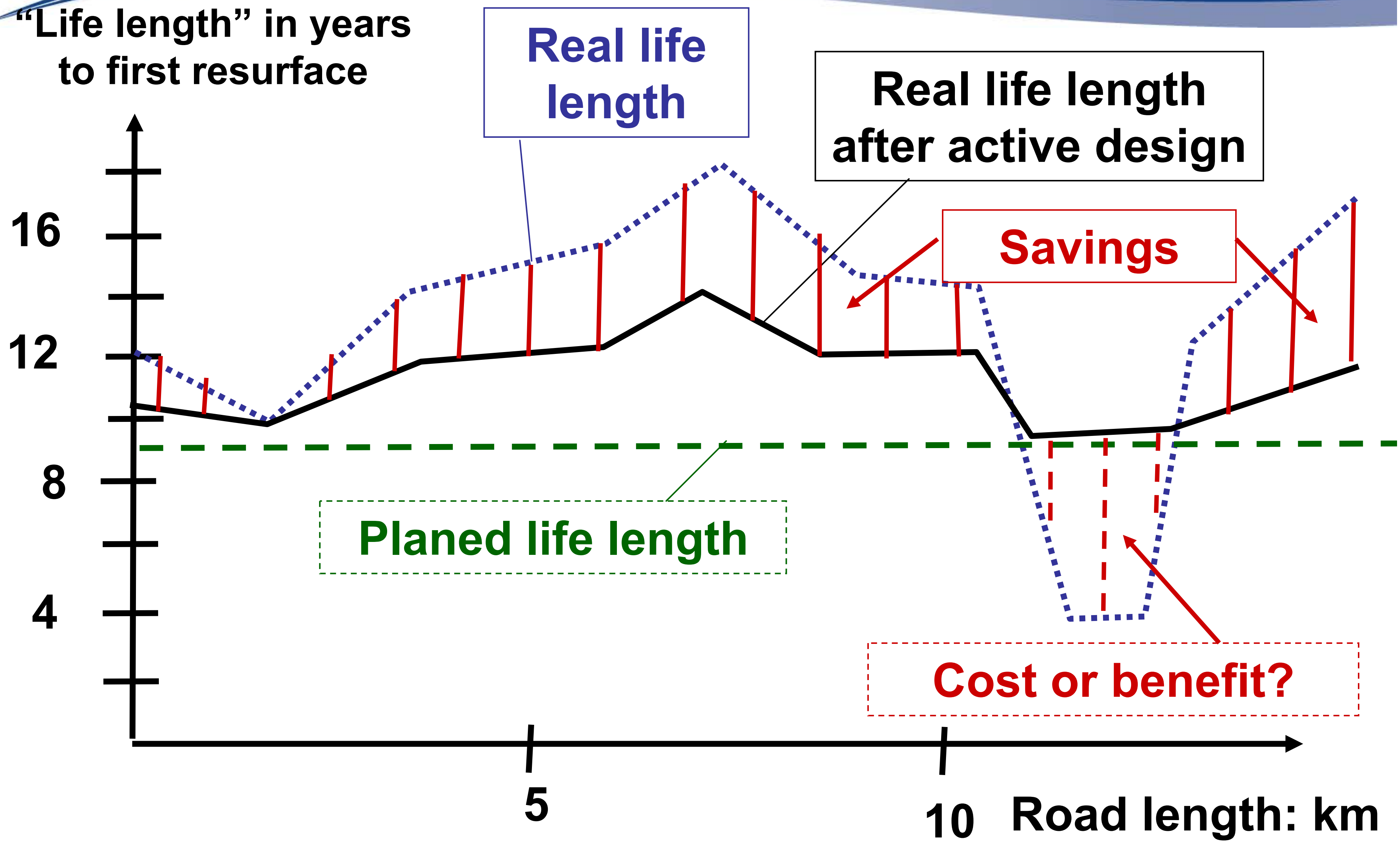
New design models: VägFEM and newly developed Excel programs to calculate rutting

Incentives for better quality: reduced asphalt thickness – better bearing capacity on top of unbound material

Active Design

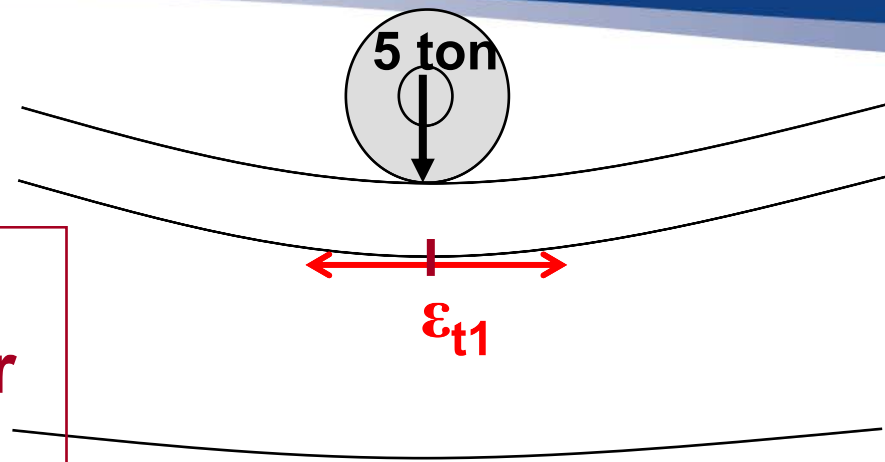

"Life length" in years
to first resurface
Real life
length
16
12
8
4
Planed life length
5
10
Road length: km


"Life length" in years
to first resurface
Real life
length
Real life length
after active design
16
12
8
4
Planed life length
Improved life length:
possible bonus
5
10
Road length: km


"Life length" in years
to first resurface
Real life length
Real life length after active design
Savings
16
12
8
4
Planed life length
Cost or benefit?
5
10
Road length: km

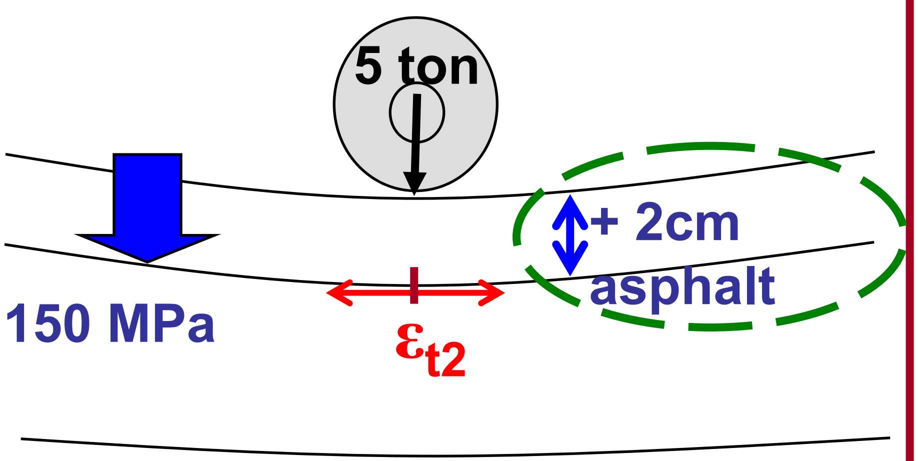
FATIGUE OF PAVEMENT

Improved life length of; lower ε_{t1} to ε_{t2}

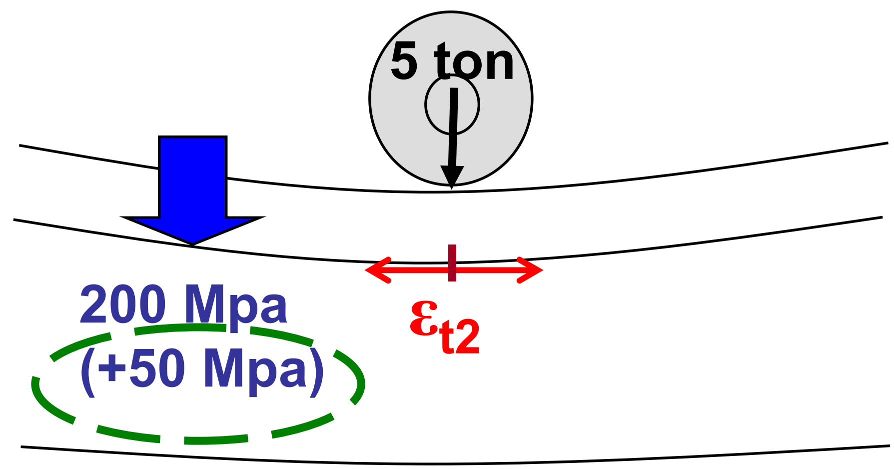


N heavy loads

ε = strain in bottom of asphalt



Alt 1: Thicker pavement, 2 cm, cost ca 2 Euro/m²



Alt 2: Extra compaction, cost ca 0,2 – 0,4 Euro/m2

Swedish standard before 1974

29 cm
(24 cm)

Soil subgrade

19 cm
(16 cm)

Rock subgrade

Thickness highest class
(second highest class)

Analyse of rutting (laser car) during 5 years

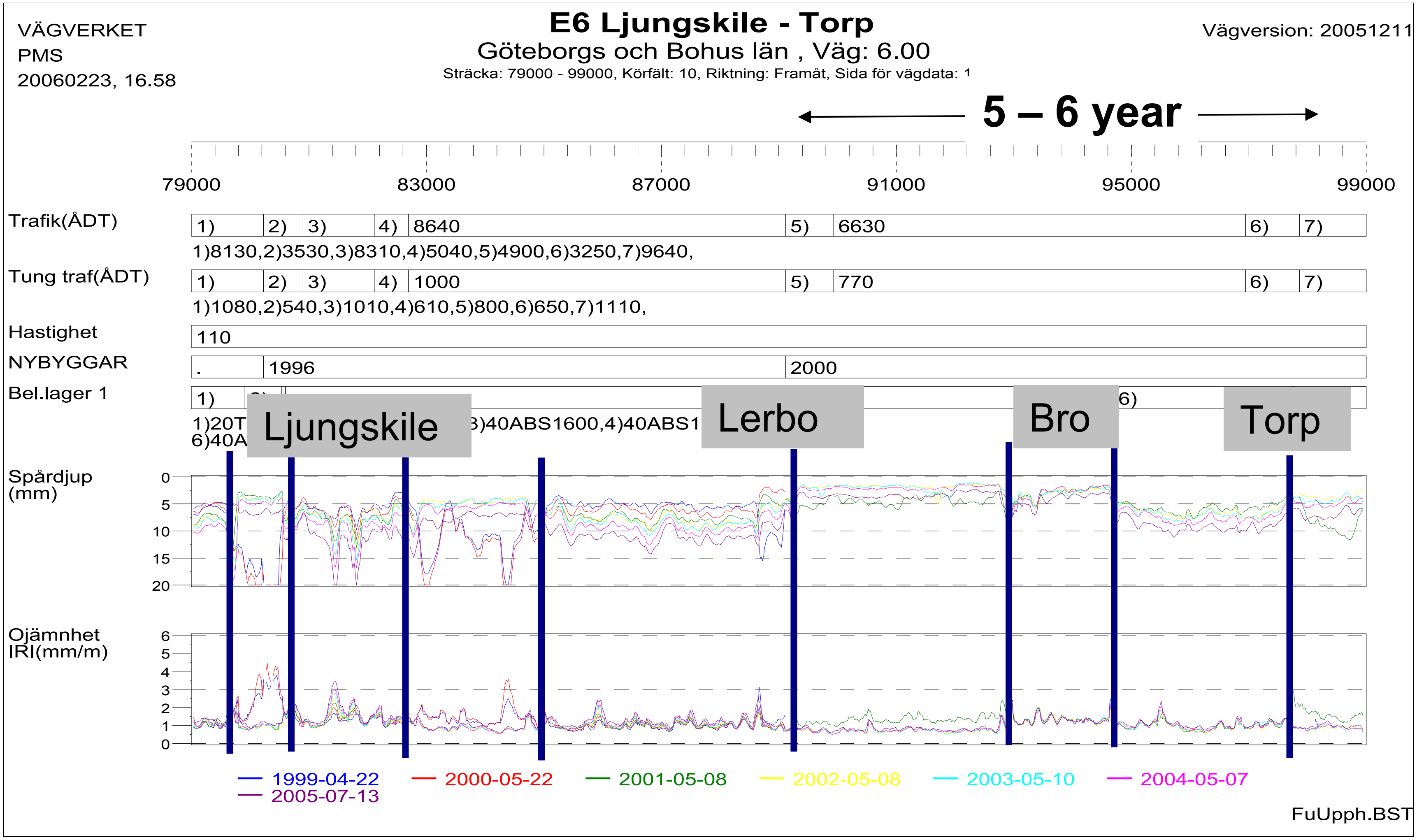
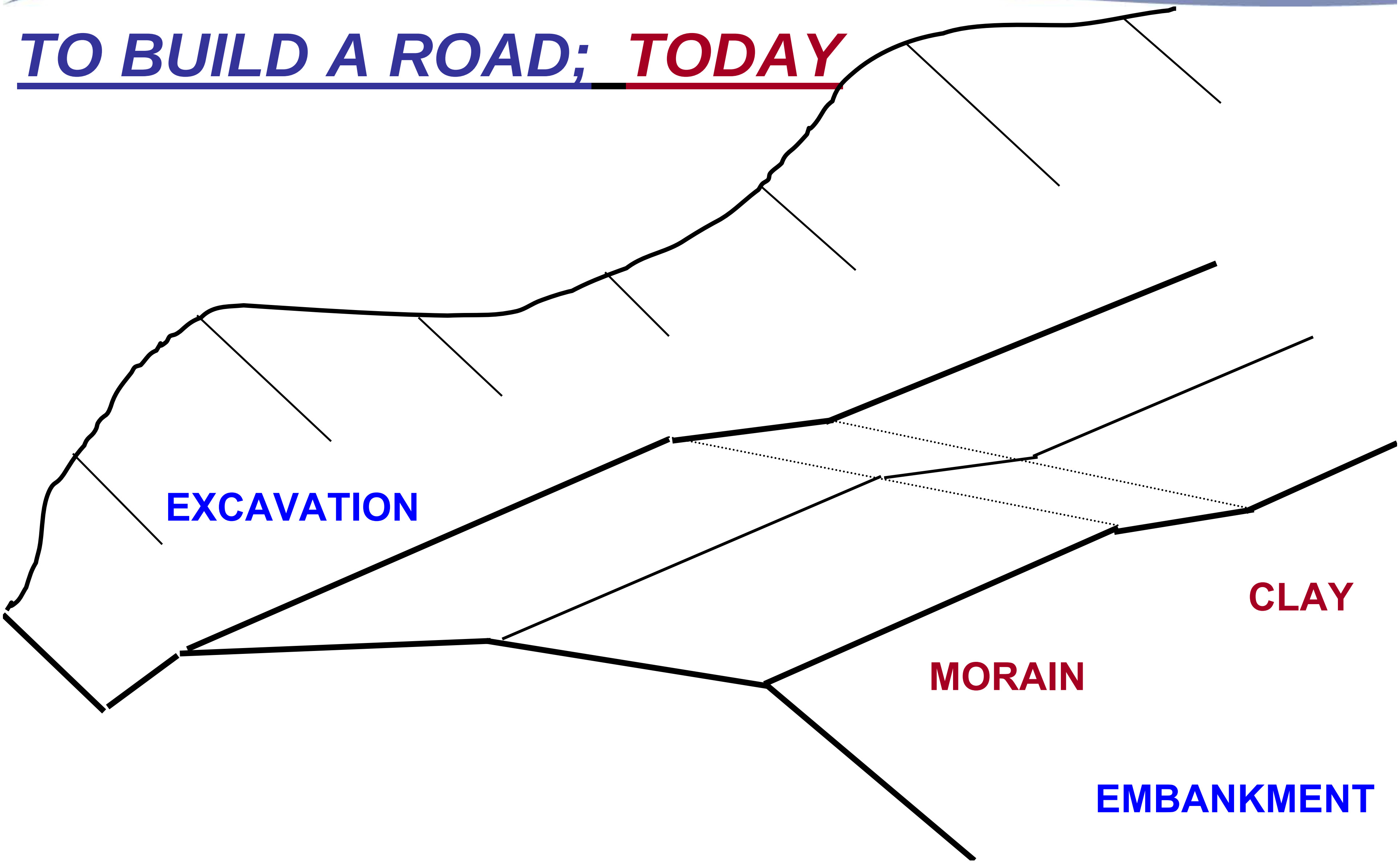


Plate loading: ca 90 MPa 250 – 500 MPa ca 150 MPa

TO BUILD A ROAD; TODAY



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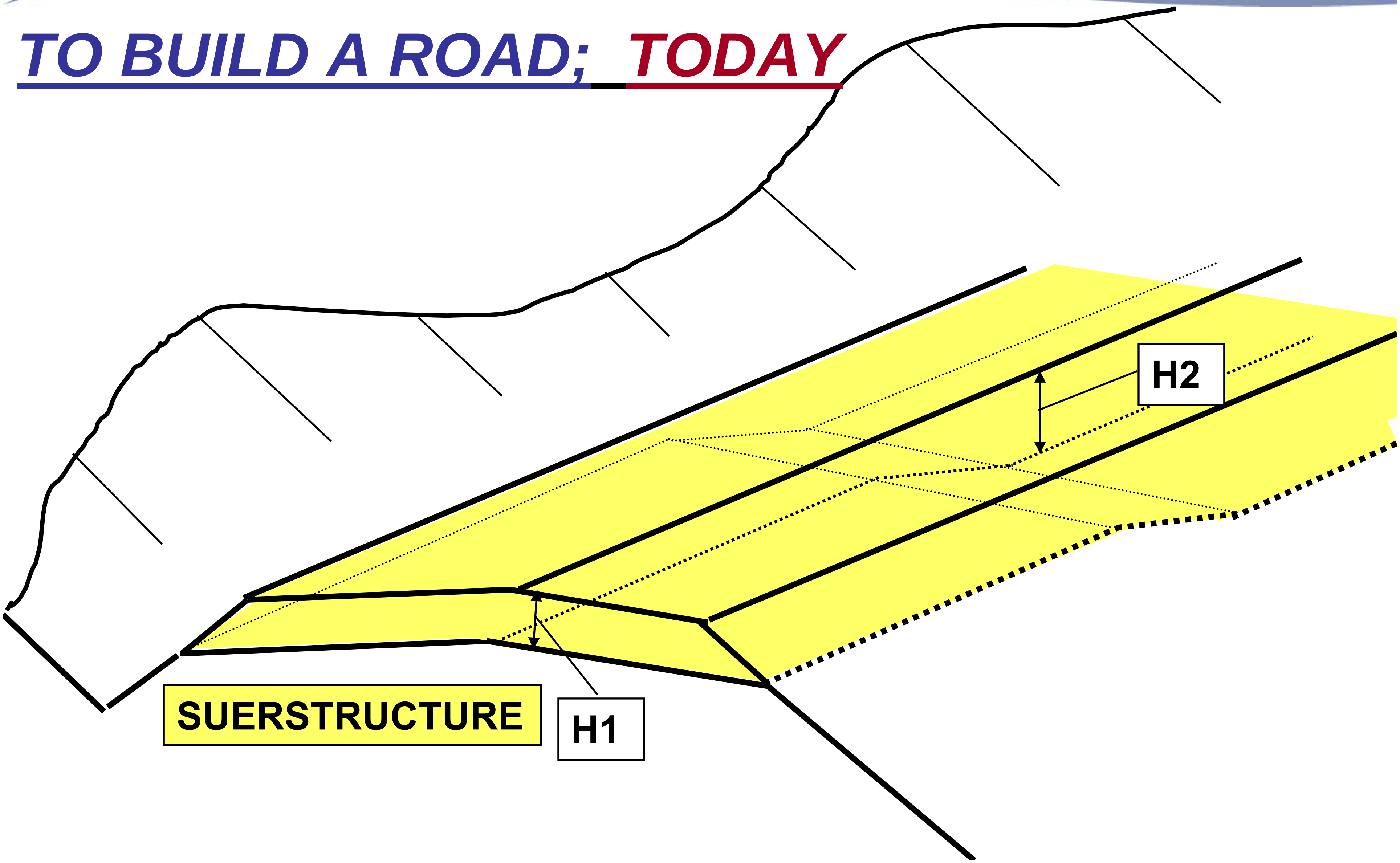

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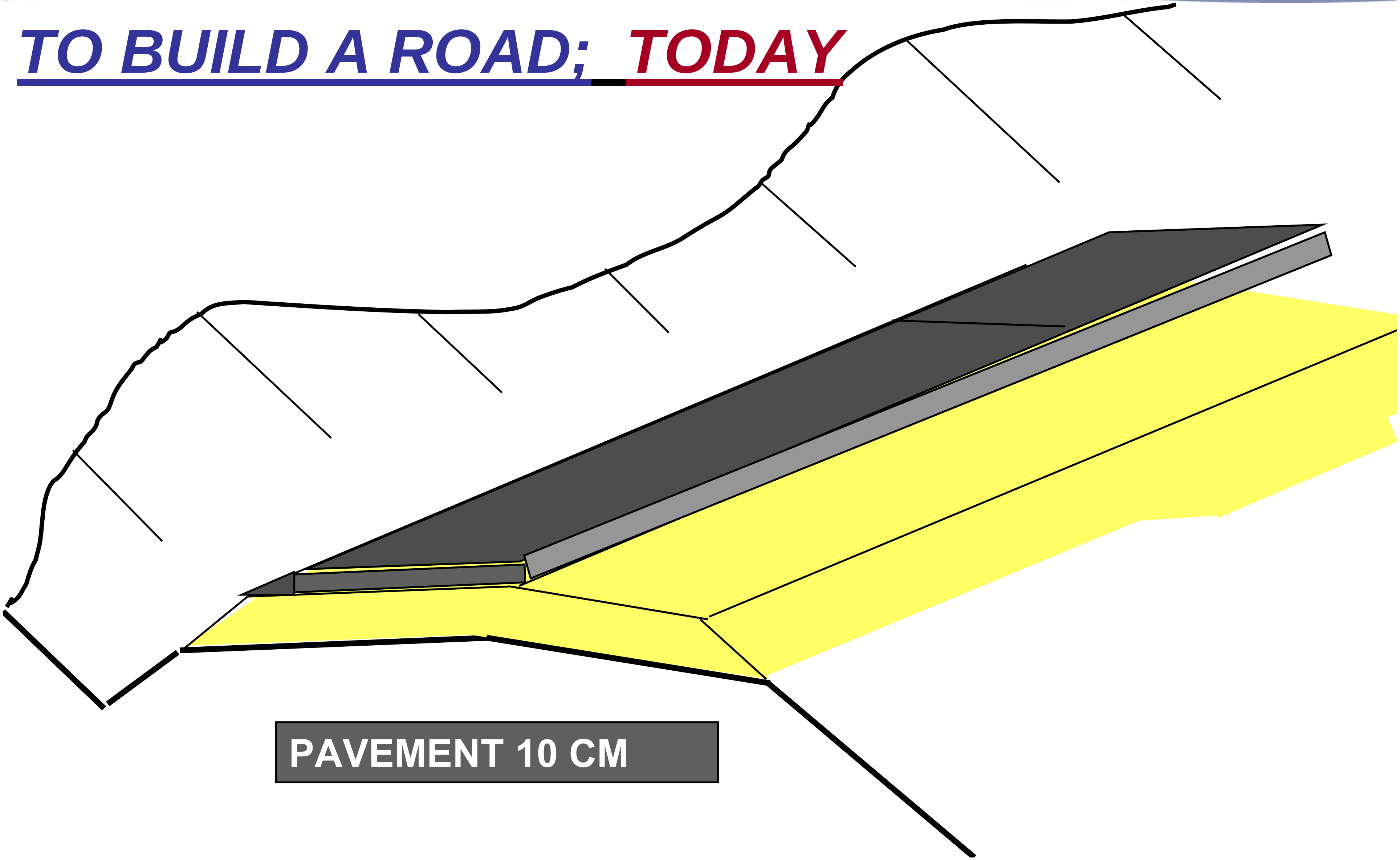
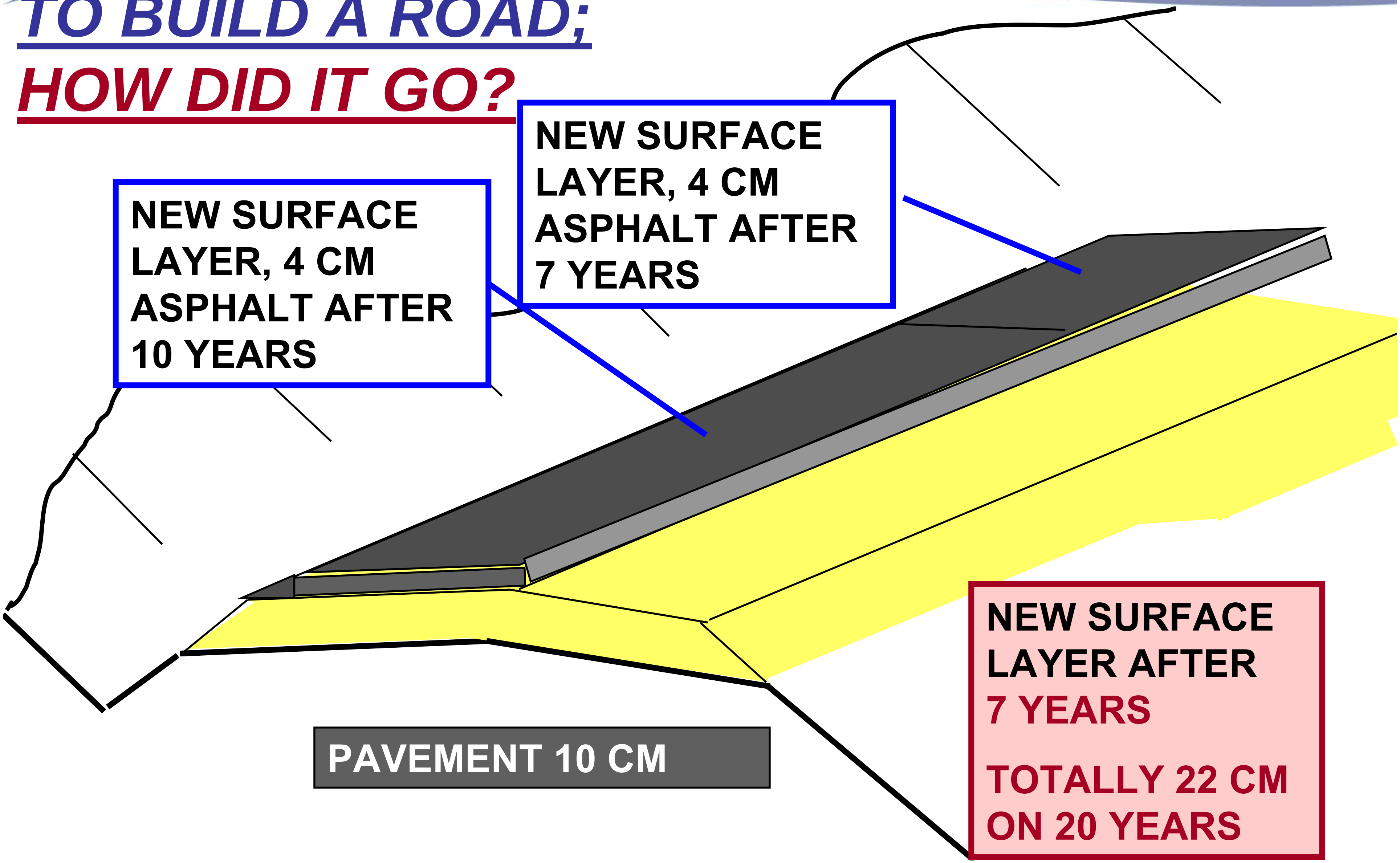
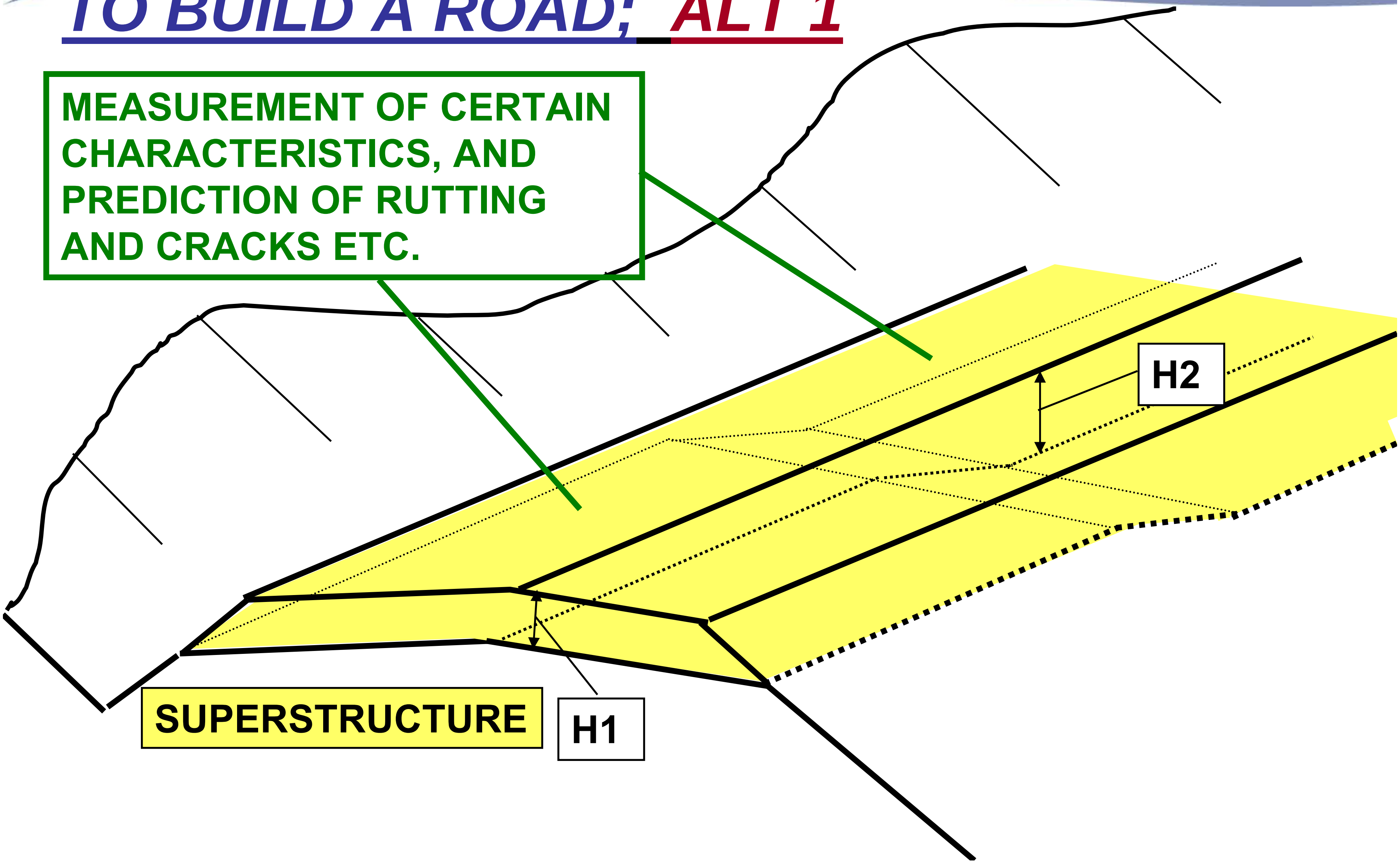


TO BUILD A ROAD; HOW DID IT GO?

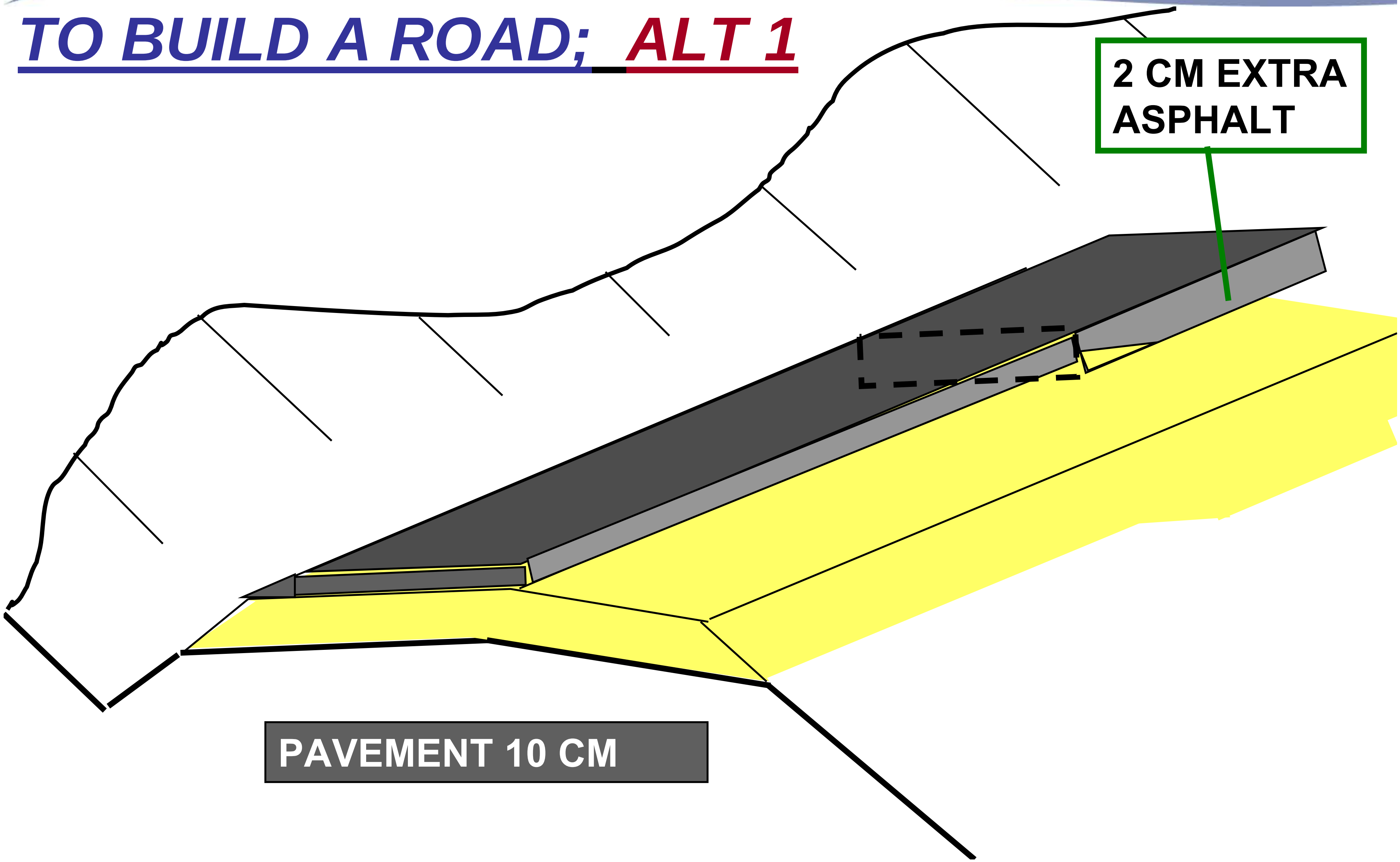


TO BUILD A ROAD; ALT 1

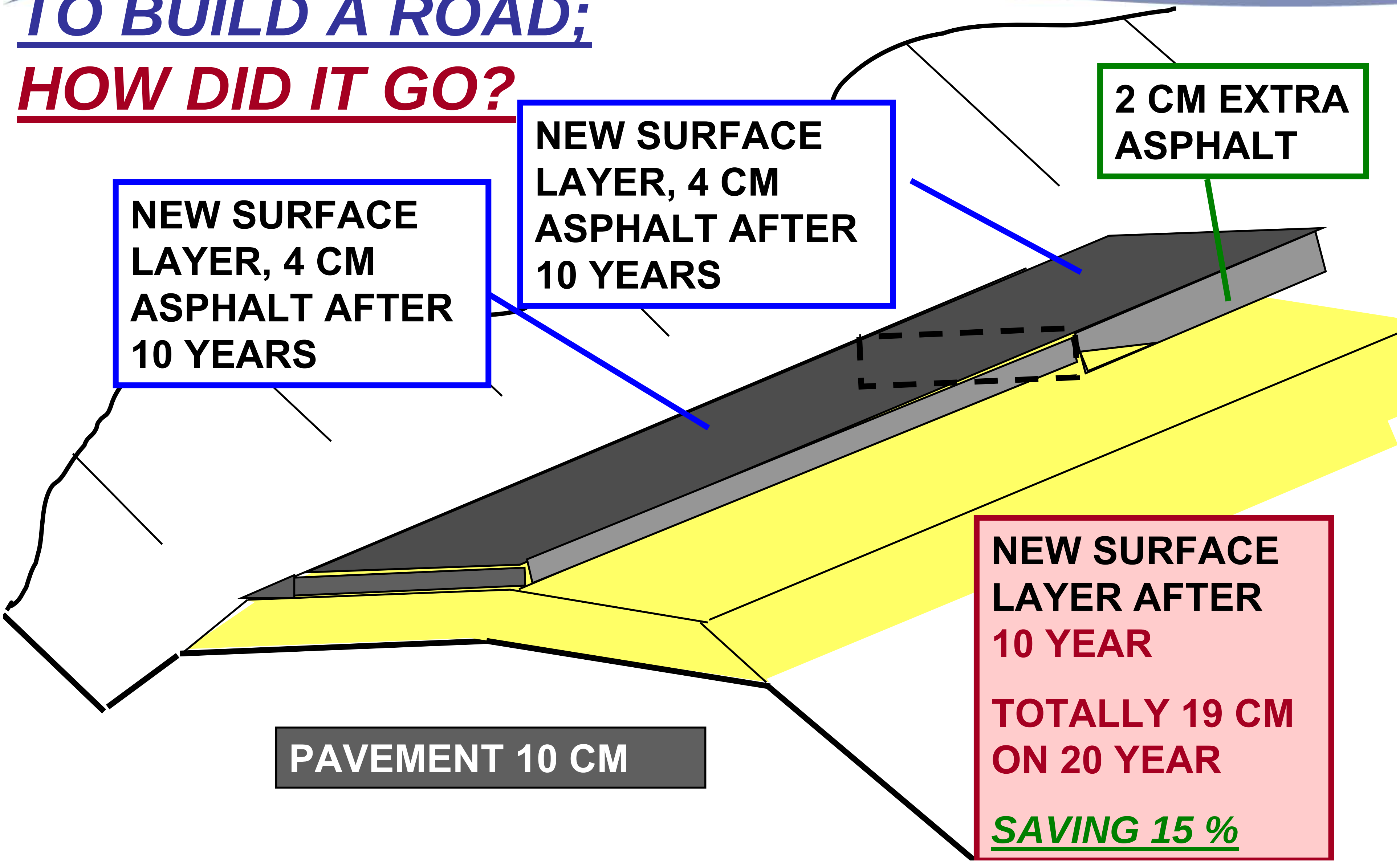
MEASUREMENT OF CERTAIN CHARACTERISTICS, AND PREDICTION OF RUTTING AND CRACKS ETC.



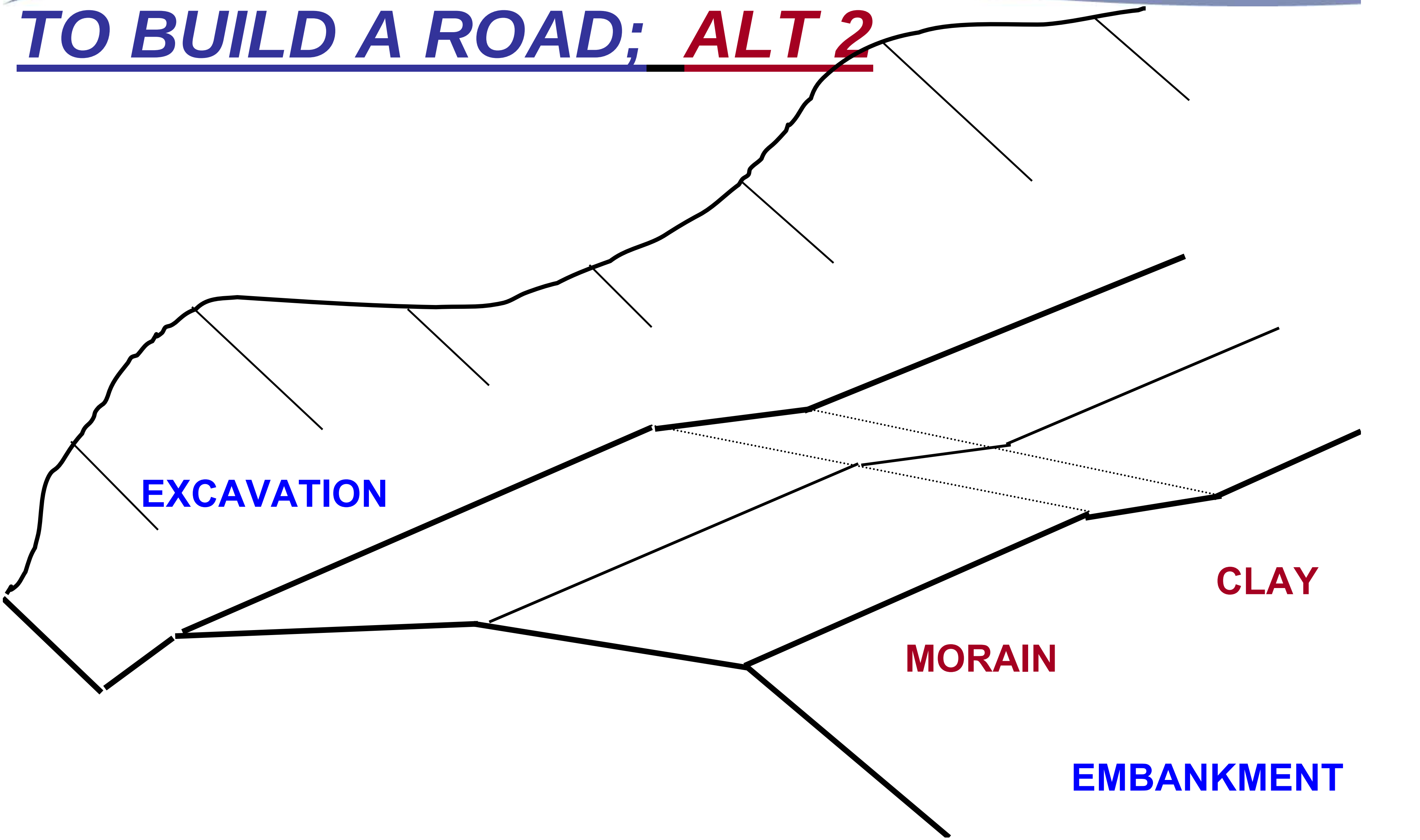
TO BUILD A ROAD; ALT 1



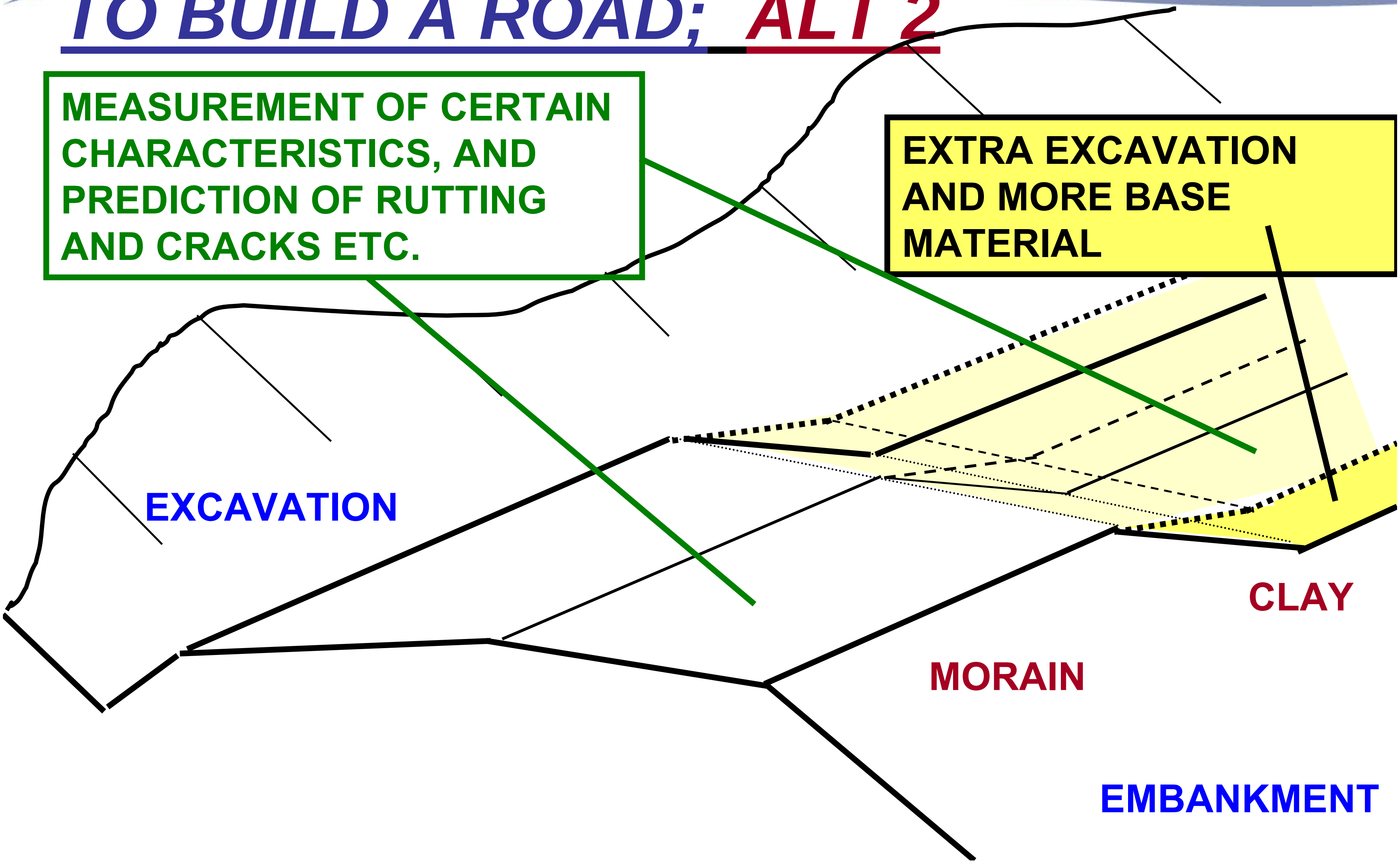
TO BUILD A ROAD;
HOW DID IT GO?



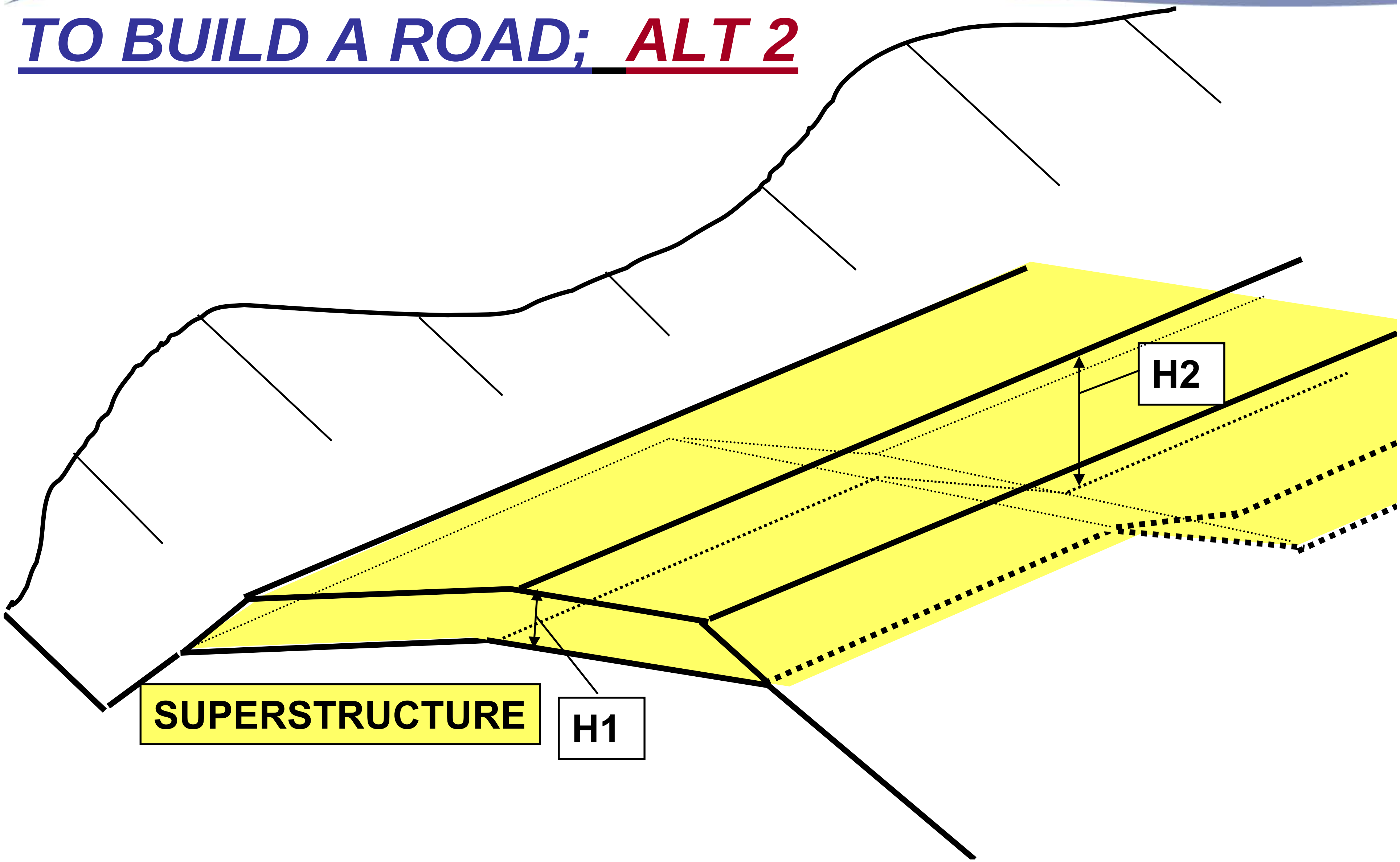
TO BUILD A ROAD; ALT 2



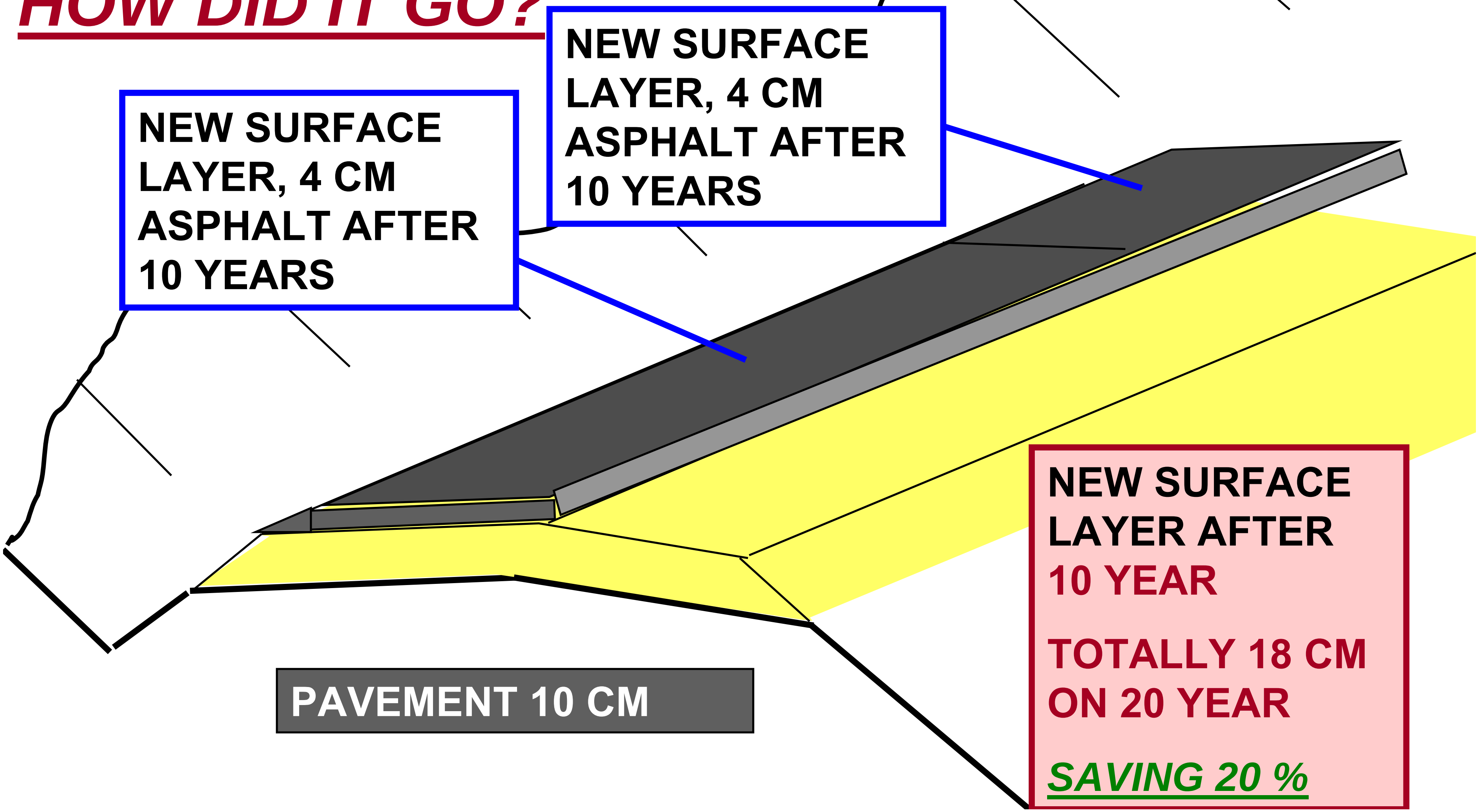
TO BUILD A ROAD; ALT 2



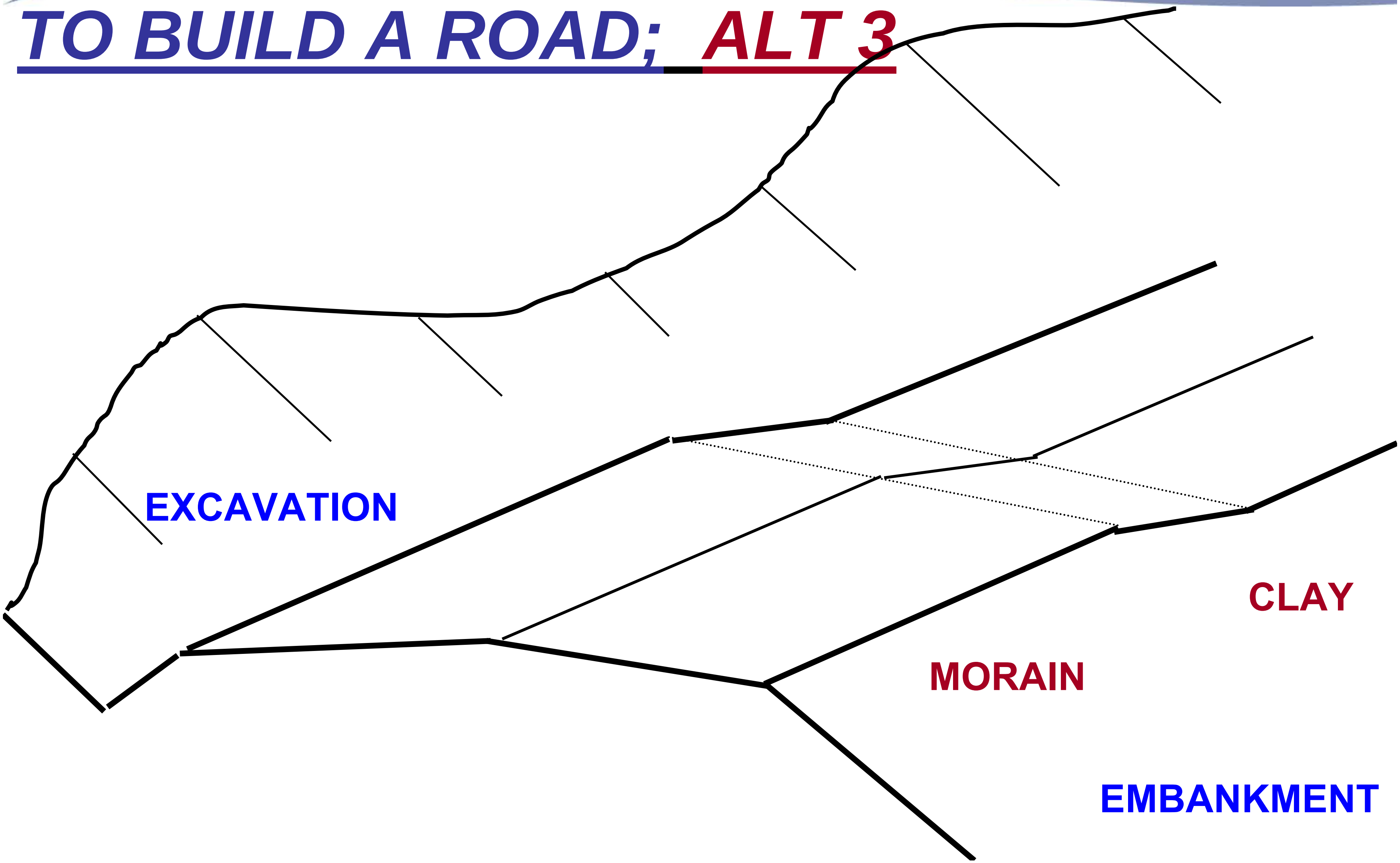
TO BUILD A ROAD; ALT 2



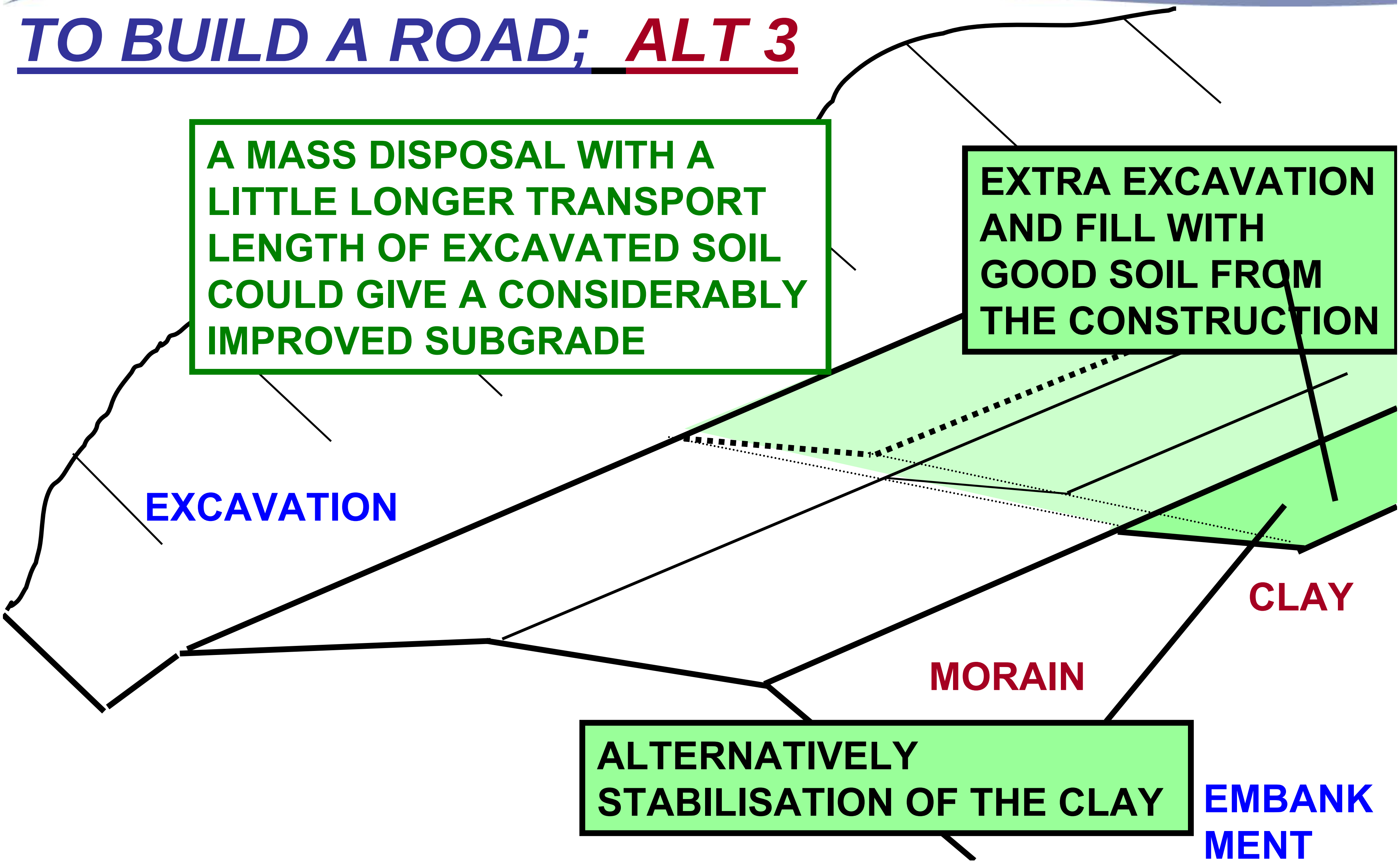
TO BUILD A ROAD;
HOW DID IT GO?



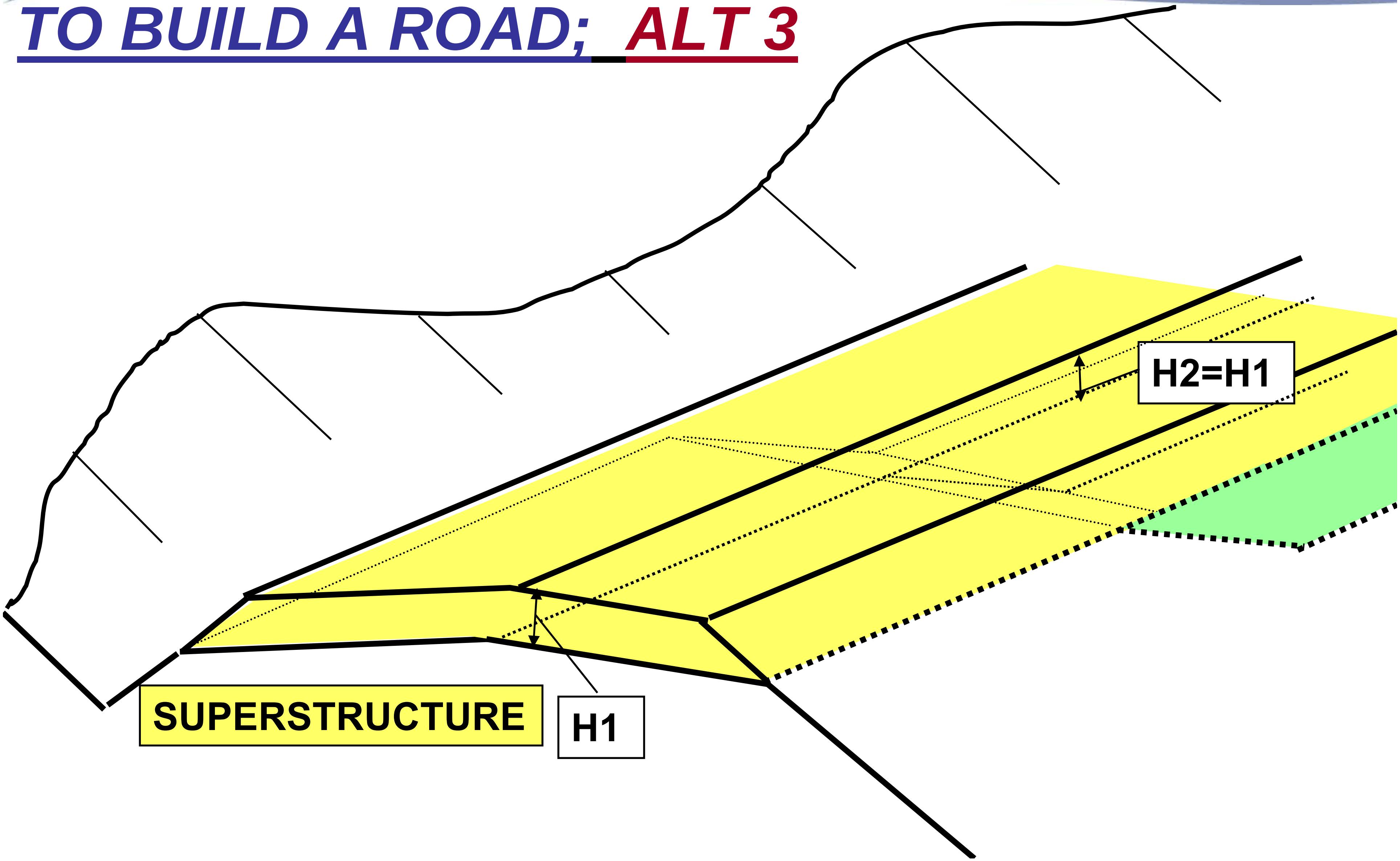
TO BUILD A ROAD; ALT 3



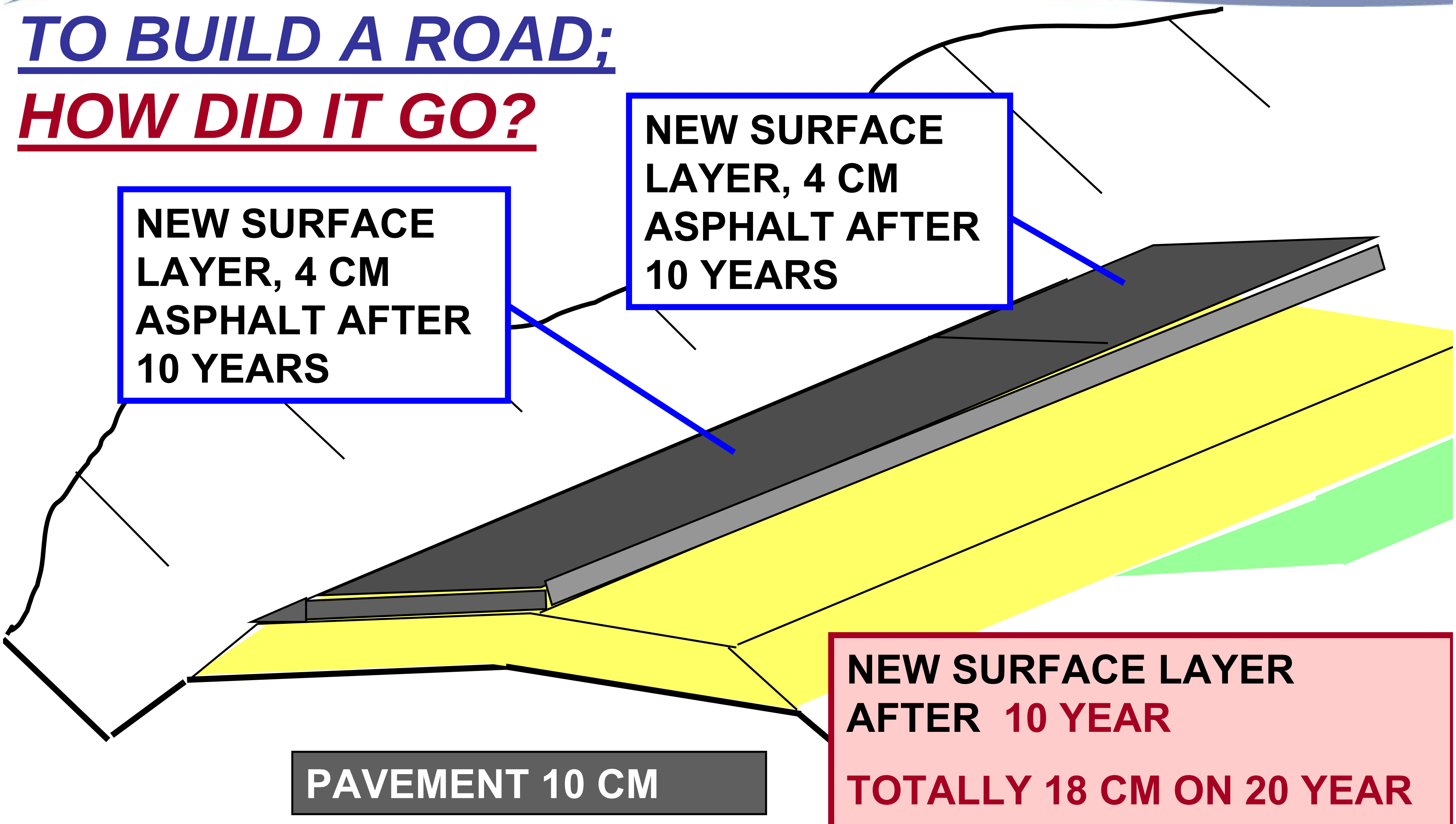
TO BUILD A ROAD; ALT 3



TO BUILD A ROAD; ALT 3



TO BUILD A ROAD;
HOW DID IT GO?

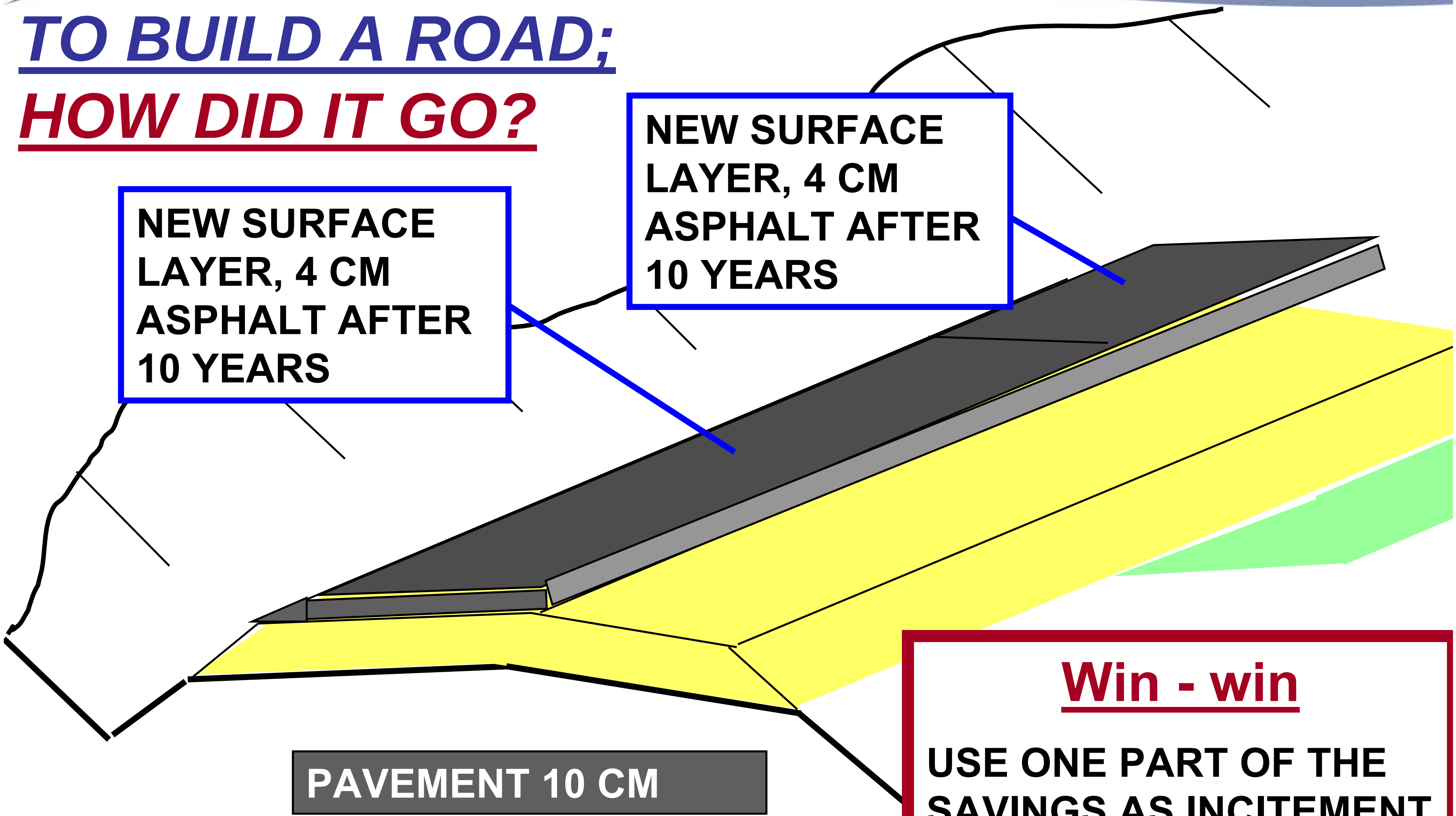


NEW SURFACE LAYER AFTER 10 YEAR

TOTALLY 18 CM ON 20 YEAR

SAVING 20 %

TO BUILD A ROAD;
HOW DID IT GO?



Win - win

USE ONE PART OF THE SAVINGS AS INCITEMENT FOR A BETTER QUALITY

ACTIVE DESIGN

Soil and rock, used in road construction has an uneven quality: Design after real quality!

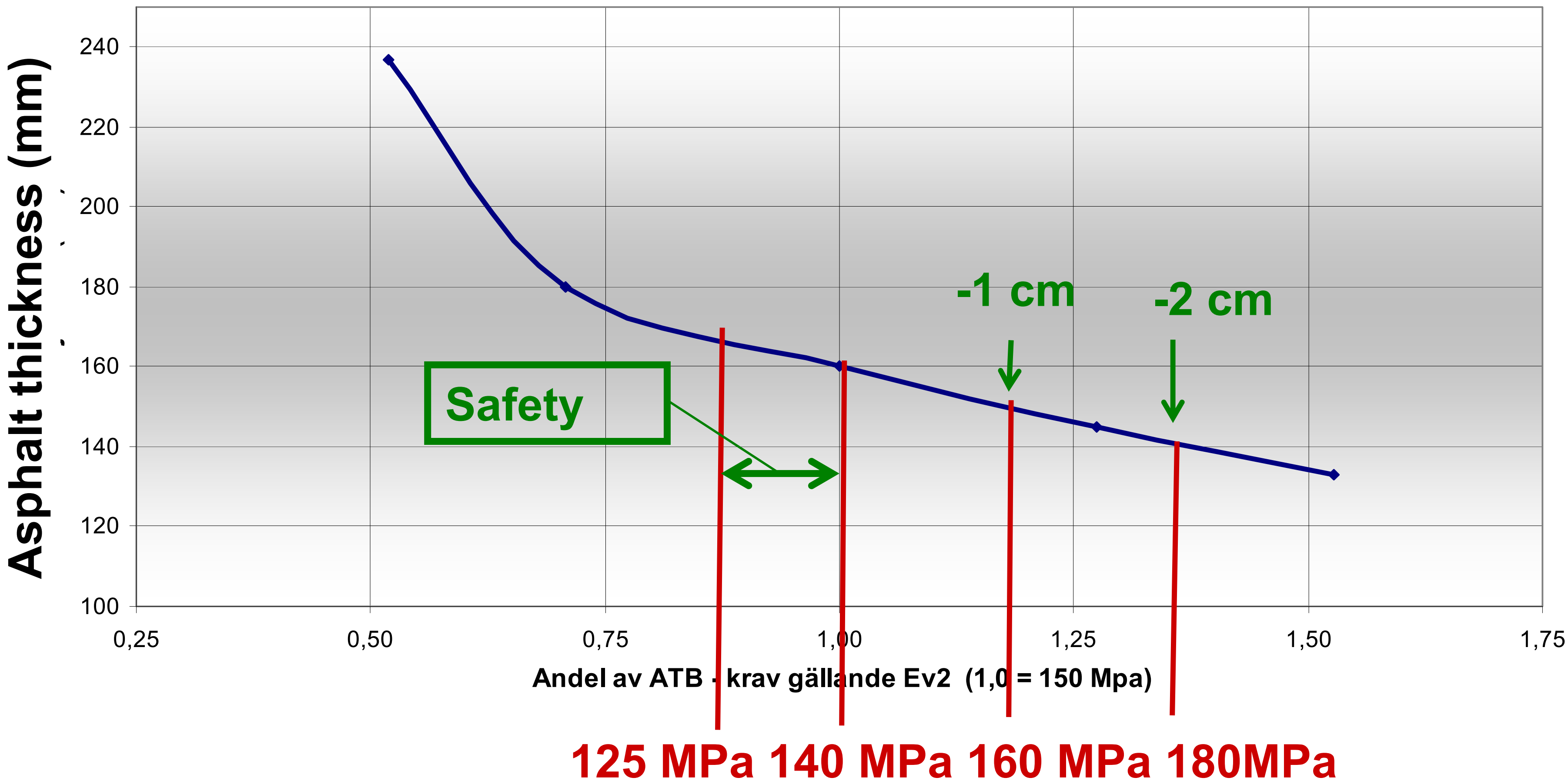
Use the best material close to the subgrade surface to get better bearing capacity

Calculate future function from test results on site in order to choose the optimal alternative

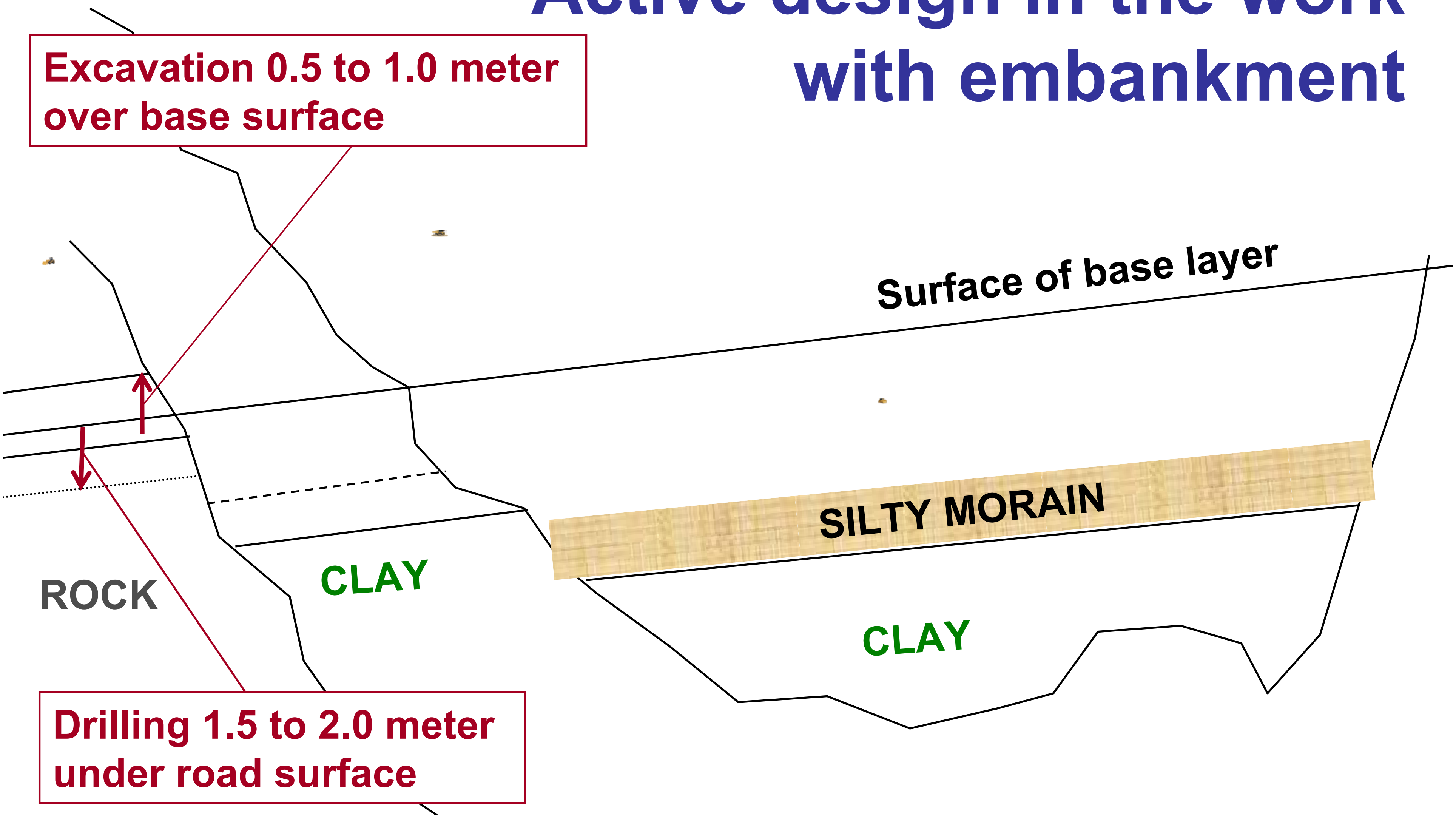
Incentive for better quality gives resources for improvement of the competence and technical development, and it also gives a strong motivation to produce with an improved quality

QUALITY LEVELS

Change in pavement thickness with surface covering measurement on the compactor

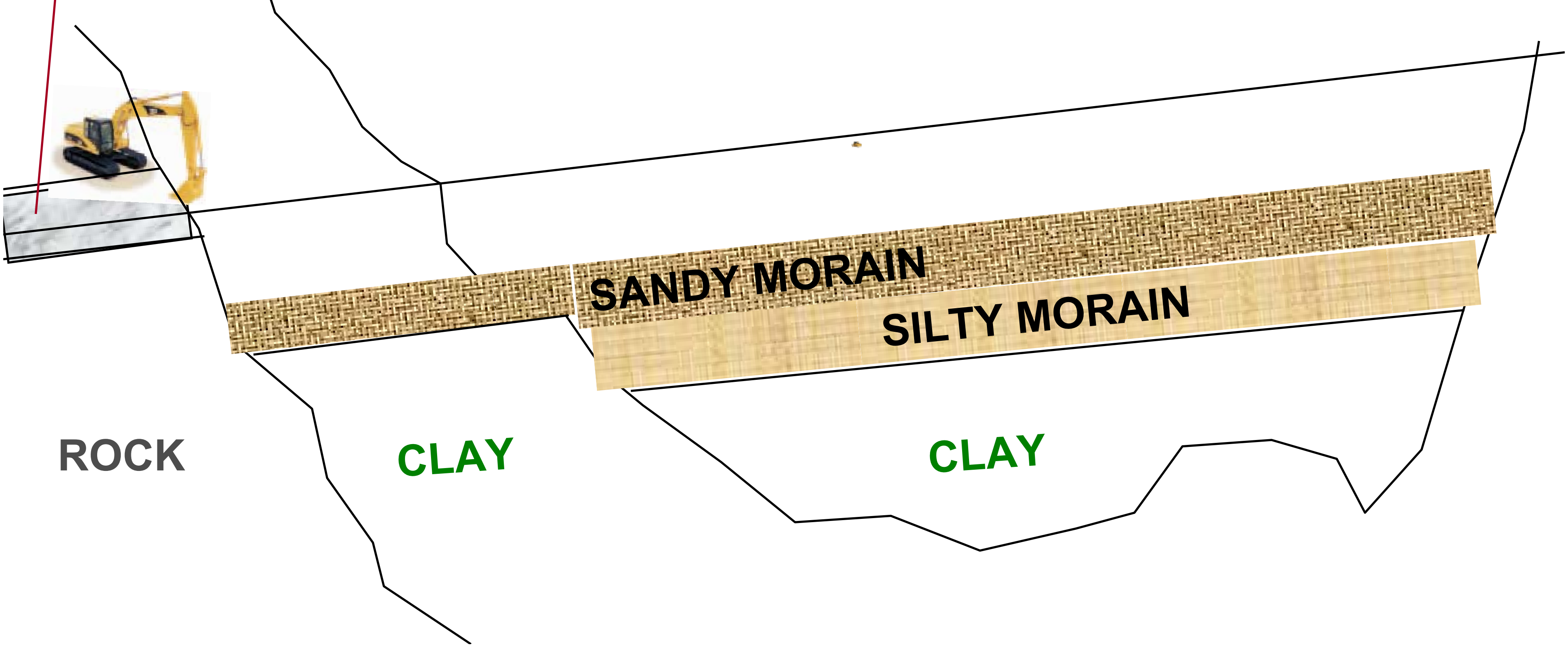


Active design in the work with embankment

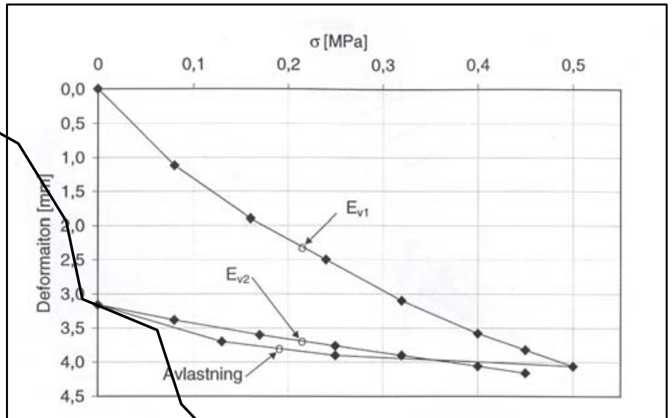


Active design in the work with embankment

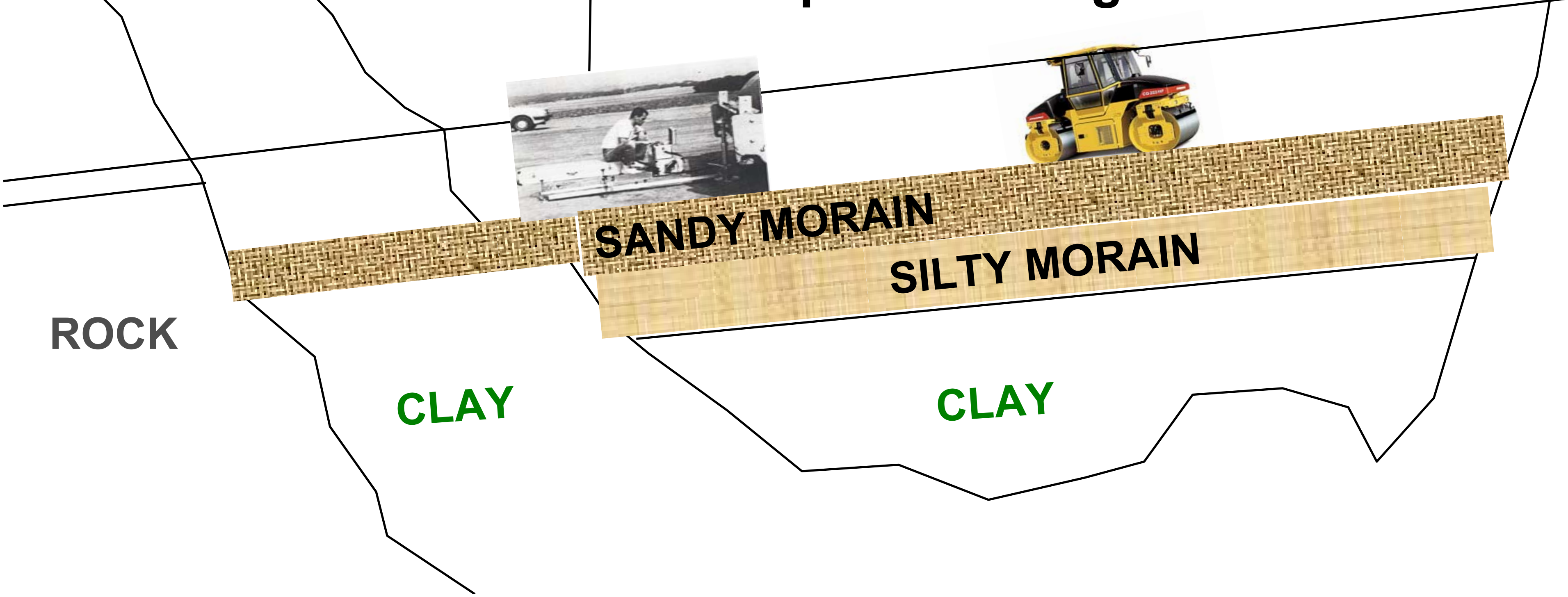
”Lowest meter” of rock excavation



Active design in the work with embankment

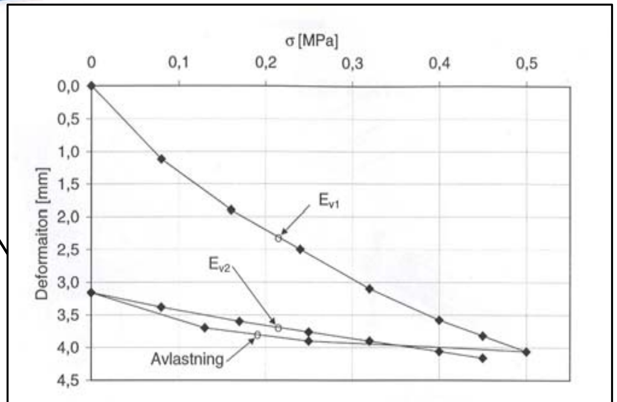


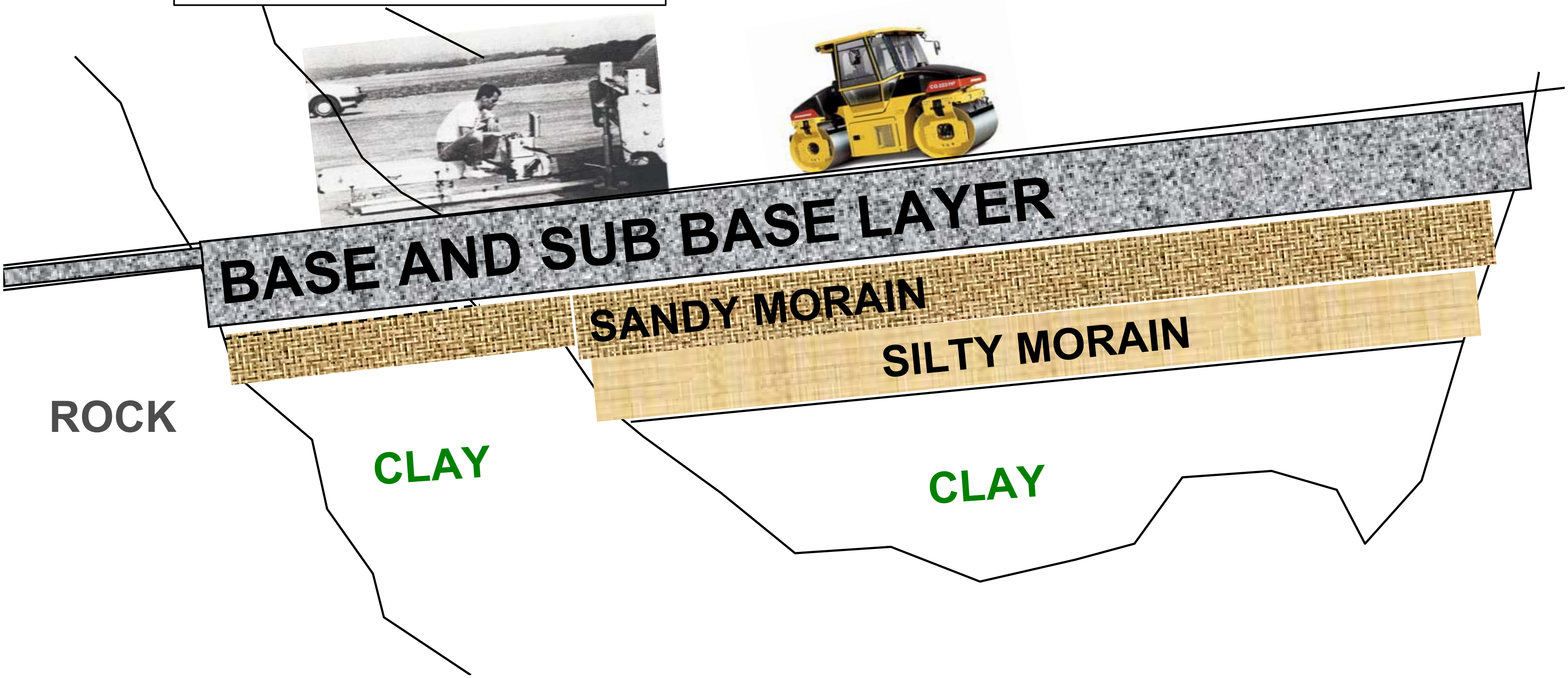
Measurment with plate loading



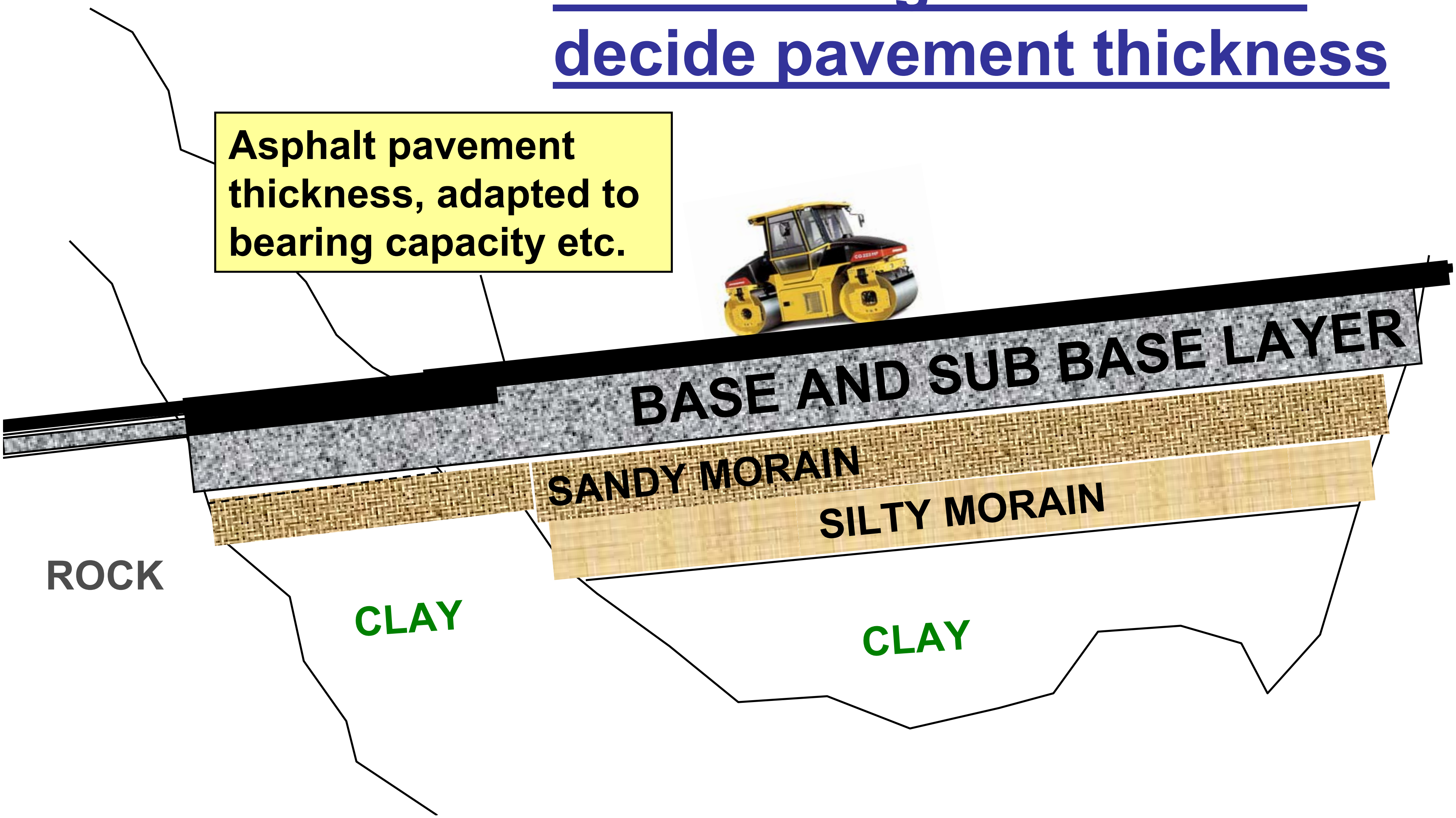
Active design the work with base layers

Measurment with plate loading





Active design in order to decide pavement thickness



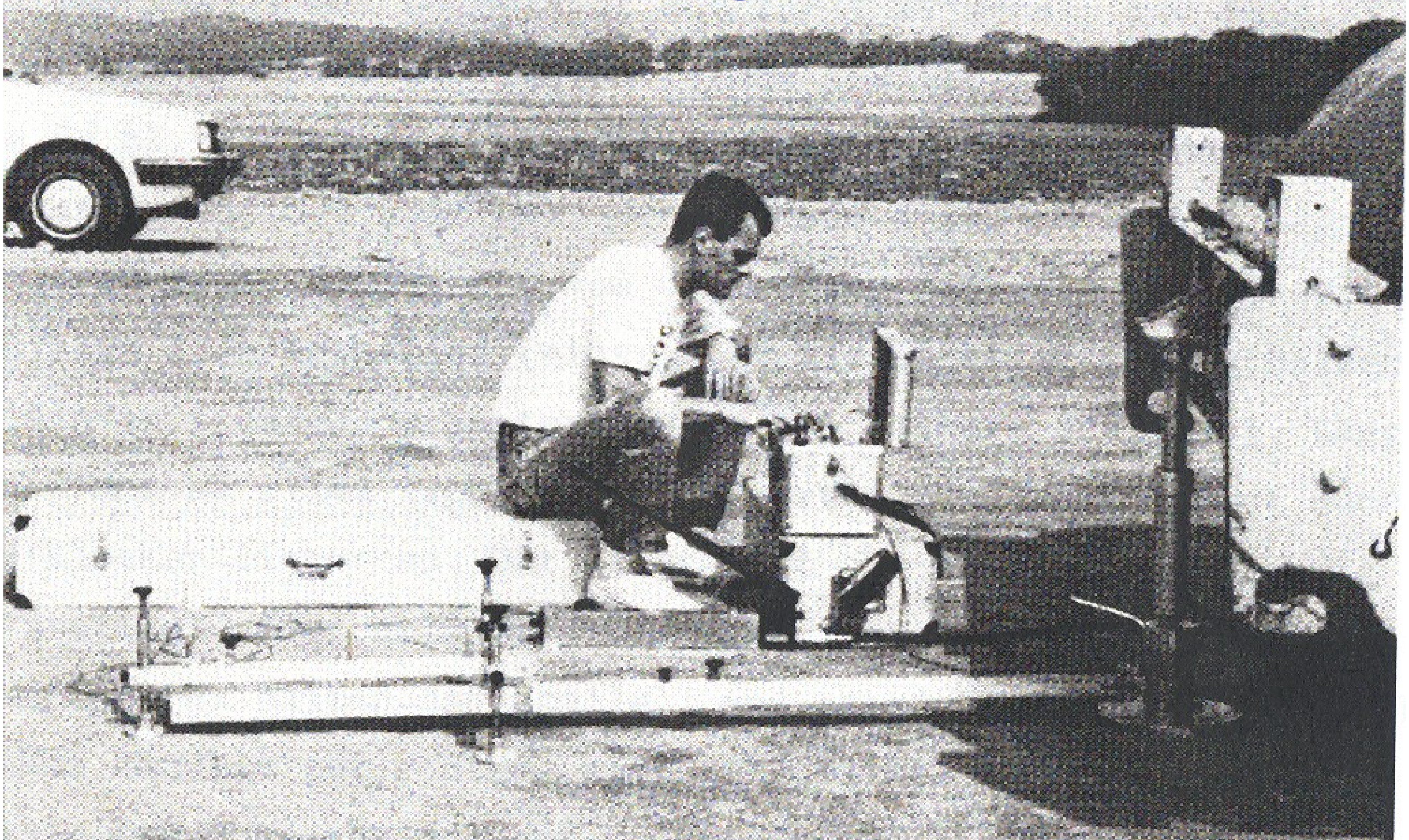
Test Projects

- Initial agreement between client and contractor
- Incitement to use the soil and rock in order to improve bearing capacity during embankment
- Plate loading test on top of subgrade
- Triaxial test on subbase material (permitted stress 80 % of shake down load, or classified in accordance to the standard for triaxil tests)
- Improved compaction with instrumented roller compactor
- Plate loading on top of the subbase
- Choose asphalt thickness from plate loading results
- The benefit is shared between client and contractor

TEST METODS
Unbound layers

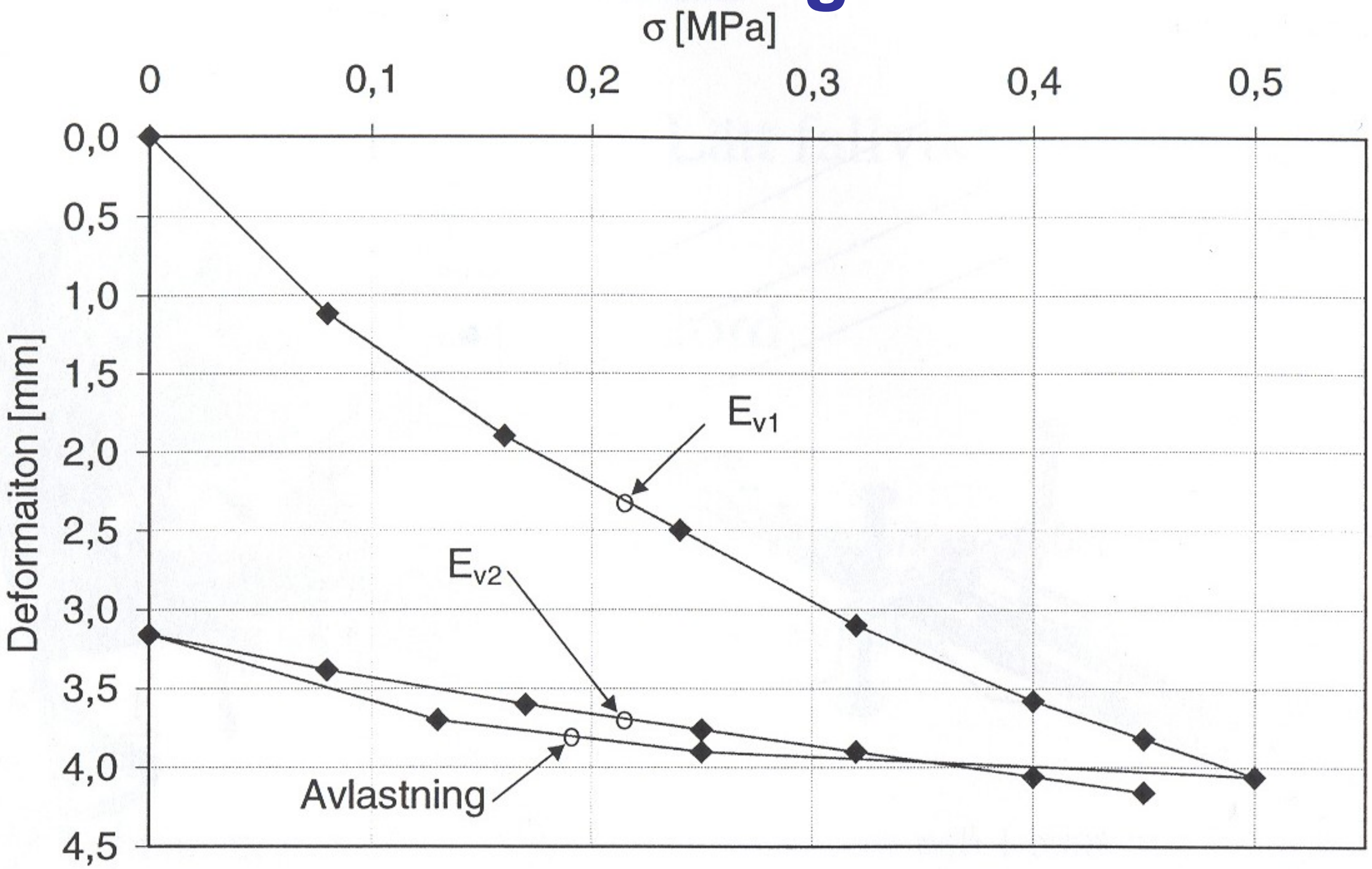
Measurement with instrumented roller compactor with GPS

Test: Plate loading



Equipment for measuring bearing capacity with plate loading

Test: Plate loading

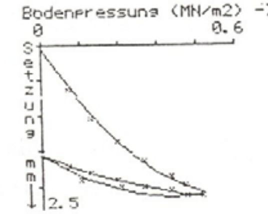


PLATTENDRUCKVERSUCH
nach DIN 18134

Projekt:
HEBERG/LANGAS
Meßstelle:
022/003 V10.2 T2ö
Datum: 09.08.91 10:54

Plattendurchm.: 300 mm
Laengenverh. : 1:2.0

Normal-spannung	Setzung		
	Uhr1	Uhr2	Uhr3
MN/m2	0.01 mm		
*** Belastung ***			
0.08	72		
0.16	114		
0.24	146		
0.32	175		
0.40	198		
0.45	212		
0.50	227		
*** Entlastung ***			
0.25	215		
0.13	203		
0.00	165		
*** Belastung ***			
0.08	183		
0.16	194		
0.24	202		
0.32	215		
0.40	221		
0.45	228		



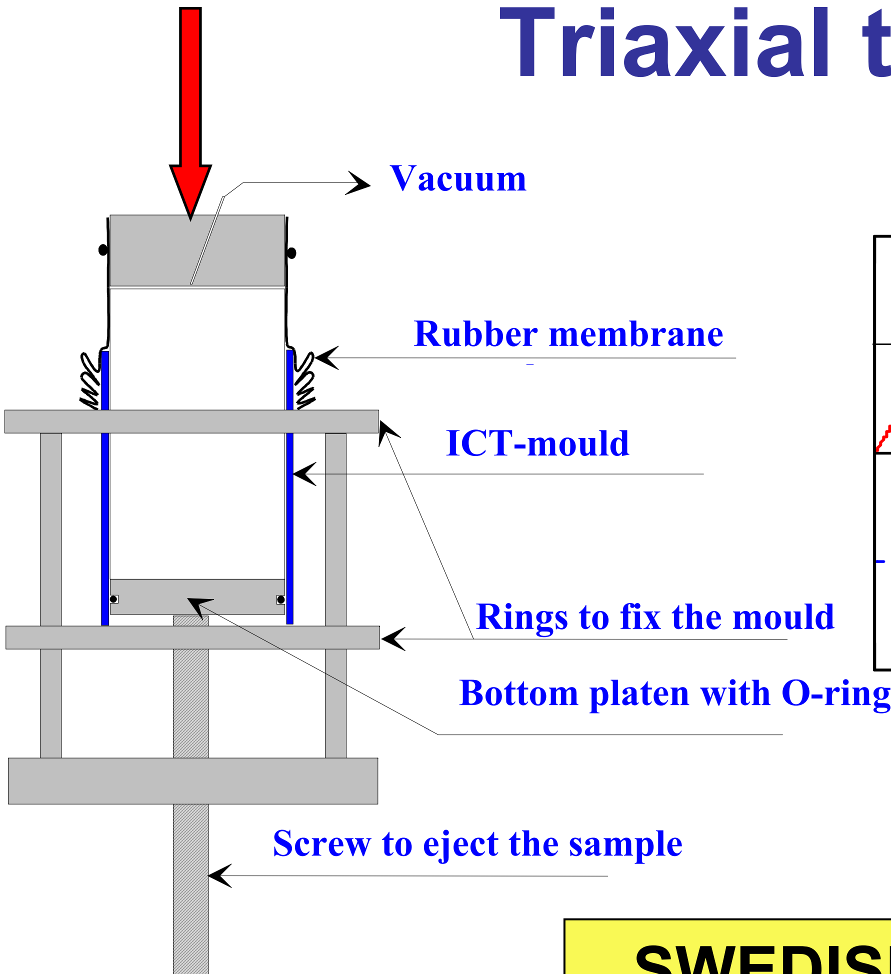
Ergebnisse: neue DIN

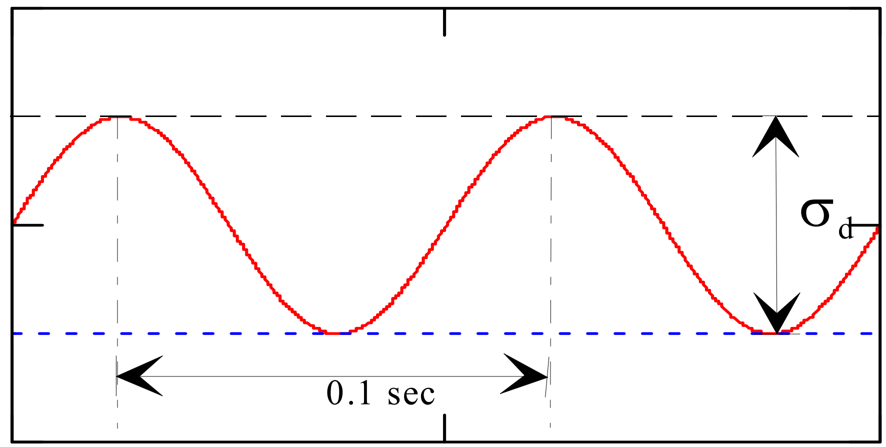
Kurve	a1	a2
1	5.87	-3.85
2	1.45	-0.46

Ev1 = 57.00 MN/m2
Ev2 = 184.44 MN/m2
Ev2/Ev1 = 3.24

Diagram of result from plate loading

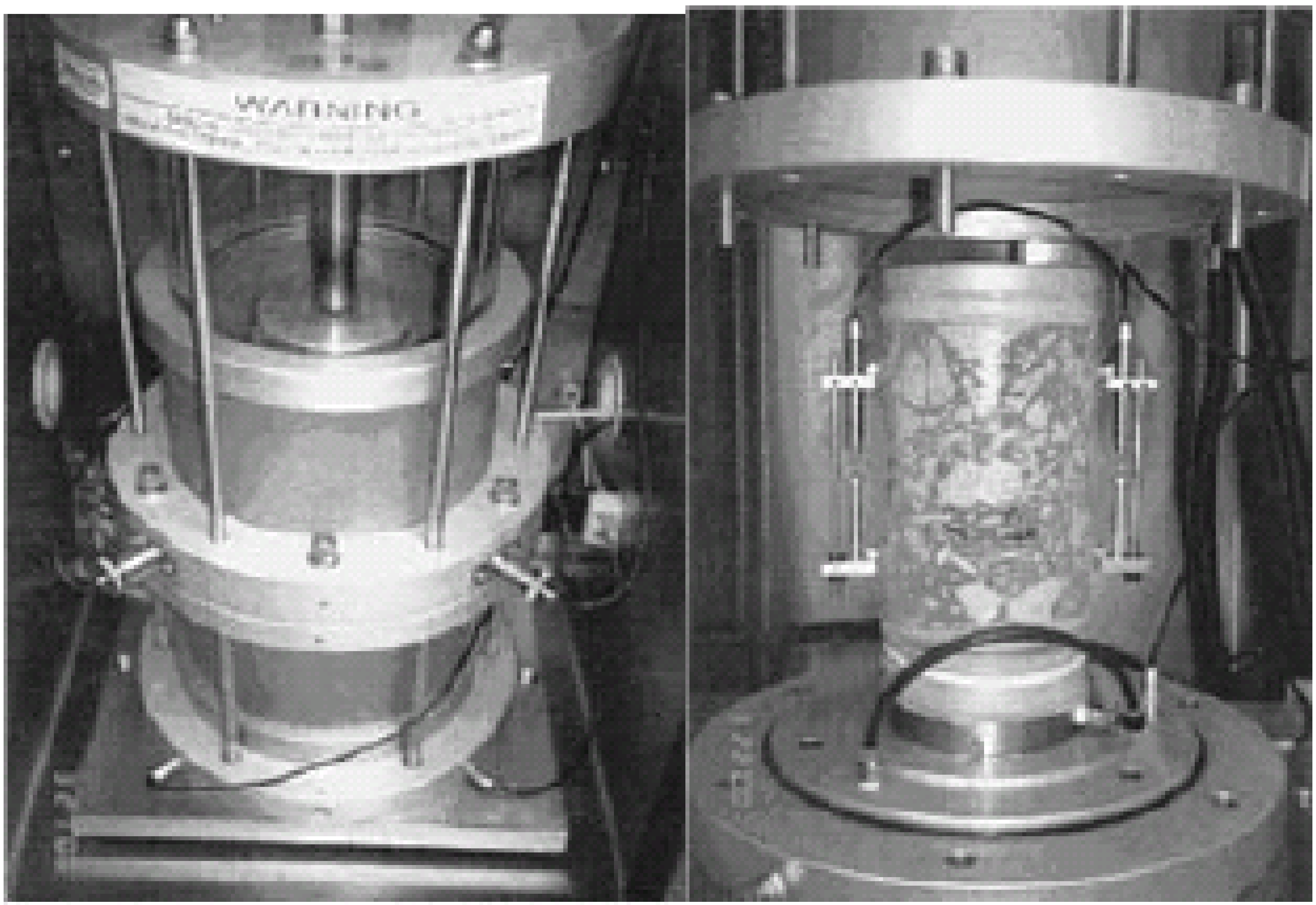
Triaxial test



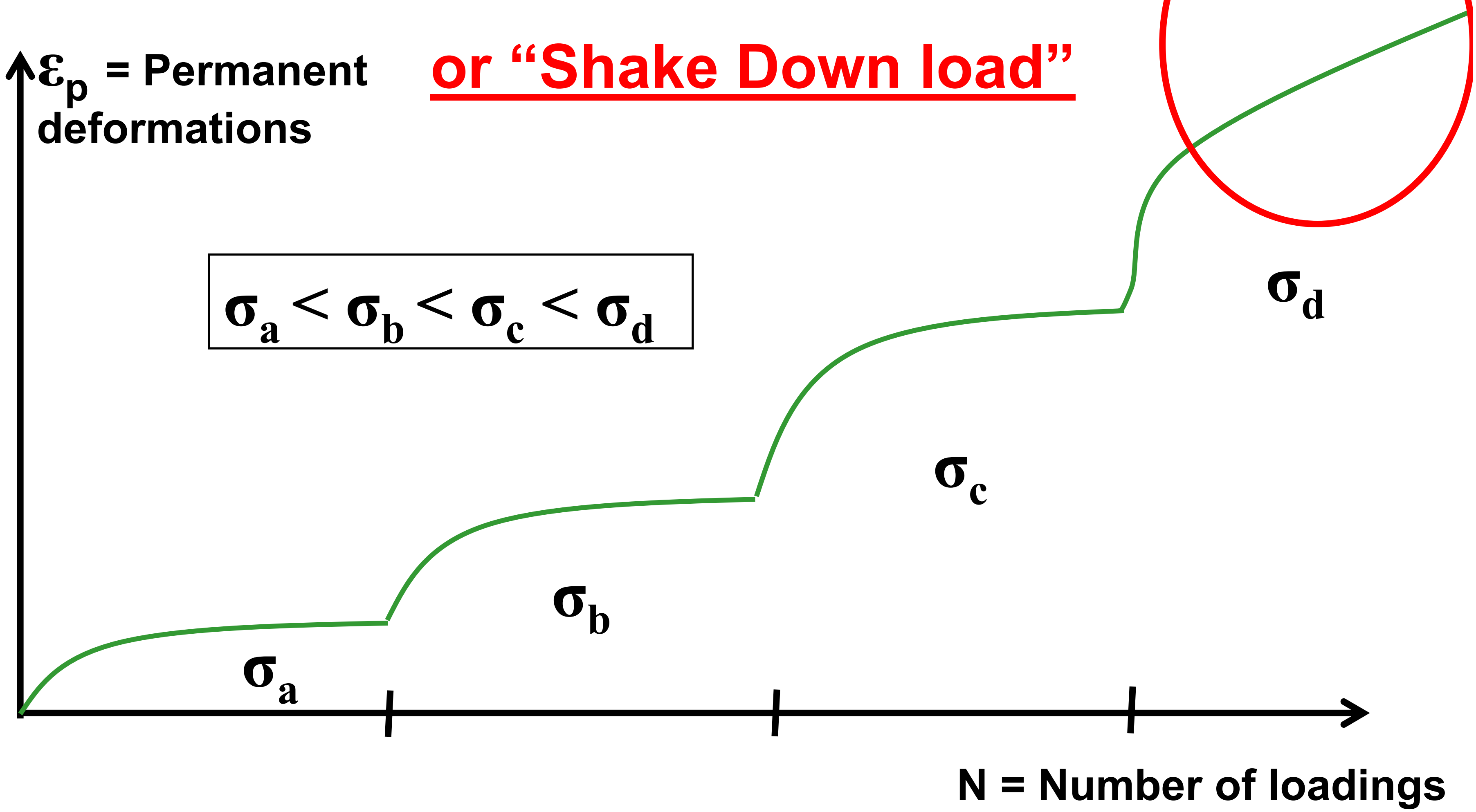


SWEDISH STANDARD
SS-EN 13286-7:2004
Appointed 2004-02-13

Equipment for Triaxial tests



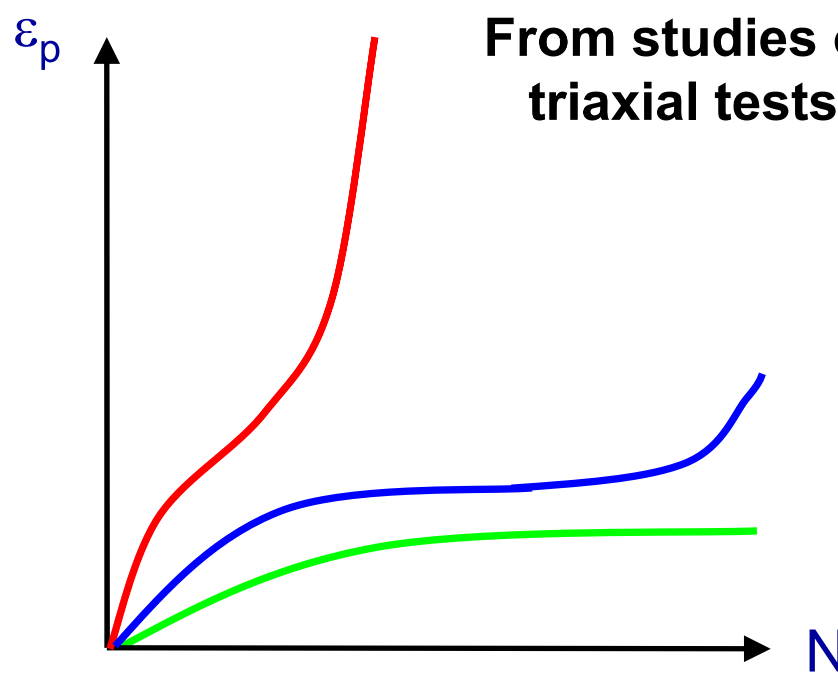
Treaxial test ”Fatigue load”



Decision of critical stress conditions in unbound layers

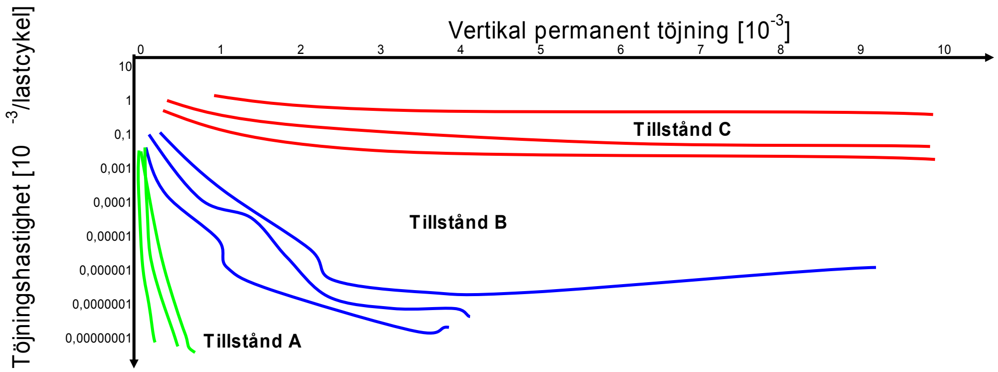
- Shakedownkoncept
  - Stable state (little rutting)
  - Unstable state (severe rutting)

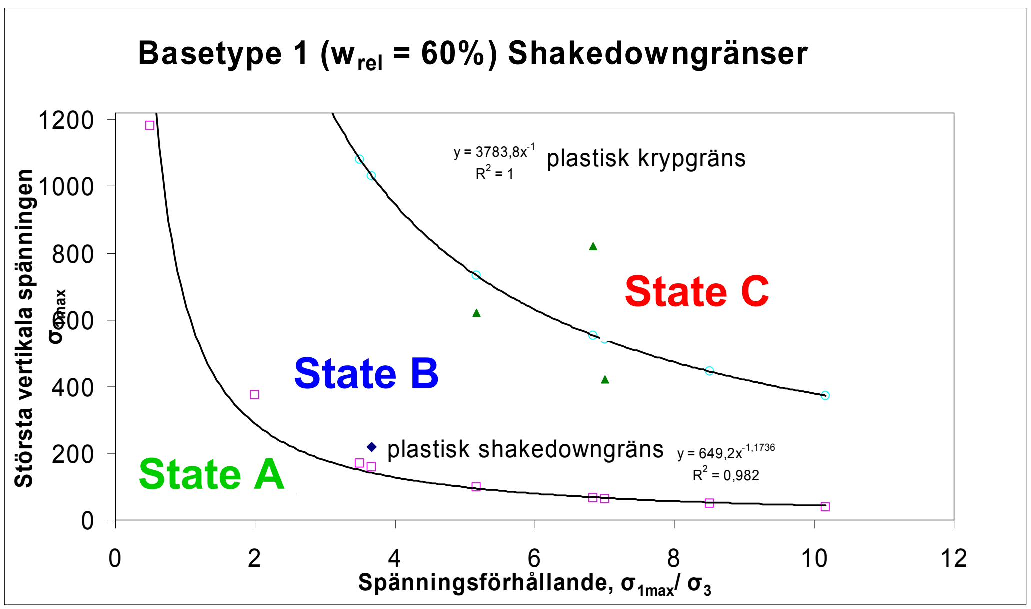
- State A (stable behaviour)
- State B (unstable behaviour)
- State C (collapse)



From studies of triaxial tests

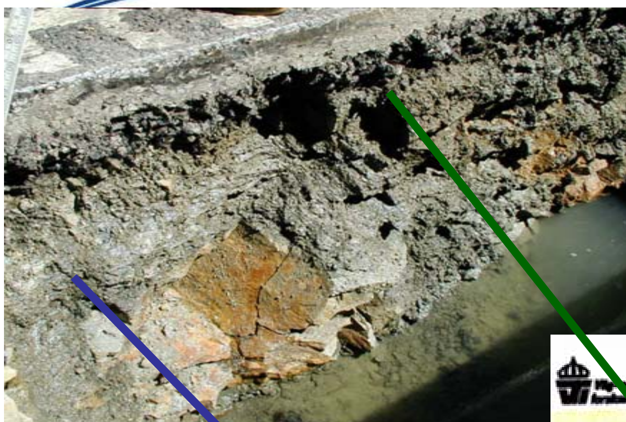
The Shake Down concept





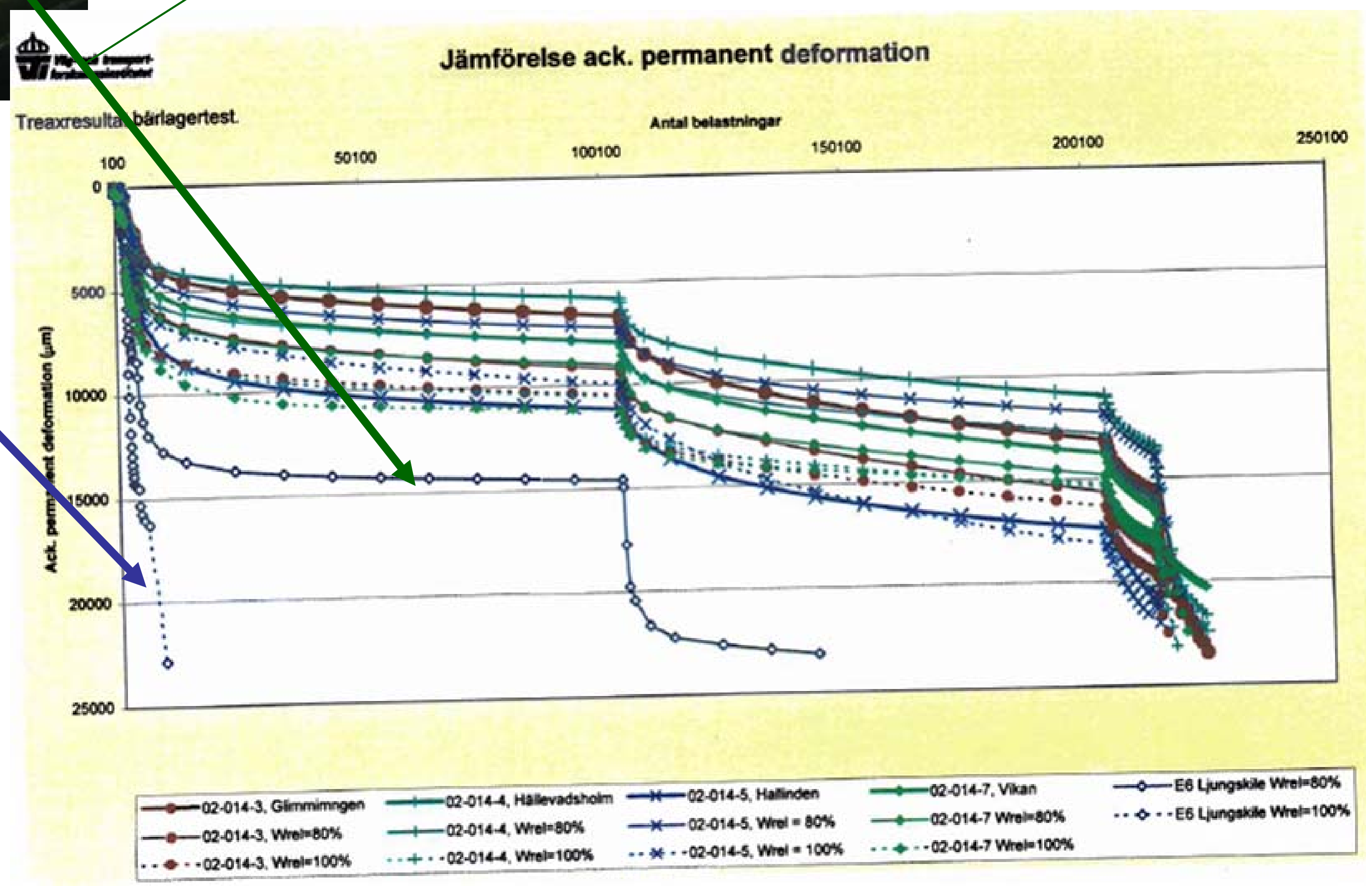
$$\sigma_{1,\max} = \alpha \cdot \left(\frac{\sigma_{1,\max}}{\sigma_c} \right)^{\beta}$$

Triaxial test on different materials



Dry

Humid



Triaxial tests on unbound layers

Gives following data / material characteristics:

- Unlinear static elasticity modulus (resilient modulus)
- Unlinear dynamic elasticity modulus (resilient modulus)
- Fatigue strength (”Shake Down” load)
- Input data for calculation of permanent deformations

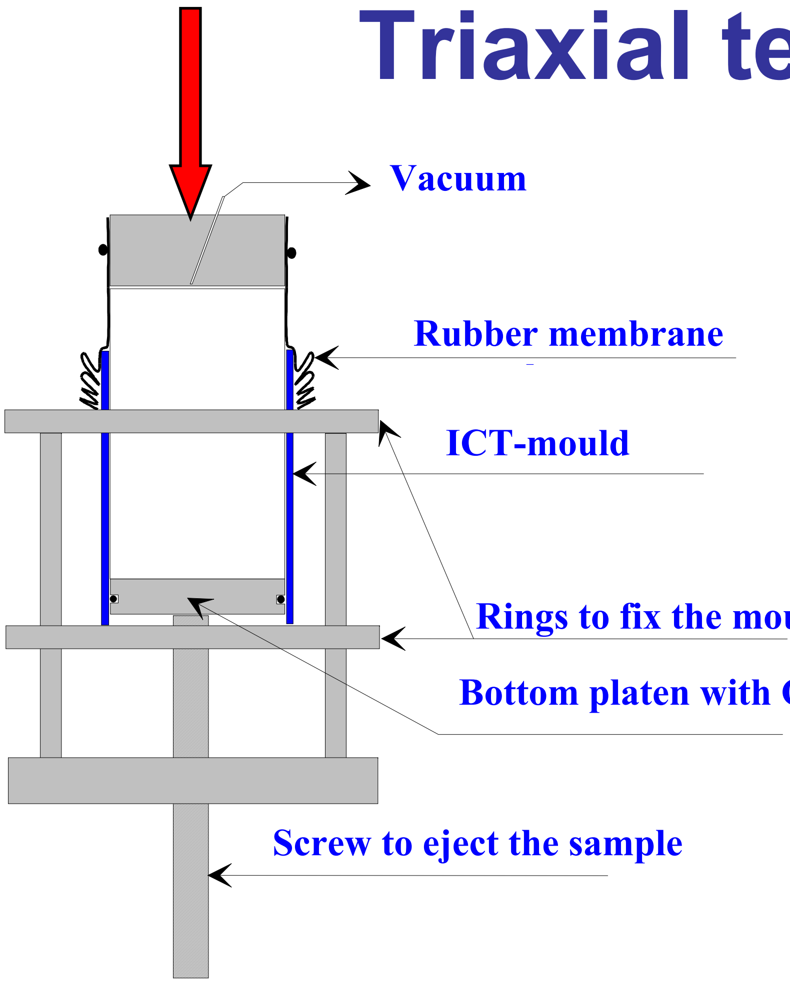
Plate loading in combination with compactor measurment

Gives accepted bearing capacity and following data:

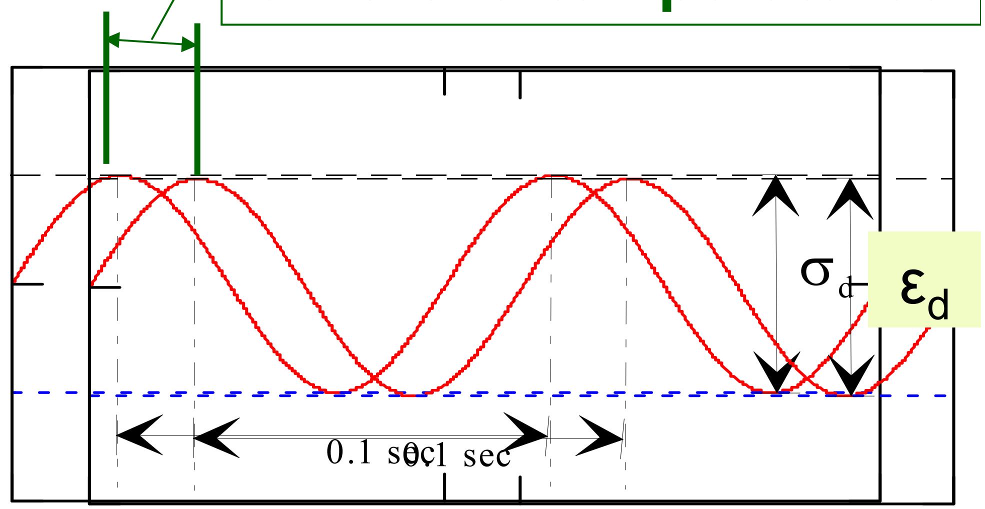
- **Unlinear elasticity modulus (resilient modulus)**
- **Deflection in bottom of the asphalt layer – Fatigue (cracks)**

TEST METHODS
bituminous bound layers

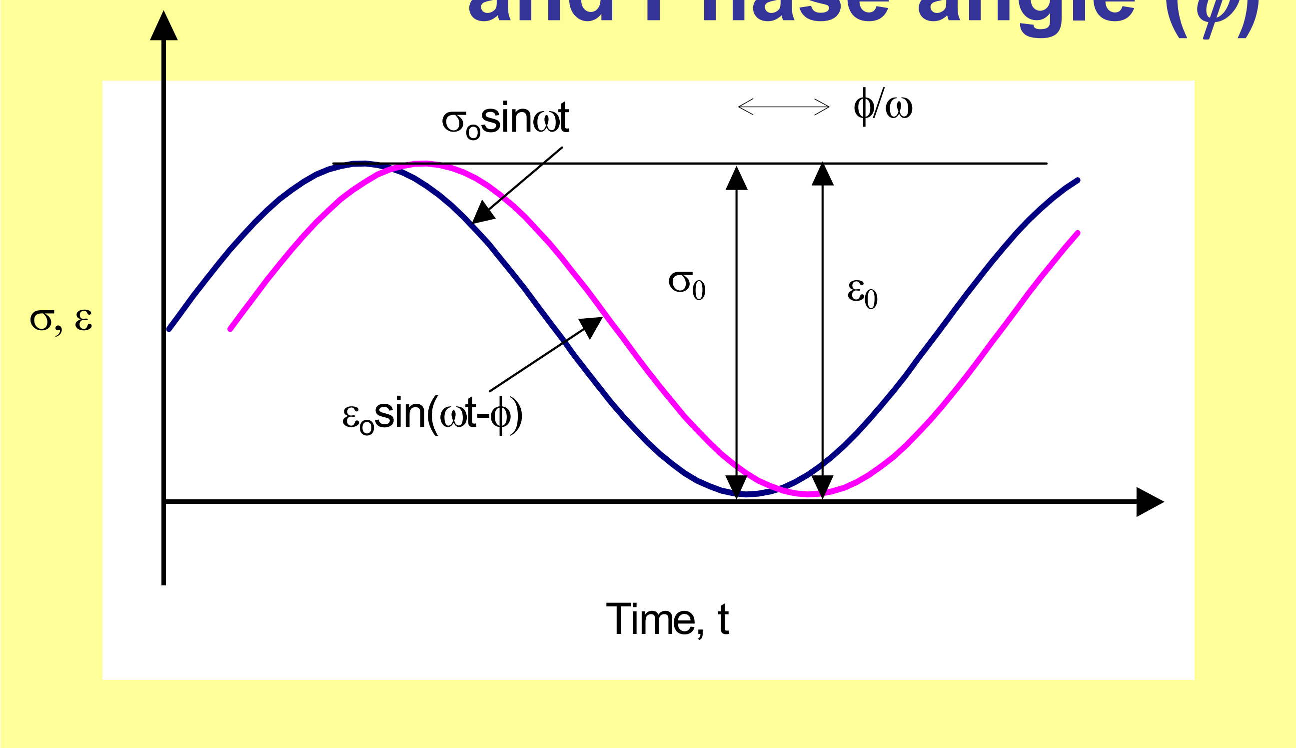
Triaxial test

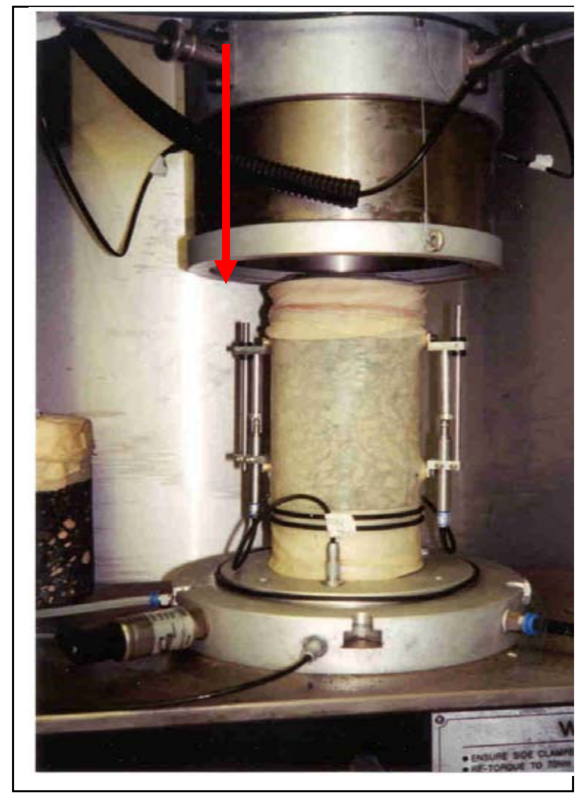


Phase displacement at different temperatures



Compressive Dynamic Modulus (|E*|) and Phase angle (ϕ)

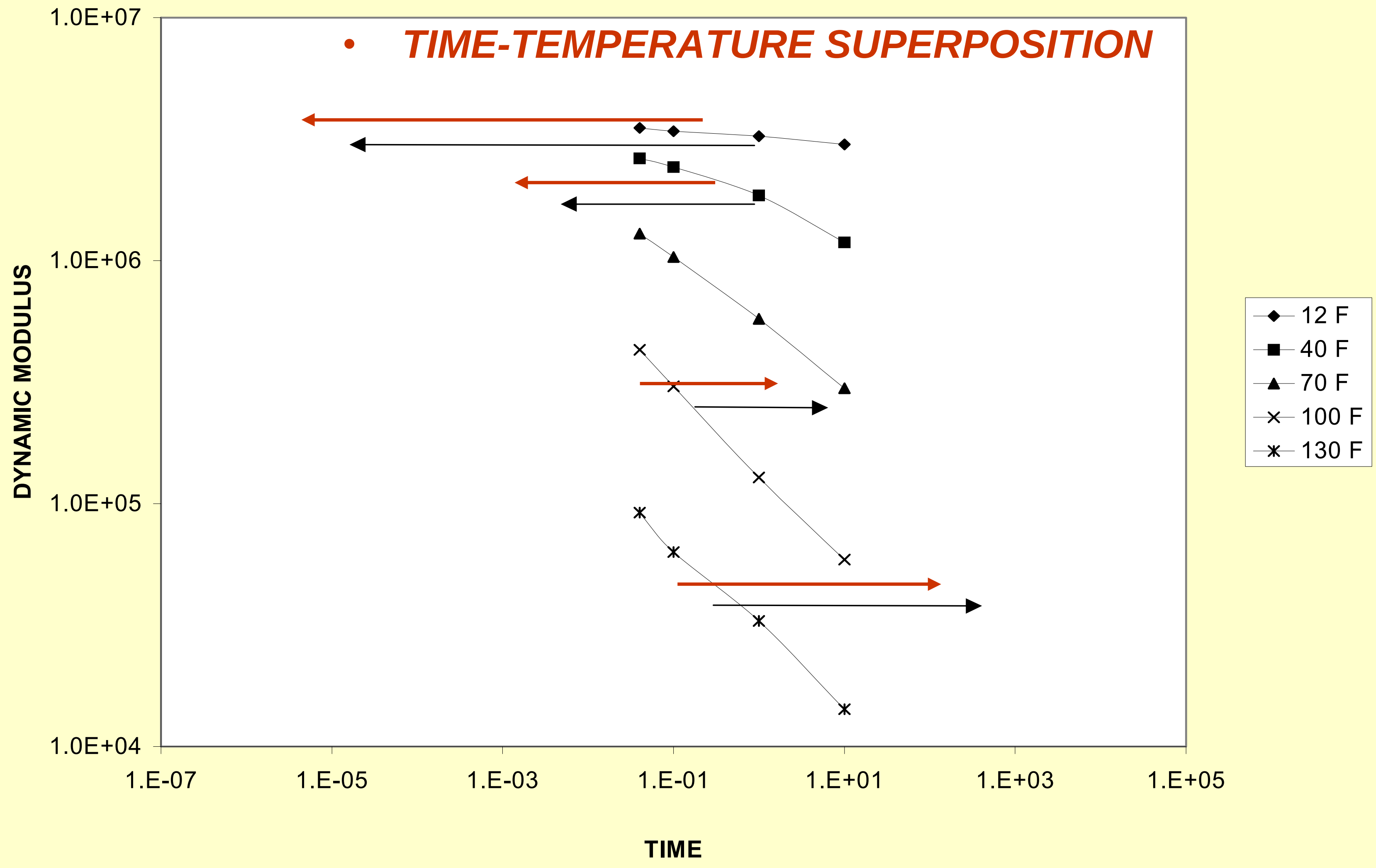




$$|E^*| = \frac{\sigma_0}{\varepsilon_0}$$

$$\phi = \omega t_i$$

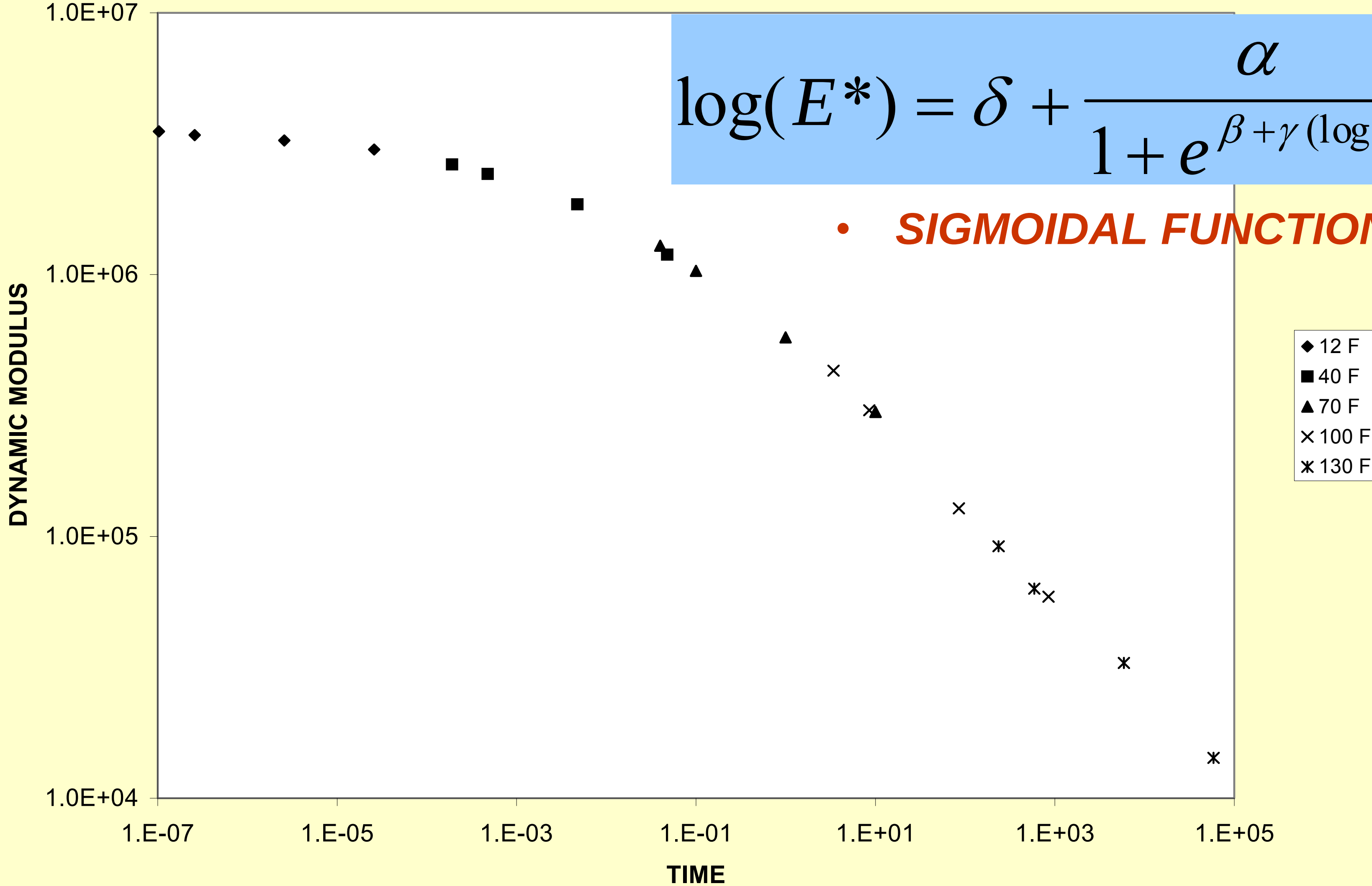
Dynamic Modulus Master Curve



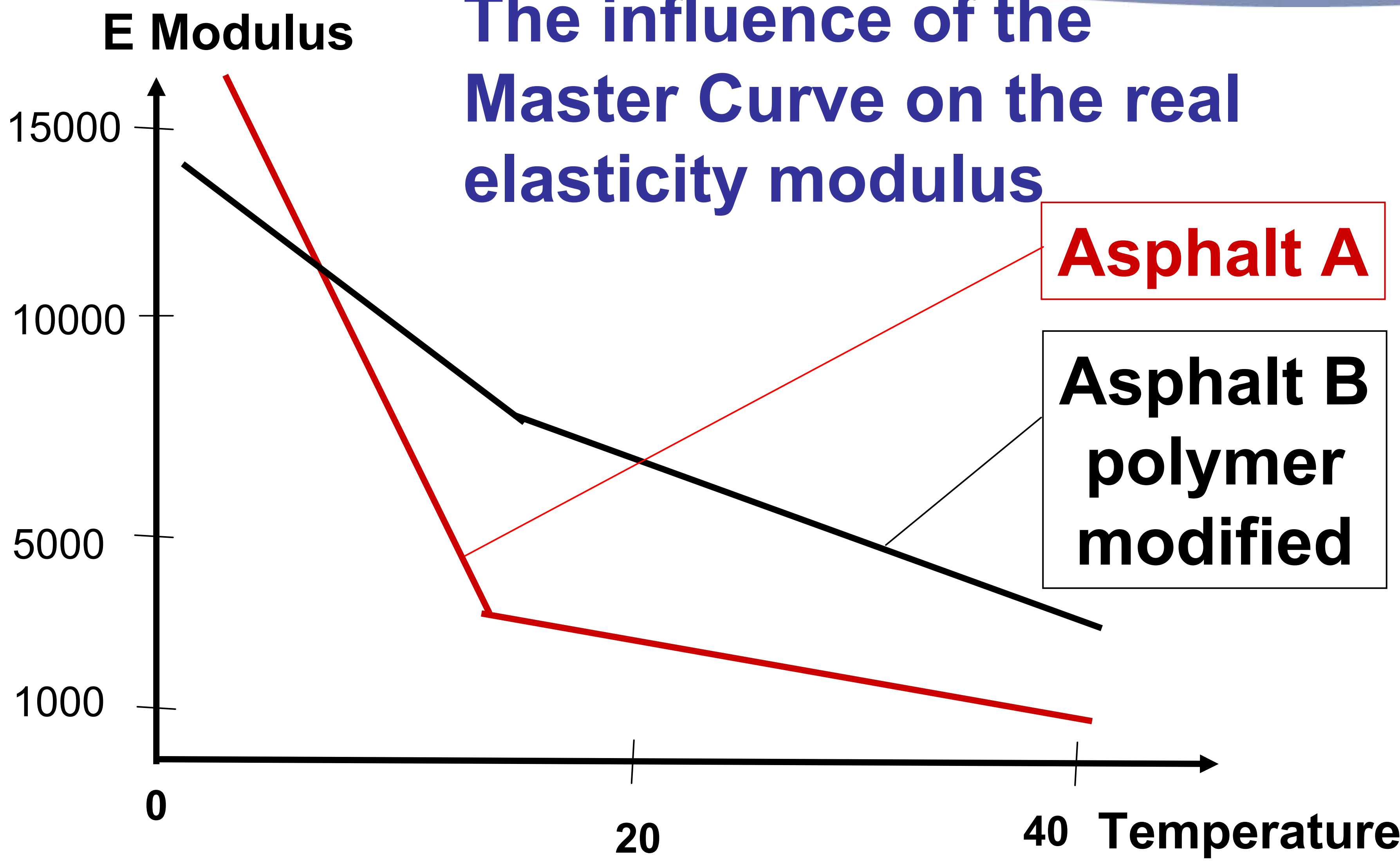
Dynamic Modulus Master Curve

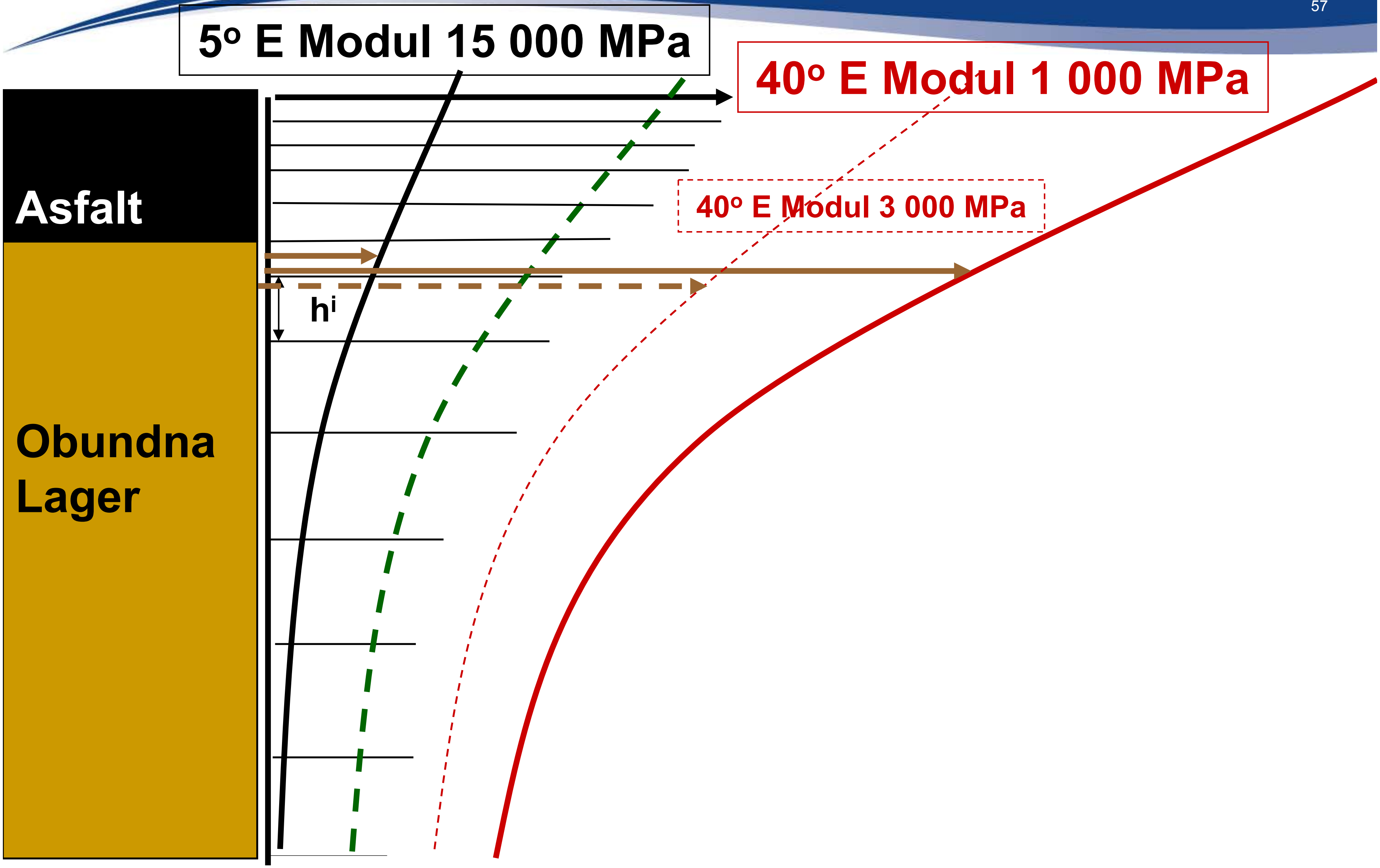
$$\log(E^*) = \delta + \frac{\alpha}{1+e^{\beta+\gamma(\log t_r)}}$$

- *SIGMOIDAL FUNCTION*



The influence of the Master Curve on the real elasticity modulus

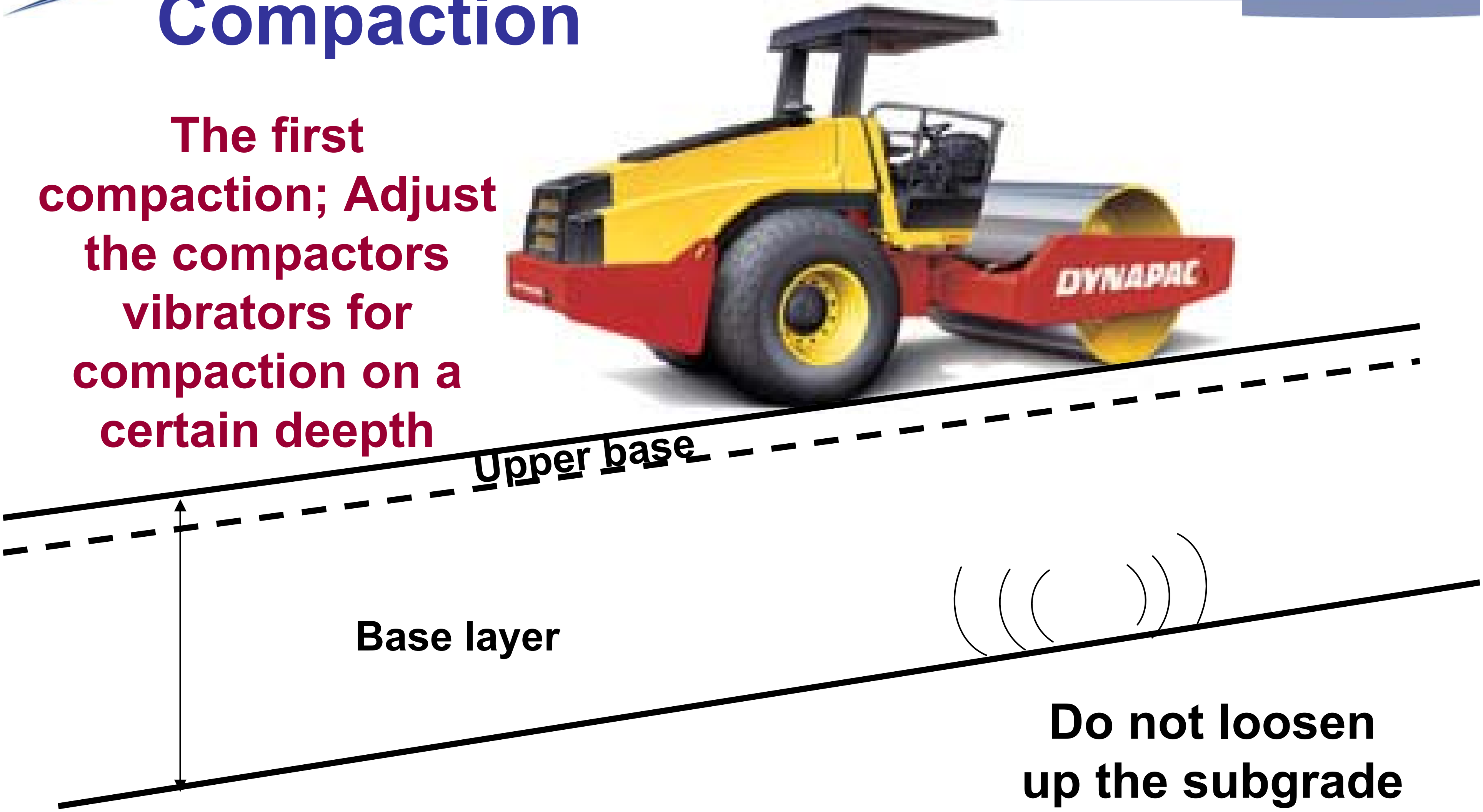



5º E Modul 15 000 MPa
40º E Modul 1 000 MPa
40º E Modul 3 000 MPa
Asfalt
hi
Obundna
Lager

Compaction

Compaction

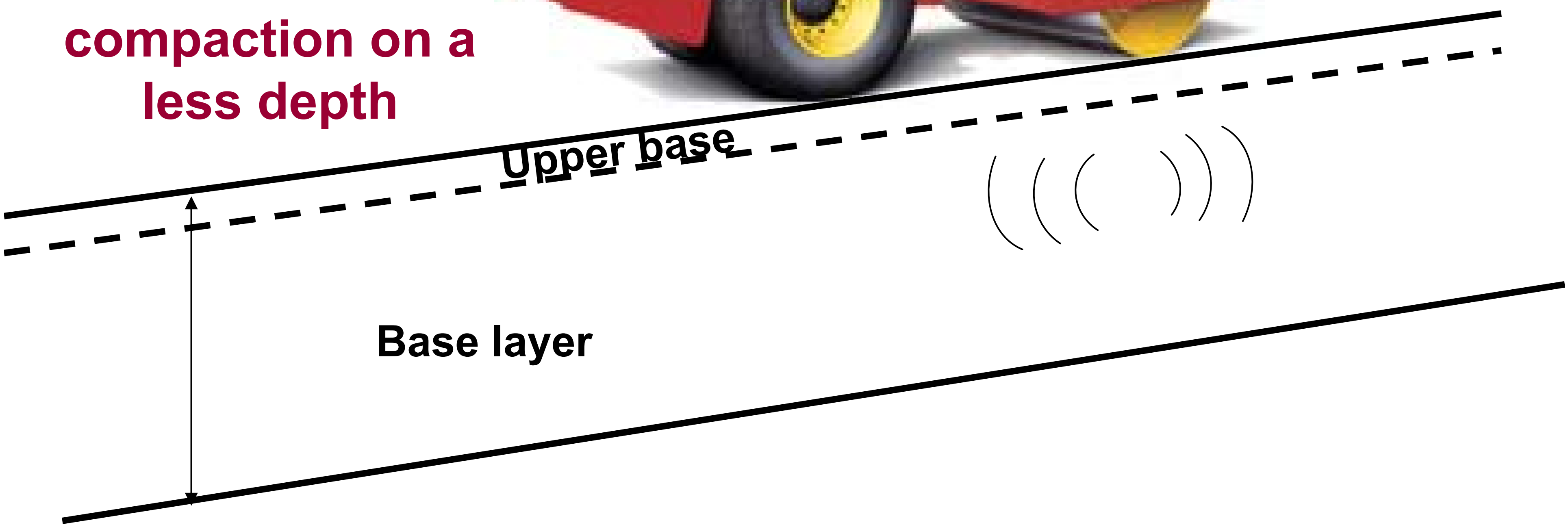
The first compaction; Adjust the compactors vibrators for compaction on a certain deepth



Do not loosen up the subgrade

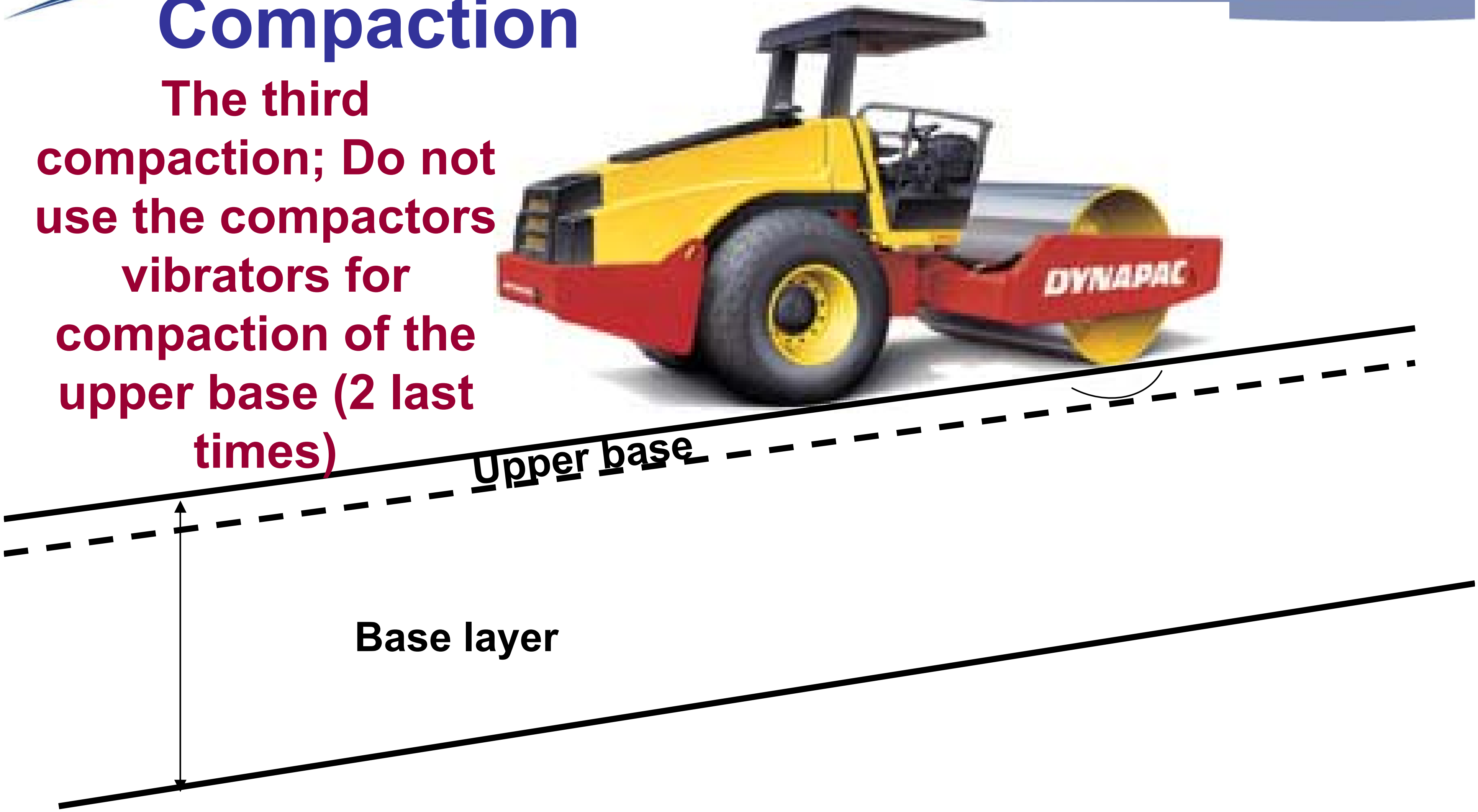
Compaction

The second compaction; Adjust the compactors vibrators for compaction on a less depth



Compaction

The third compaction; Do not use the compactors vibrators for compaction of the upper base (2 last times)

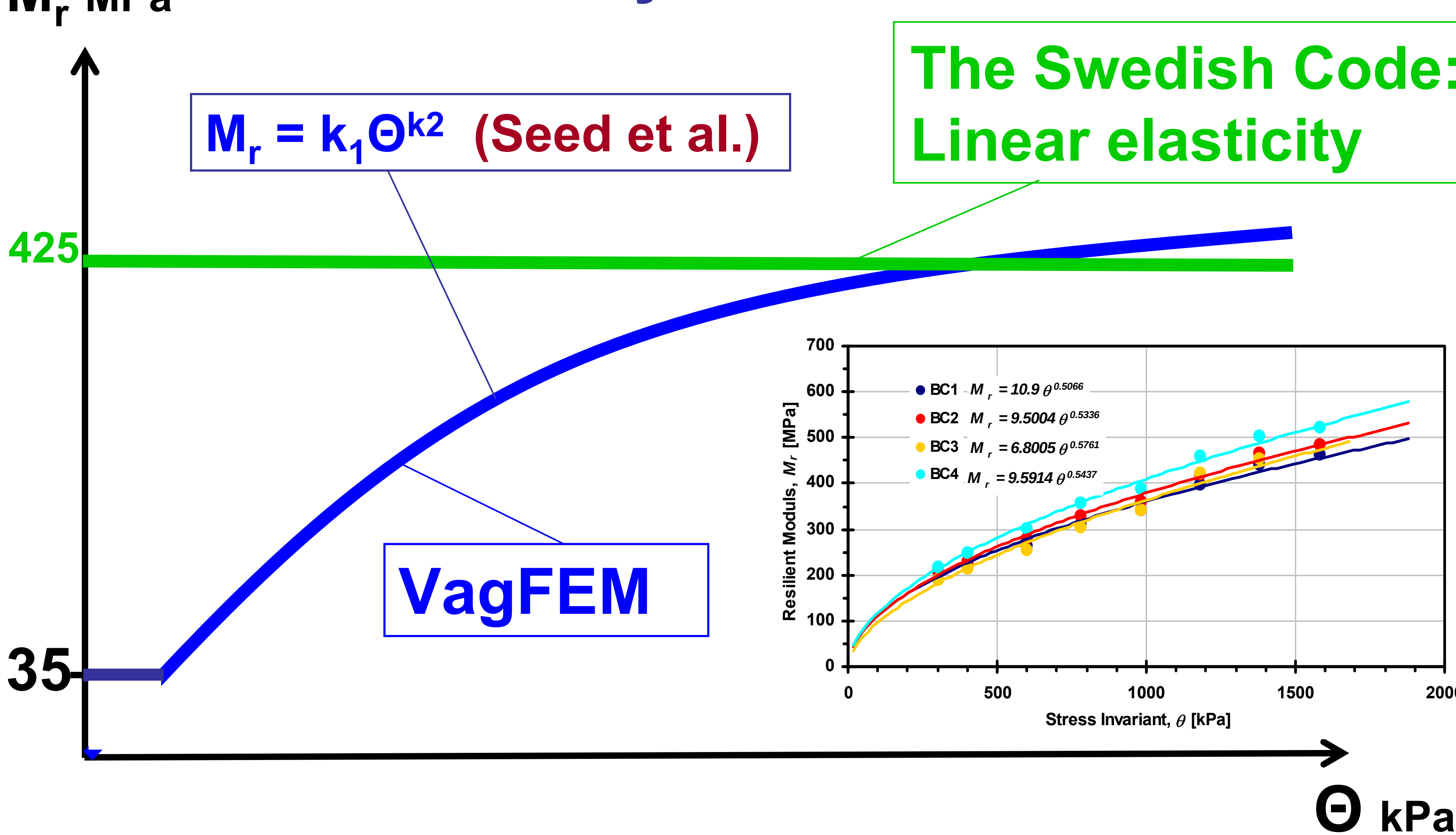


In the project "Active Design" SRA co-operates with the contractors (SBUF) and consultants in order to use new knowledge for mechanistic design.

This knowledge is taken from research in Sweden and other countries above all from SAMARIS and Design Guide

MATERIAL MODELS
unbound layers

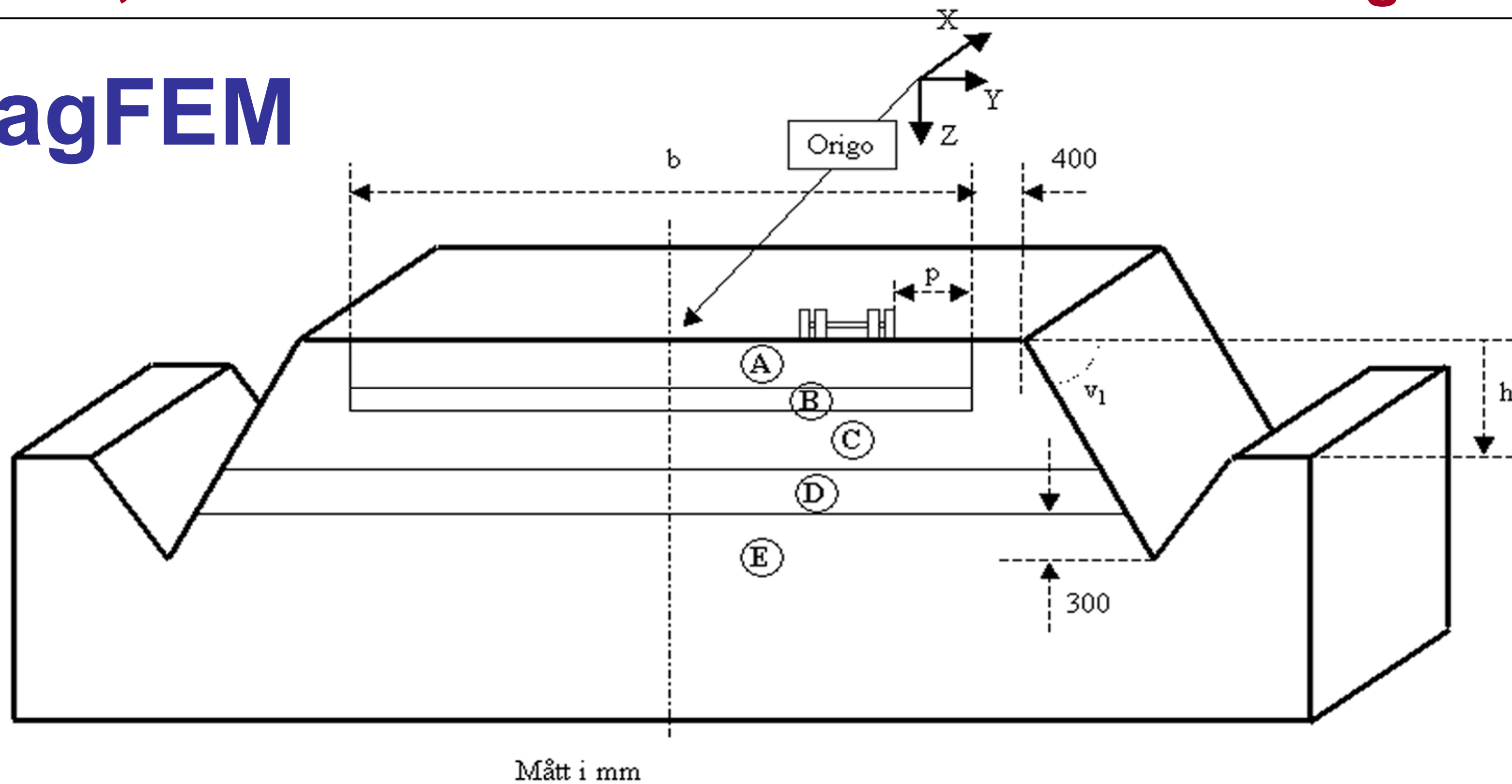
Unbound layer: Simulated E-modulus



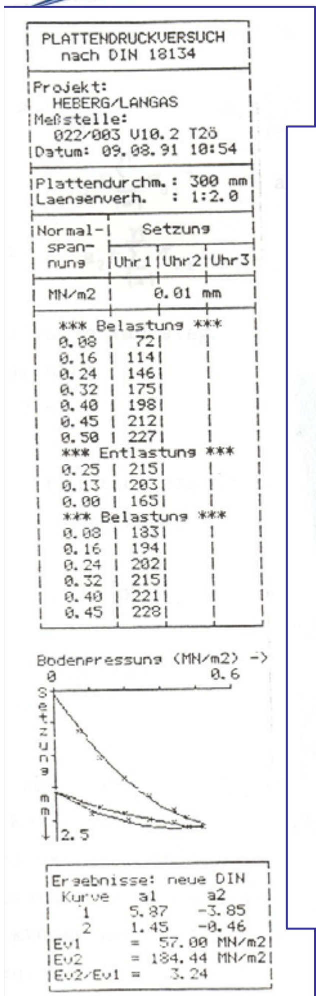
USER FRIENDLY PROGRAMS

VagFEM is a 3D finite element program, built on ABAQUS, and run in a large computer. The result is coming back as a PDF-file inside 20 minutes. The input data is very easy to handle, it could be done in 3 minutes on a working site.

VagFEM



Test: Plate loading


PLATTENDRUCKVERSUCH
nach DIN 18134

Projekt:
HEBERG/LANGAS
Meßstelle:
022/003 V10.2 T2ö
Datum: 09.08.91 10:54

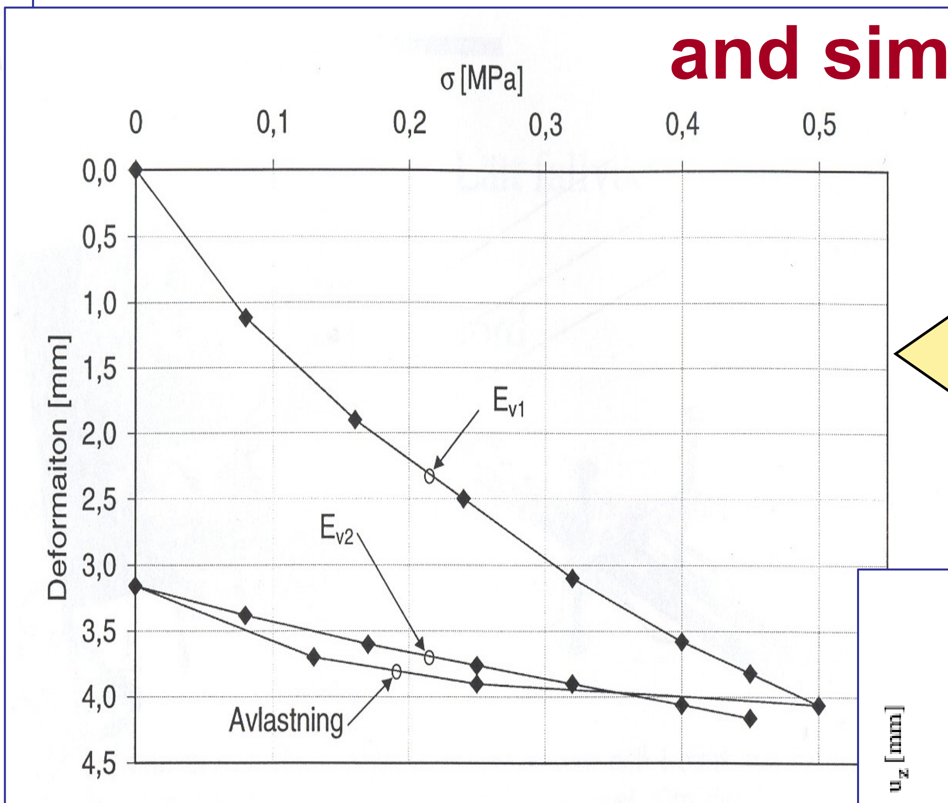
Plattendurchm.: 300 mm
Laengenverh. : 1:2.0

Normal-spannung	Setzung		
	Uhr1	Uhr2	Uhr3
MN/m2	0.01 mm		
*** Belastung ***			
0.08	72		
0.16	114		
0.24	146		
0.32	175		
0.40	198		
0.45	212		
0.50	227		
*** Entlastung ***			
0.25	215		
0.13	203		
0.00	165		
*** Belastung ***			
0.08	183		
0.16	194		
0.24	202		
0.32	215		
0.40	221		
0.45	228		

Ergebnisse: neue DIN

Kurve	a1	a2
1	5.87	-3.85
2	1.45	-0.46

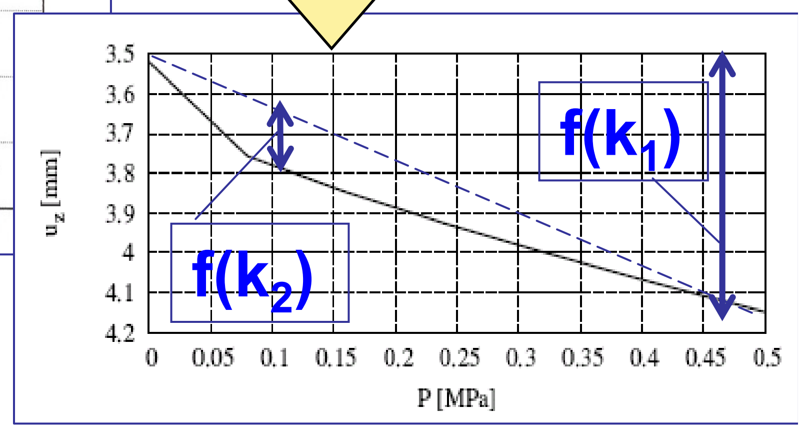
Ev1 = 57.00 MN/m2
Ev2 = 184.44 MN/m2
Ev2/Ev1 = 3.24



Result from Plate loading and simulation in VagFEM

Resilient Module

$$Mr = k_1 \Theta^{k2}$$

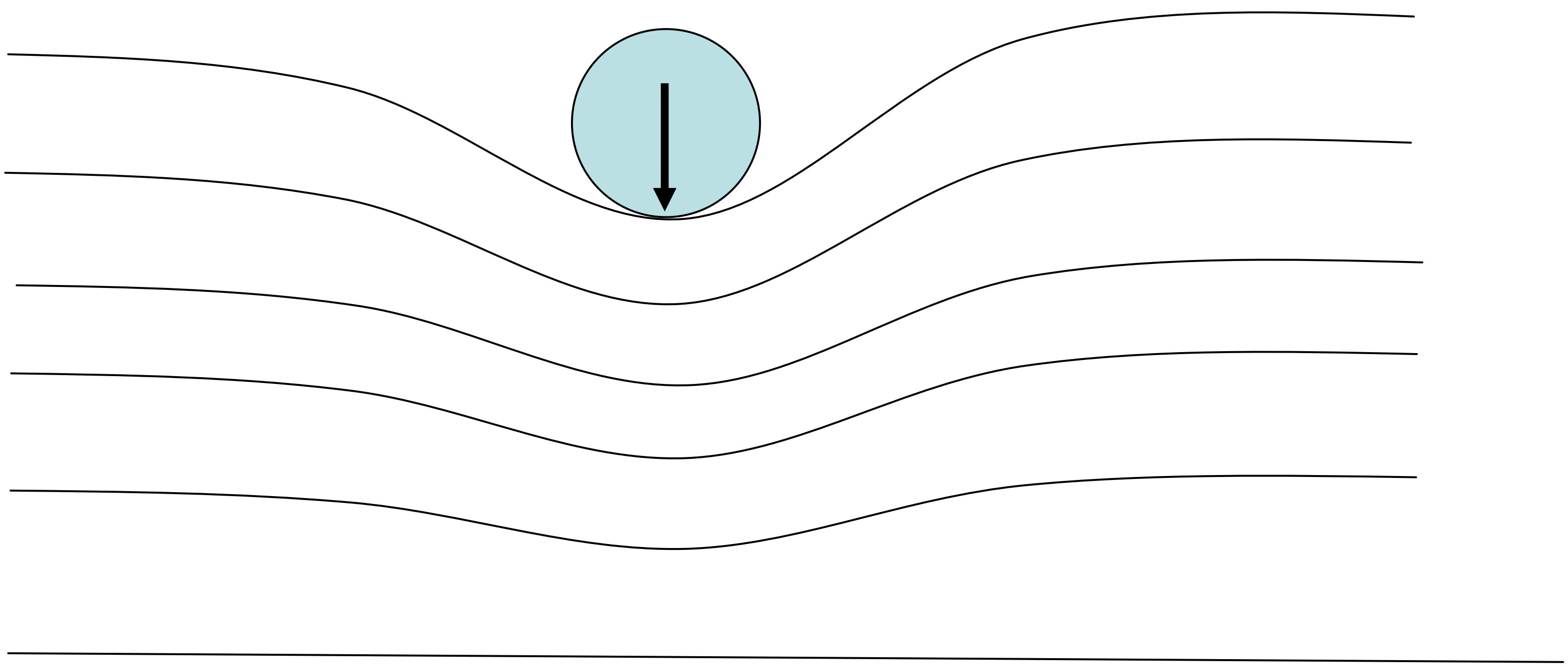


Measured Mr_1 in subgrade is used as input data in calculation of Mr_2 in subbase

Calculation of rutting

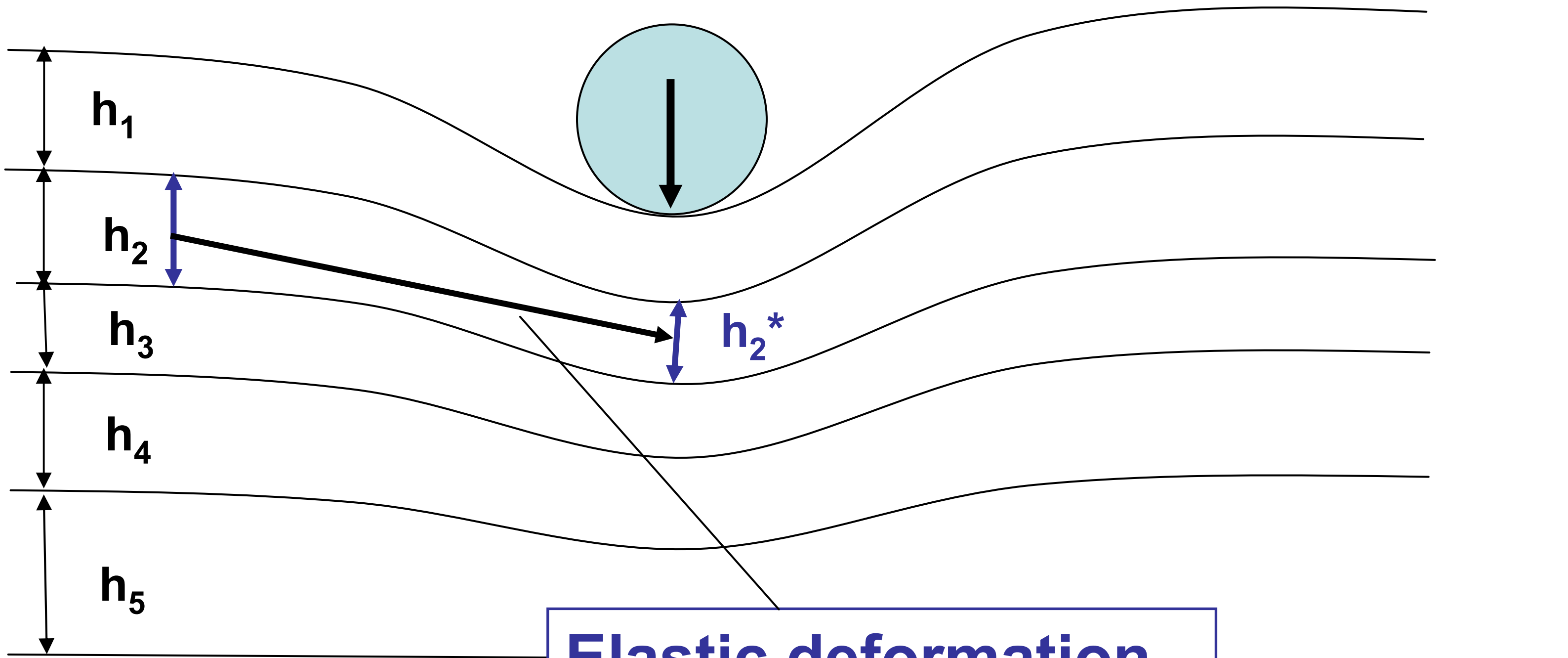
Elastic deflection from a heavy vehicle

Elastic deflection from a heavy vehicle



Elastic deflection from a heavy vehicle

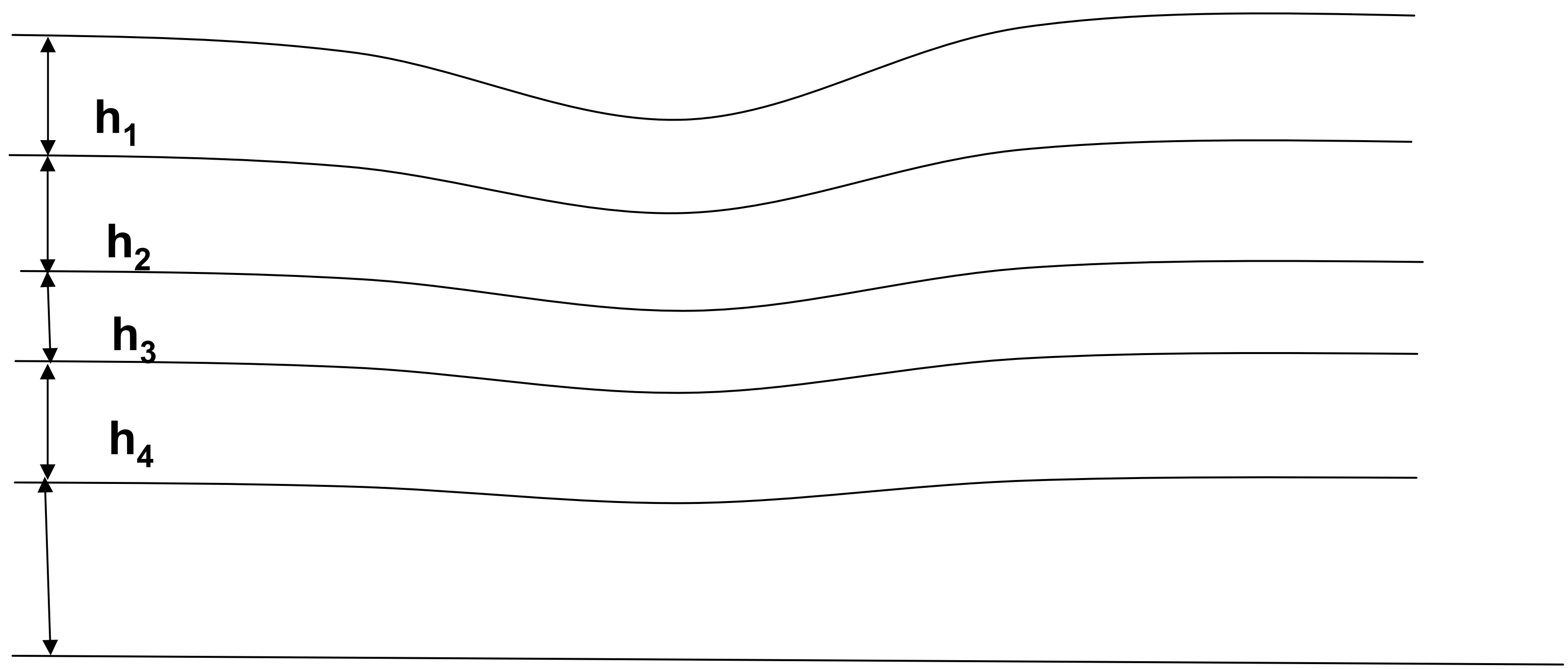
Elastic deflection from a heavy vehicle



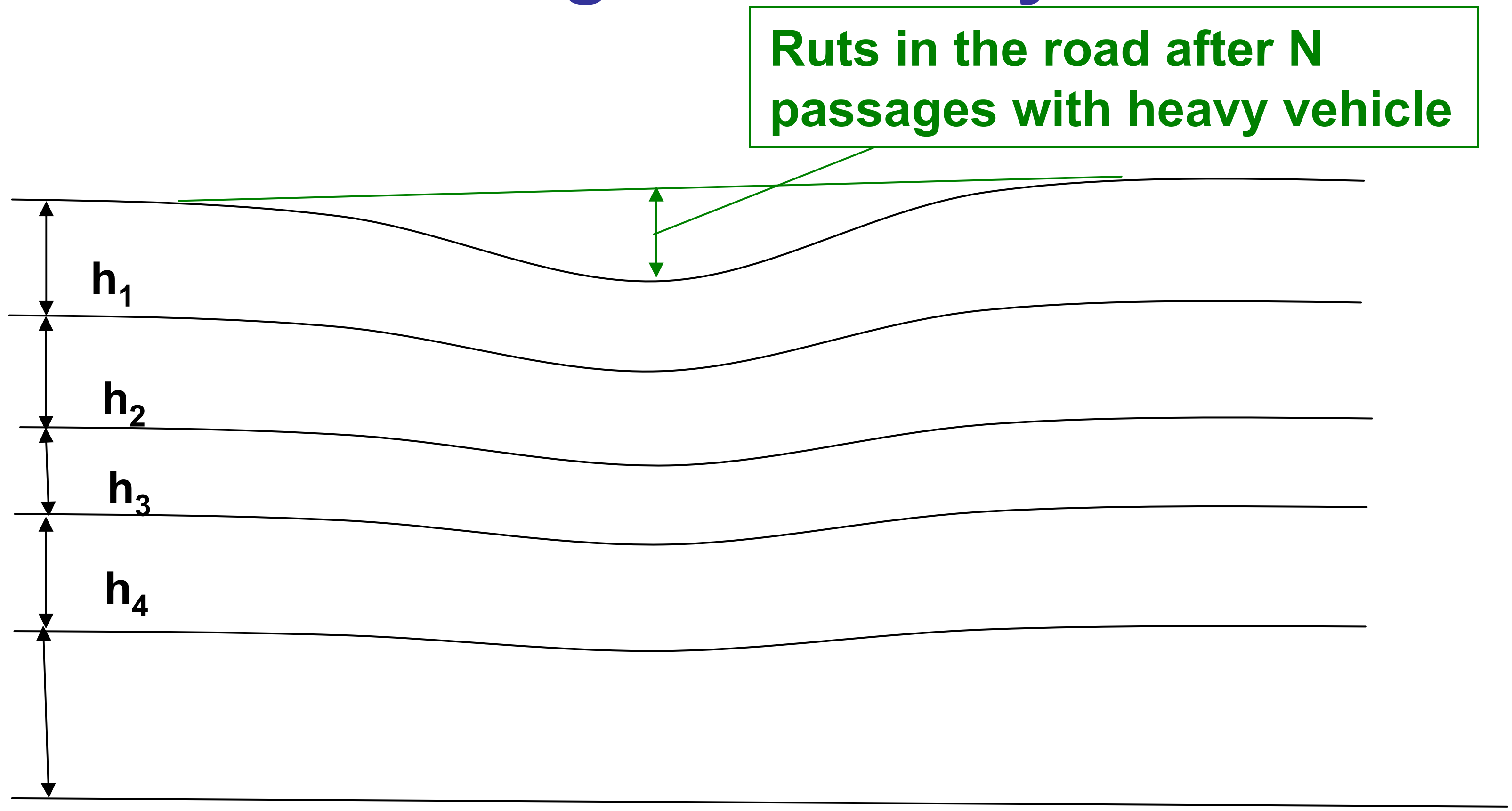
Elastic deformation

$$\varepsilon_e = (h_2 - h_2^*)/h_2$$

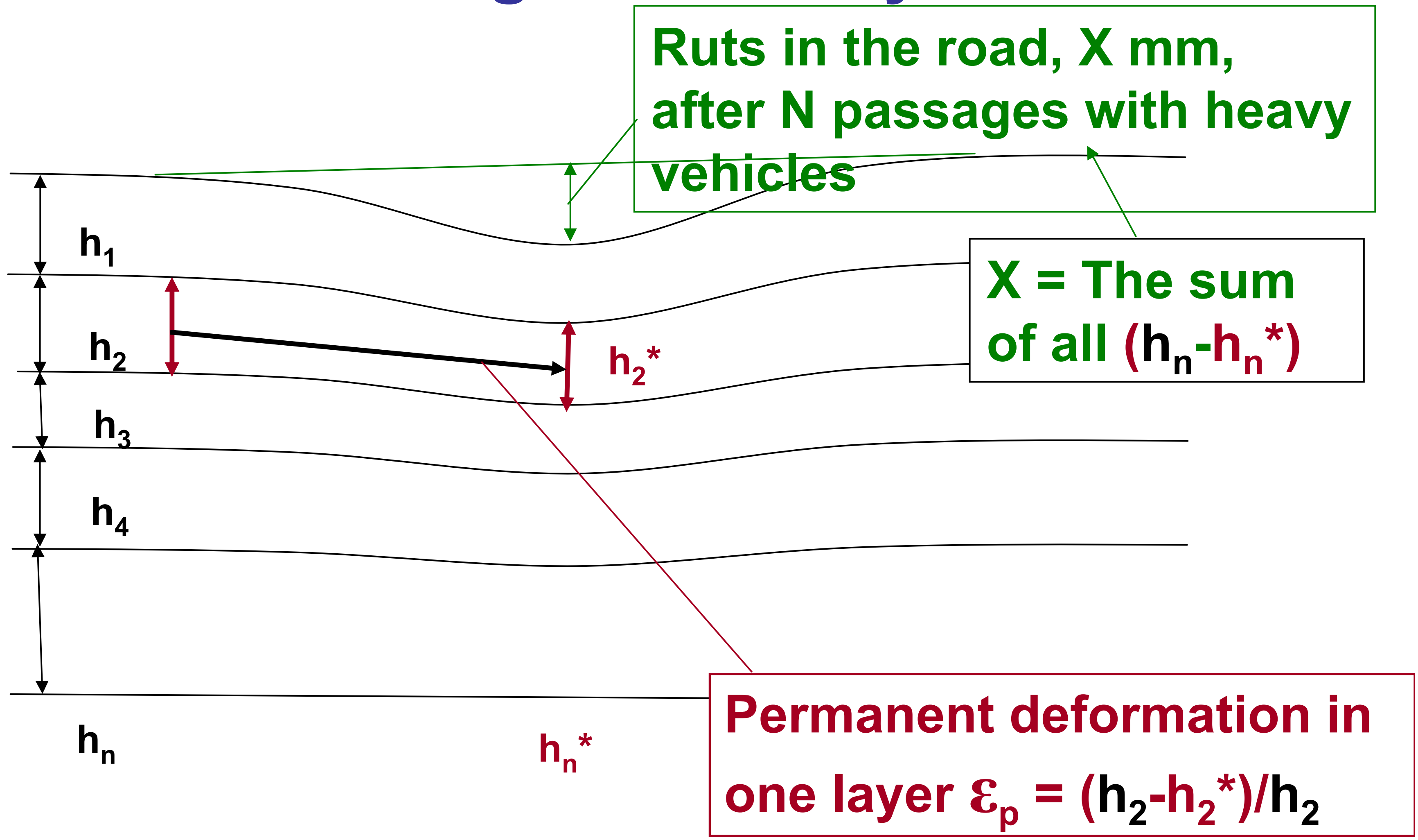
Permanent rutting from heavy vehicle



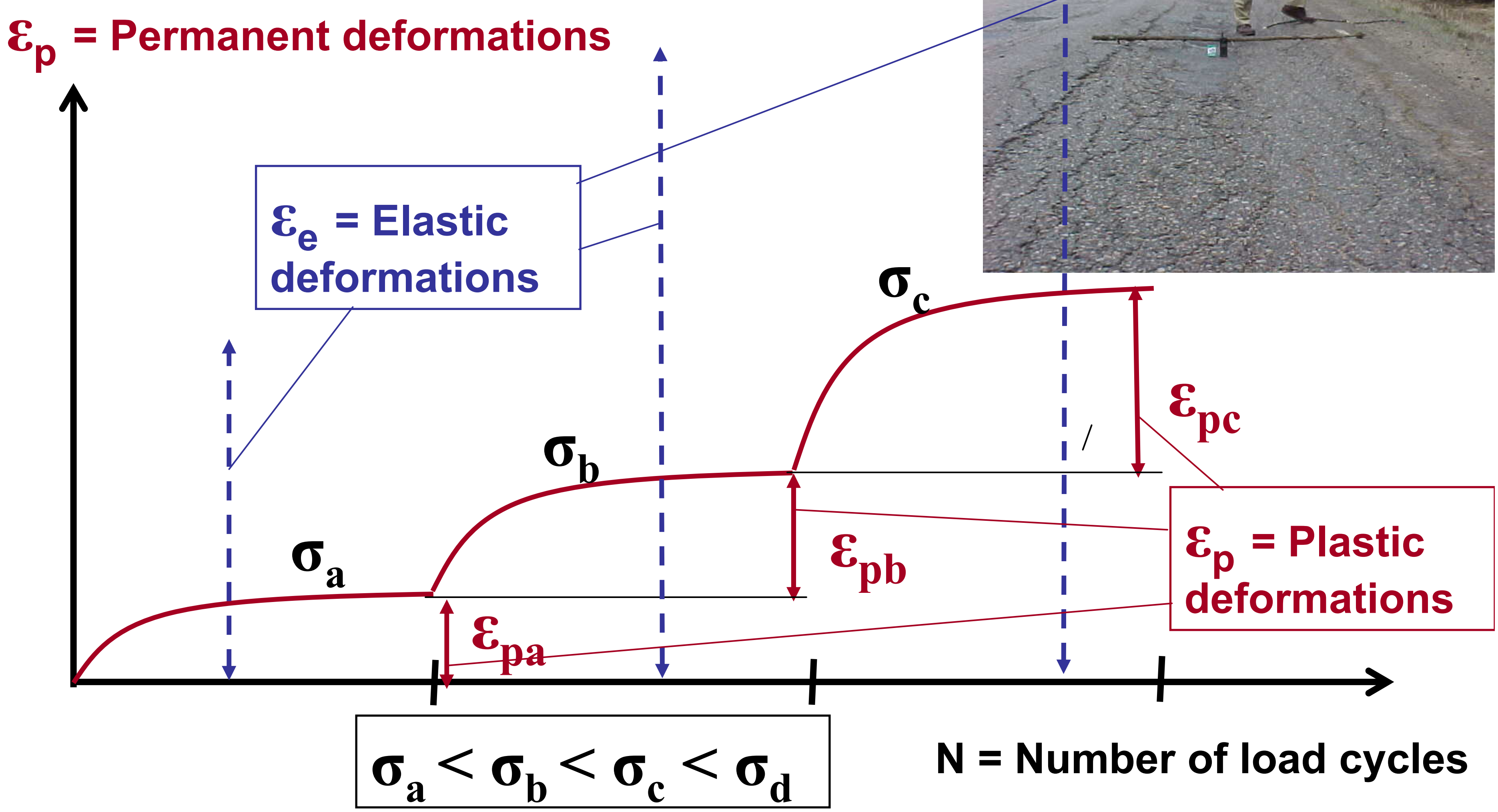
Permanent rutting from heavy vehicle

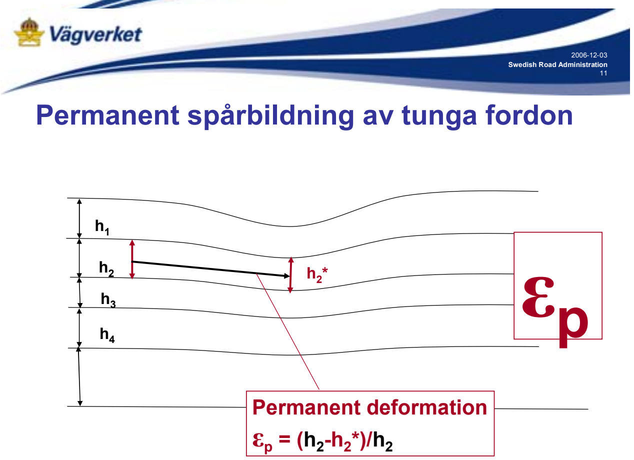


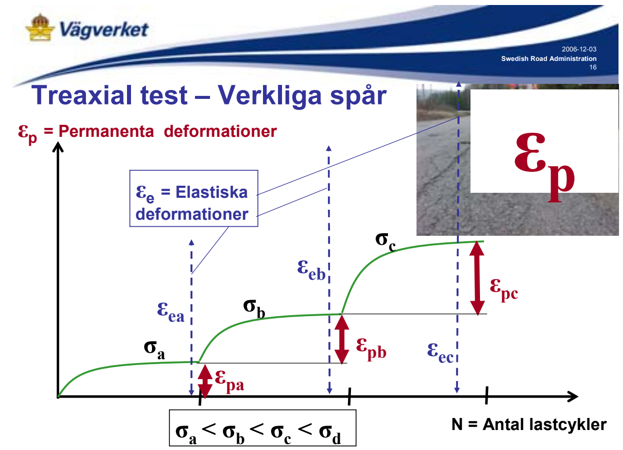
Permanent rutting from heavy vehicle



Triaxial test – Real ruts



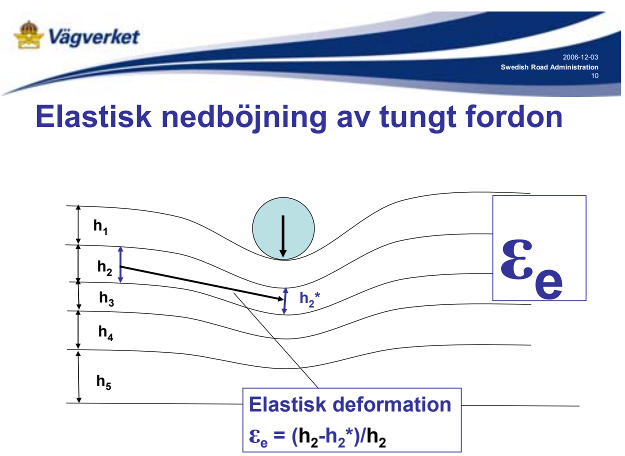


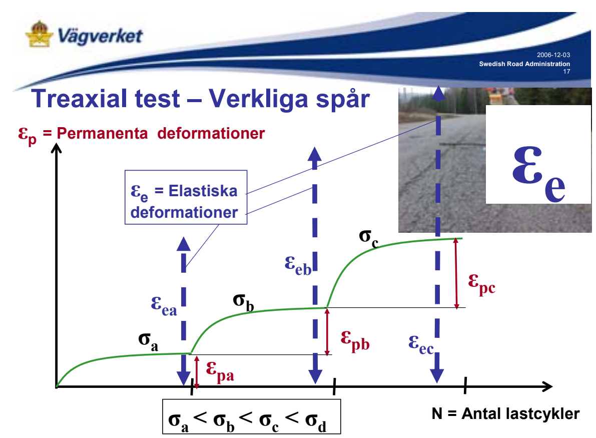


Real ruts

$$\frac{\varepsilon_p}{f(\sigma,\varepsilon_e)} = \frac{\varepsilon_p}{f(\sigma,\varepsilon_e)}$$

Triaxial test





MATERIAL MODELS
Rutting

Calculation of permanent deformations

$$\varepsilon_p = f\left(\varepsilon_{r_i}, N\right)$$

$$\frac{\varepsilon_{p_i}^{lab}}{\varepsilon_{r_i}^{lab}} = \frac{\varepsilon_{p_i}^{field}}{\varepsilon_{r_i}^{field}} \Rightarrow \varepsilon_{p_i}^{field} = \frac{\varepsilon_{p_i}^{lab}}{\varepsilon_{r_i}^{lab}} \cdot \varepsilon_{r_i}^{field}$$

Calculation of permanent deformations

NCHRP 1-37A Pavement Design Guide Prediction Models

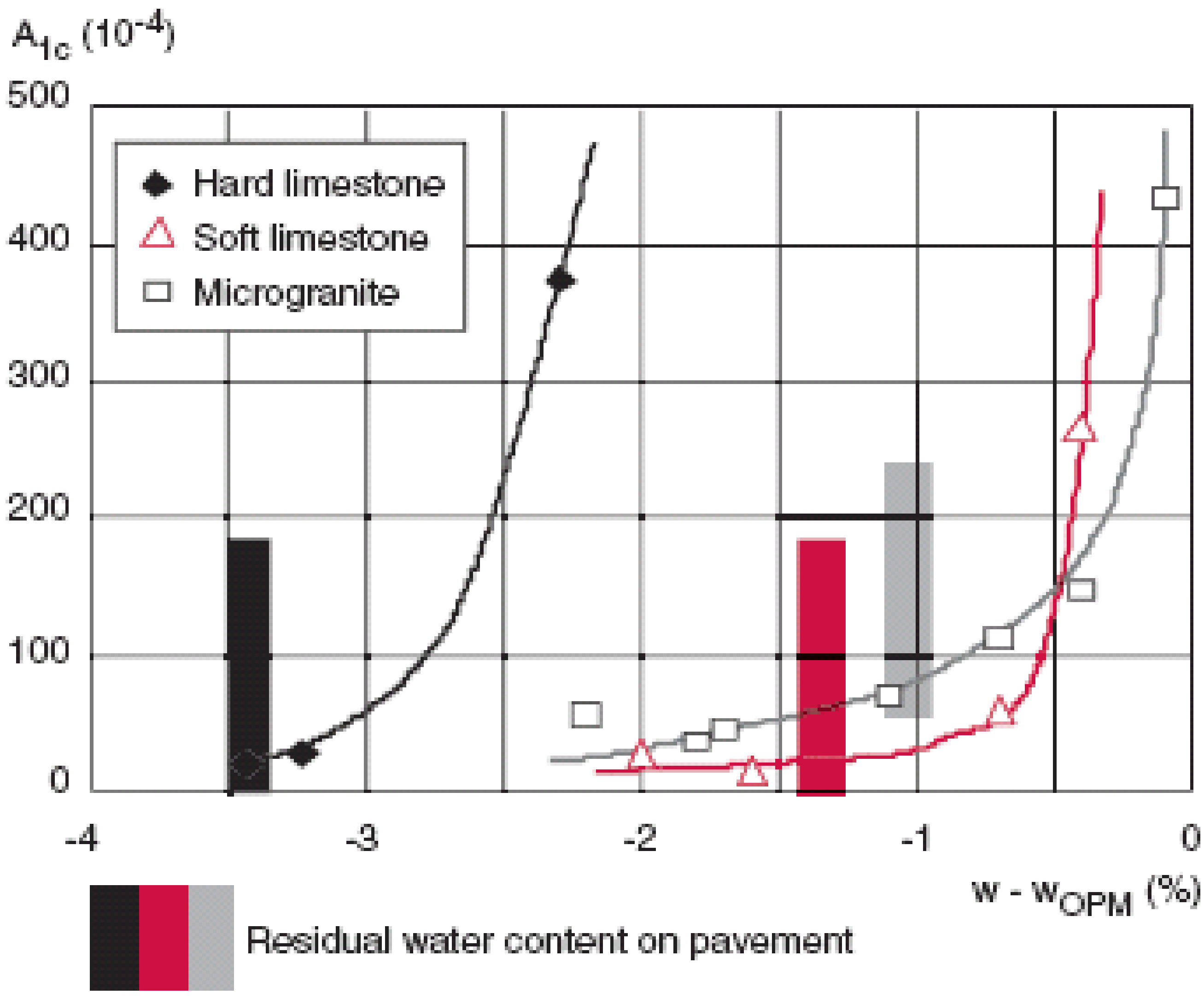
$$PD = \sum_{i=1}^{nsublayers} \varepsilon_p^i \cdot h^i$$

PD	**– Permanent deformation**
Nsublayers	**– Number of sub layers**
ε_p^i	**– Total plastic strain in sub layer i**
h^i	**– Thicness of sub layer i**

MATERIAL MODELS
Rutting in unbound materials

SAMARIS

Permanent deformations depending on moisture content



Calculation of permanent deformations – LCPC

$$\varepsilon_1^p(N) = \varepsilon_{10}^p \cdot \left[1 - \left(\frac{N}{N_0}\right)^{-B}\right] \cdot \left[\frac{L_{max}}{p_a}\right]^n \cdot \frac{1}{\left(m + \frac{s}{p_{max}} - \frac{q_{max}}{p_{max}}\right)}$$

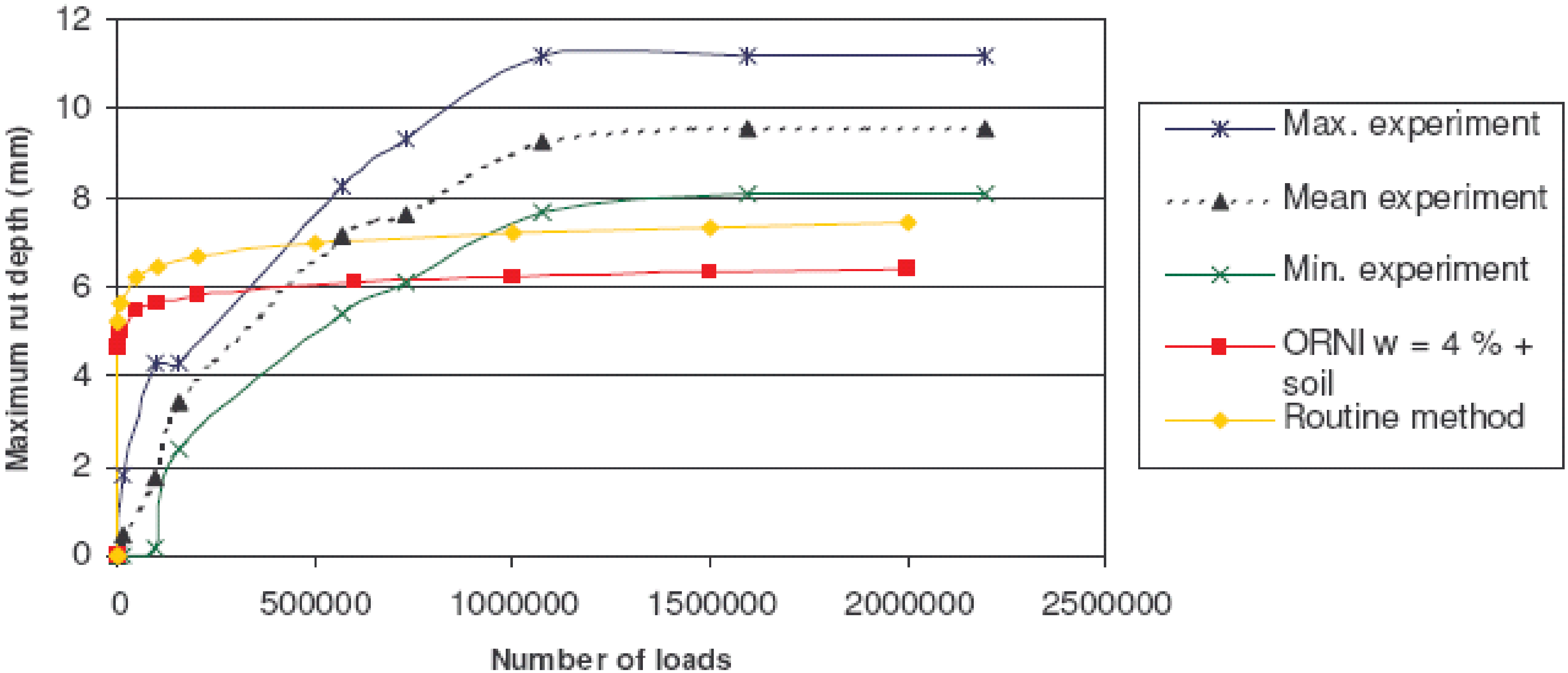
ε_1^p : permanent axial strain; N : number of load cycles;
p_{max}, q_{max} : maximum values of the mean normal stress p and deviatoric stress q;

$$L_{max} = \sqrt{p_{max}^2 + q_{max}^2}$$

Samaris

P_a : reference pressure equal to 100 kPa;
ε_1^{p0}, B, n model parameters;
m,s parameters of the failure line of the material, of equation q = m.p+s;
(from experience, m=2.5 to 2.6 and s=20 kPa)

Result: Prediction of permanent deformation, rutting



MATERIAL MODELS
Rutting in unbound materials

Design Guide

Theoretical background

Original model for calculation of permanent deformations, Tseng and Lytton

$$\delta_a(N) = \beta_{GB}\left(\frac{\varepsilon_0}{\varepsilon_r}\right)e^{-\left(\frac{\rho}{N}\right)^{\beta}}\varepsilon_v h$$

Problems with some strange results made that the choice in Design Guide is a more empirical and statistical model

Modeling permanent deformation – Unbound material

modified models for $\varepsilon_0/\varepsilon_r$, β and ρ developed in NCHRP Project 1-37A for granular and subgrade materials

Granular

$$\log\left(\frac{\varepsilon_0}{\varepsilon_r}\right) = 0.80978 - 0.06626 \cdot W_c - 0.003077 \cdot \sigma_\theta + 0.000003 \cdot E_r$$

$$\log(\beta) = -0.9190 + 0.03105 \cdot W_c + 0.001806 \cdot \sigma_\theta - 0.0000015 \cdot E_r$$

$$\log(\rho) = -1.78667 + 1.45062 \cdot W_c + 0.0003784 \cdot \sigma_\theta^{\,2} - 0.002074 \cdot W_c^{\,2} \sigma_\theta - 0.0000105 \cdot E_r$$

Subgrade

$$\log\left(\frac{\varepsilon_0}{\varepsilon_r}\right) = -1.69867 + 0.09121 \cdot W_c - 0.11921 \cdot \sigma_d + 0.91219 \cdot \log E_r$$

$$\log(\beta) = -0.9730 - 0.0000278 \cdot W_c^{\,2} \sigma_d + 0.017165 \cdot \sigma_d - 0.0000338 \cdot W_c^{\,2} \sigma_\theta$$

$$\log(\rho) = 11.009 + 0.00068 \cdot W_c^{\,2} \sigma_d - 0.40260 \cdot \sigma_d + 0.0000545 \cdot W_c^{\,2} \sigma_\theta$$

Influence from moisture; Design Guide

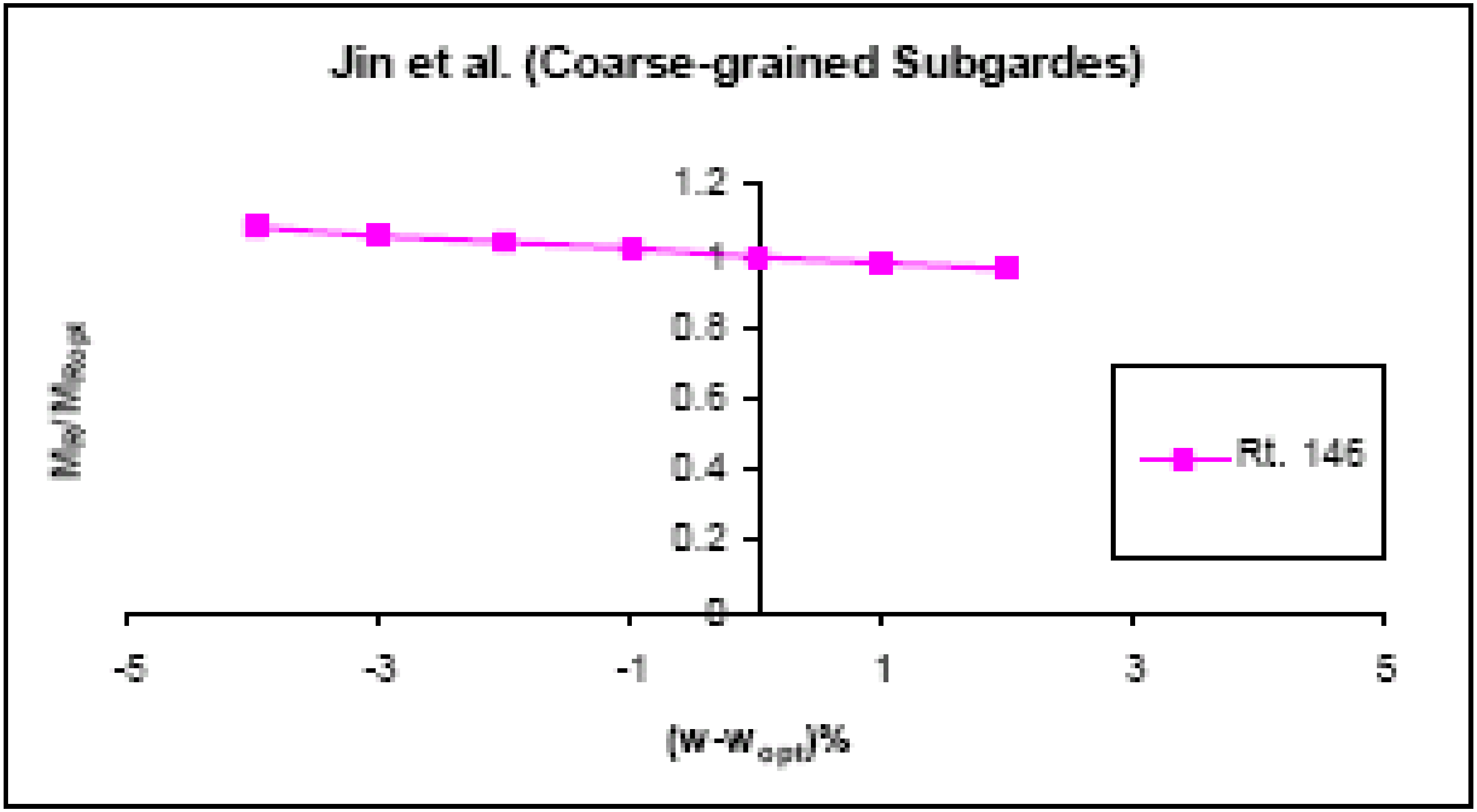


Figure 9a. Normalized Modulus Versus Variation in Moisture Content

MATERIAL MODELS
Rutting in bituminous bound materials

Design Guide

Modelling permanent deformation

Asphalt layer – Design Guide

$$\frac{\varepsilon_p}{\varepsilon_r} = a_1 \cdot N^{a_2} \cdot T^{a_3}$$

ε_p – Accumulated plastic strain at N repetitions of load
ε_r – Resilient strain of the asphalt material
N – Number of load repetitions
T – Temperature (10°C)
a_i – Non-linear regression coefficients (from NCHRP 1-37A)

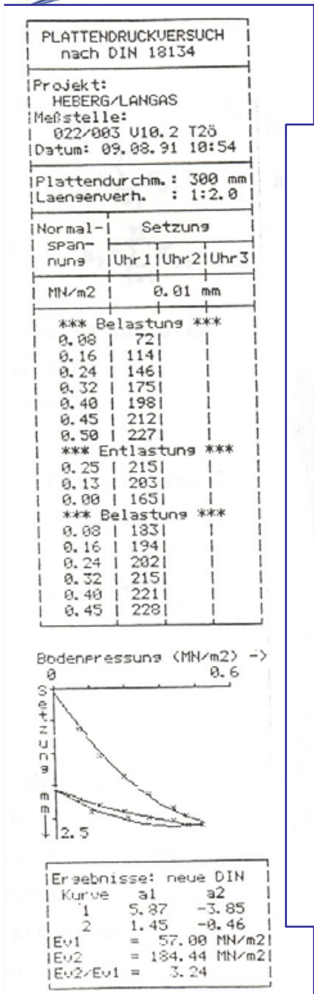
THANK YOU FOR YOUR ATTENTION

Anders Huvstig

Swedish Road Administration (SRA)

Calculations in practice

Test: Plate loading



PLATTENDRUCKVERSUCH
nach DIN 18134

Projekt:
HEBERG/LANGAS
Meßstelle:
022/003 U10.2 T2ö
Datum: 09.08.91 10:54

Plattendurchm. : 300 mm
Laengenverh. : 1:2.0

Normal-spannung	Setzung Uhr1	Uhr2	Uhr3
MN/m2	0.01 mm		
*** Belastung ***			
0.08	72		
0.16	114		
0.24	146		
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0.40	198		
0.45	212		
0.50	227		
*** Entlastung ***			
0.25	215		
0.13	203		
0.00	165		
*** Belastung ***			
0.08	183		
0.16	194		
0.24	202		
0.32	215		
0.40	221		
0.45	228		

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Kurve	a1	a2
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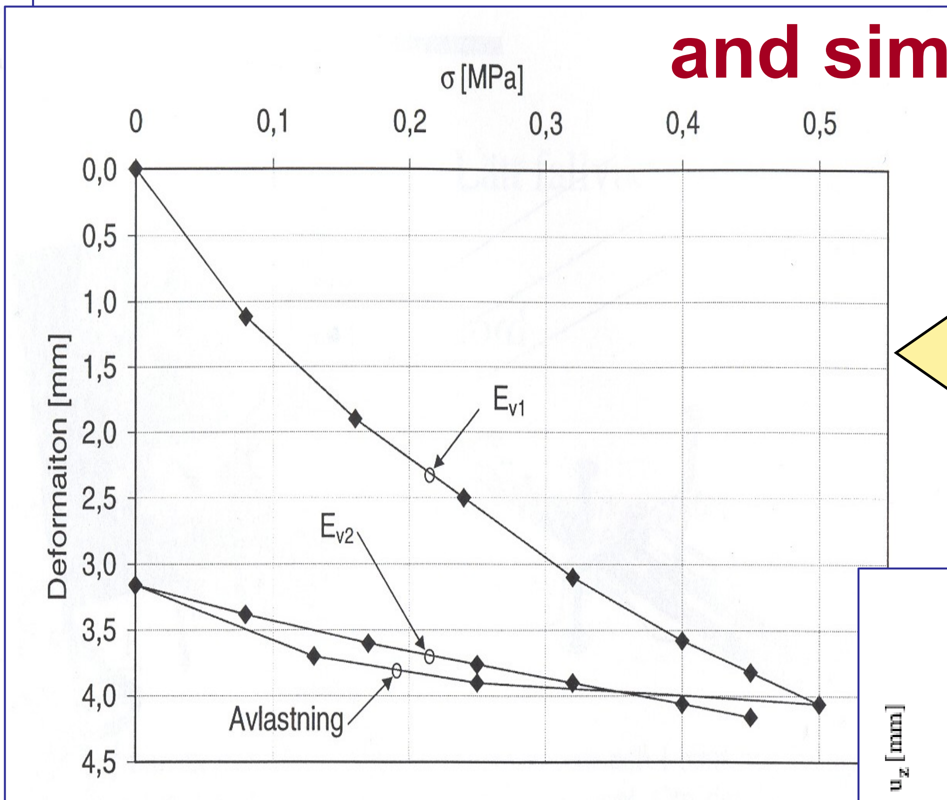
2	1.45	-0.46

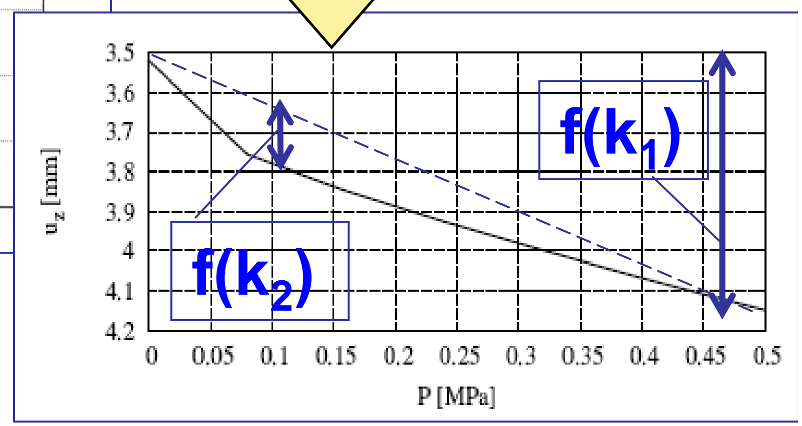
Ev1 = 57.00 MN/m2
Ev2 = 184.44 MN/m2
Ev2/Ev1 = 3.24

Result from Plate loading and simulation in VagFEM



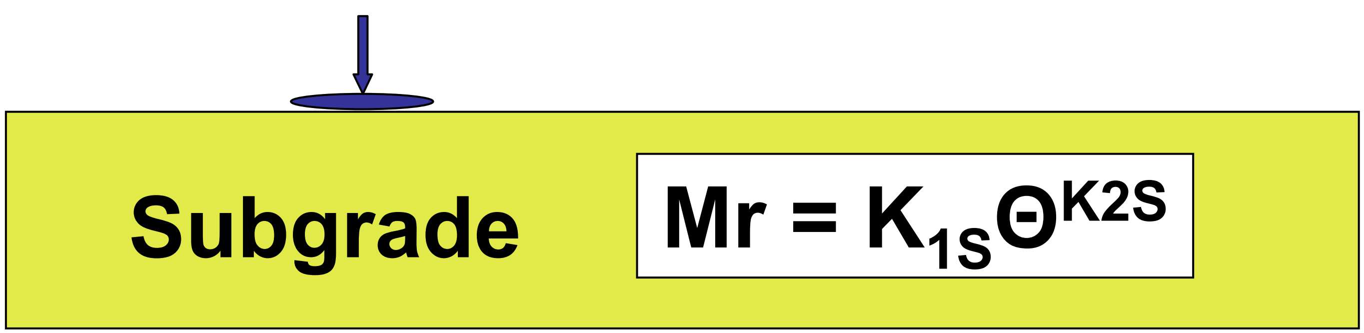
Resilient Module

$$Mr = k_1 \Theta^{k2}$$

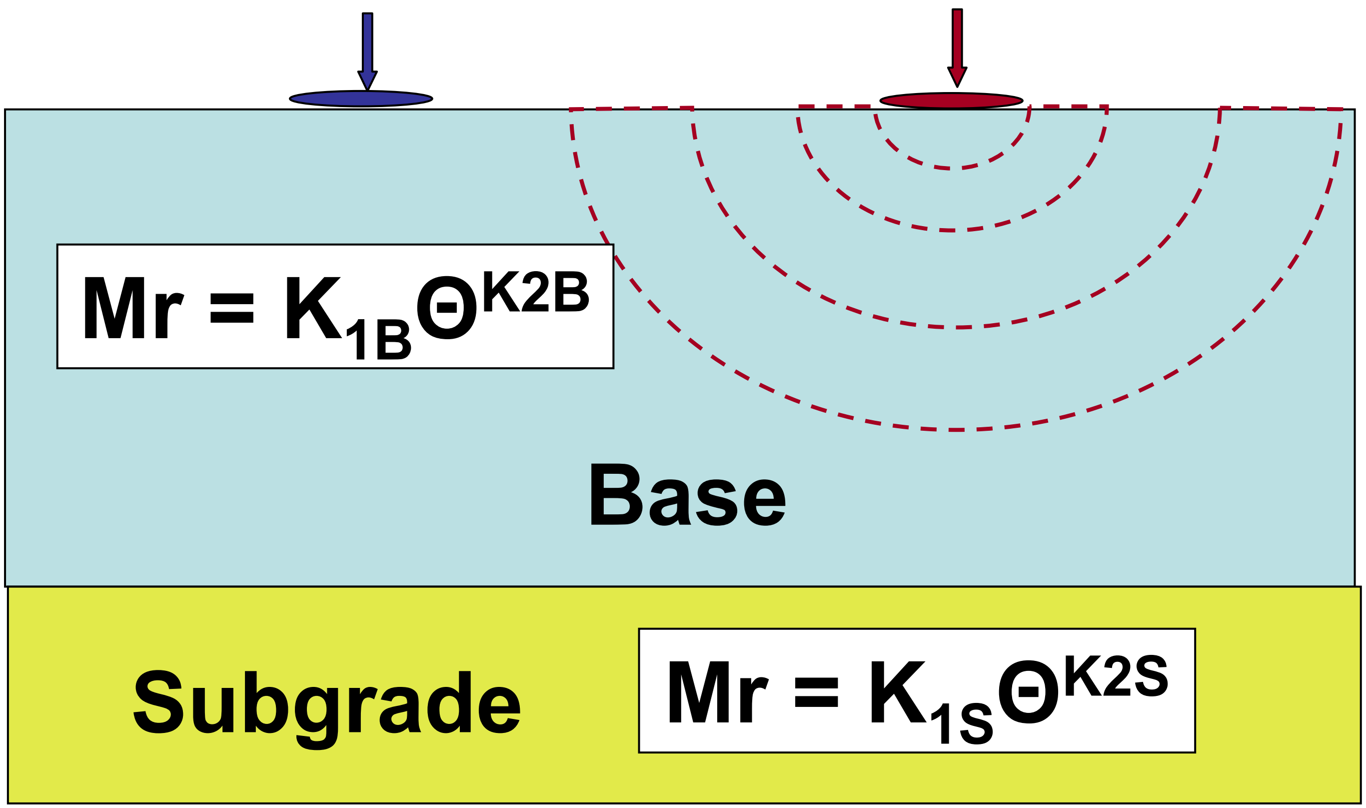


Measured Mr_1 in subgrade is used as input data in calculation of Mr_2 in subbase

Calculate the dynamic resilient modulus in the suggrade material?



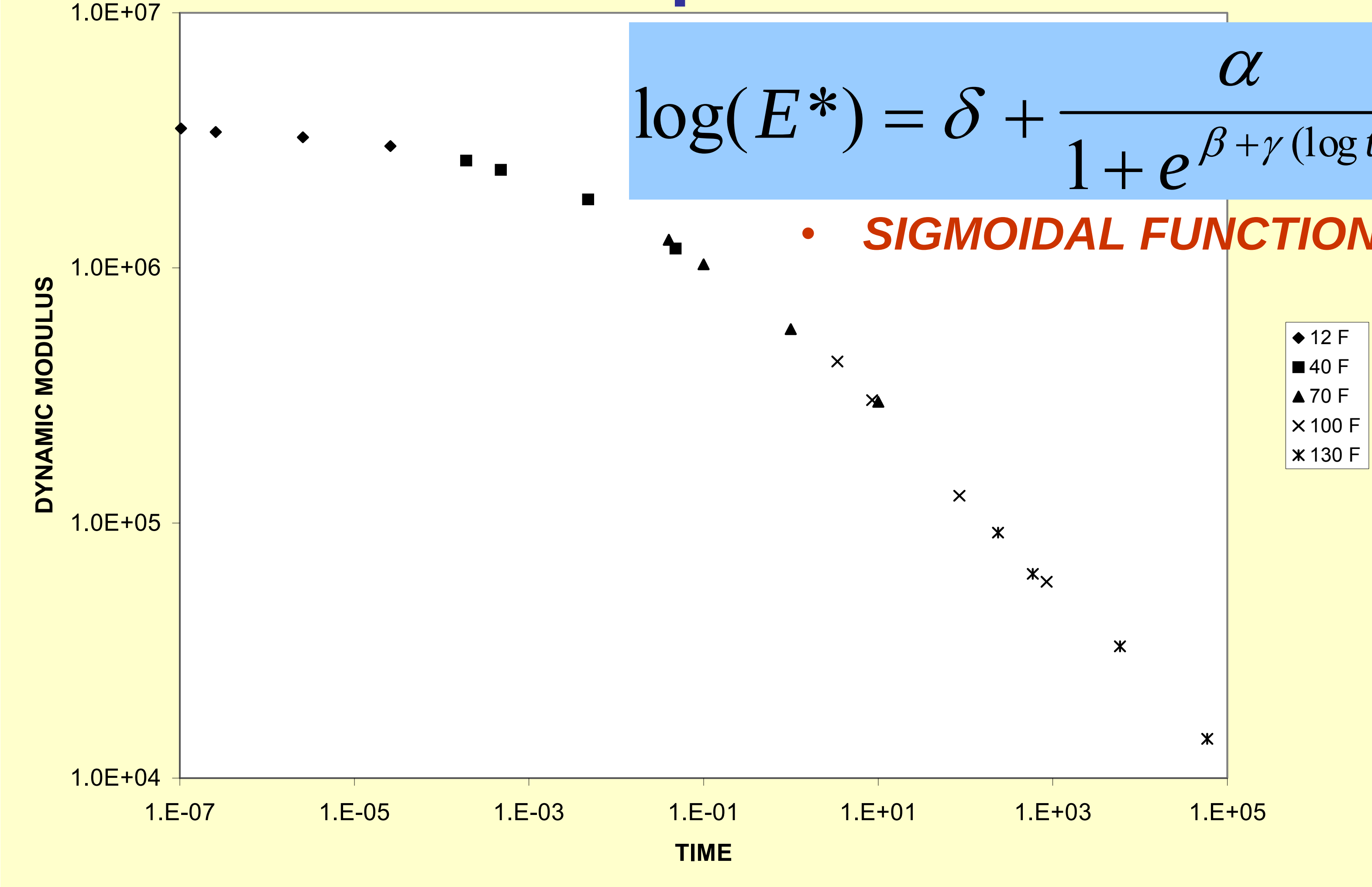
Calculate the dynamic resilient modulus in the base material?



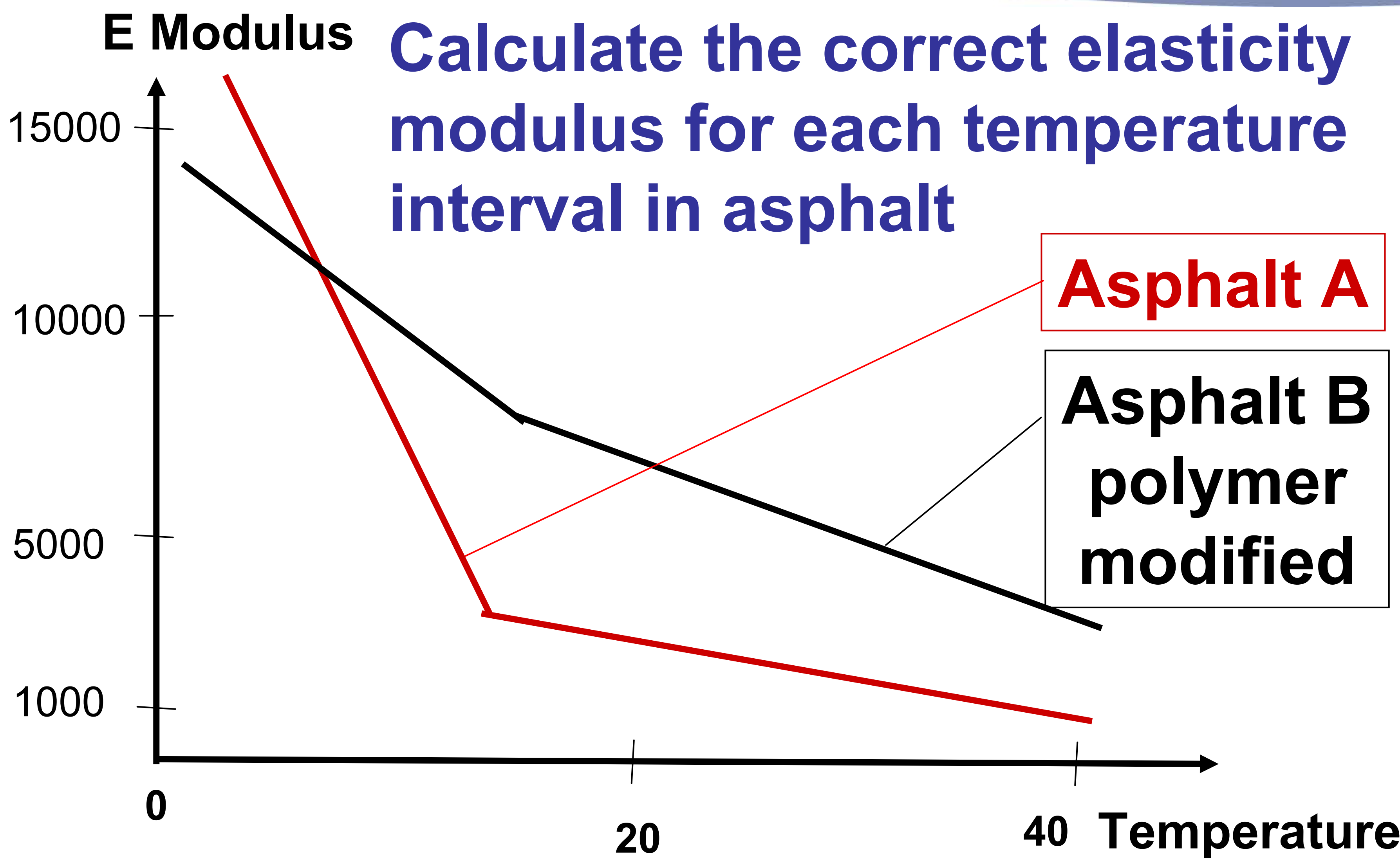
Calculate theDynamic Modulus Master Curve in Asphalt

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma(\log t_r)}}$$

- *SIGMOIDAL FUNCTION*

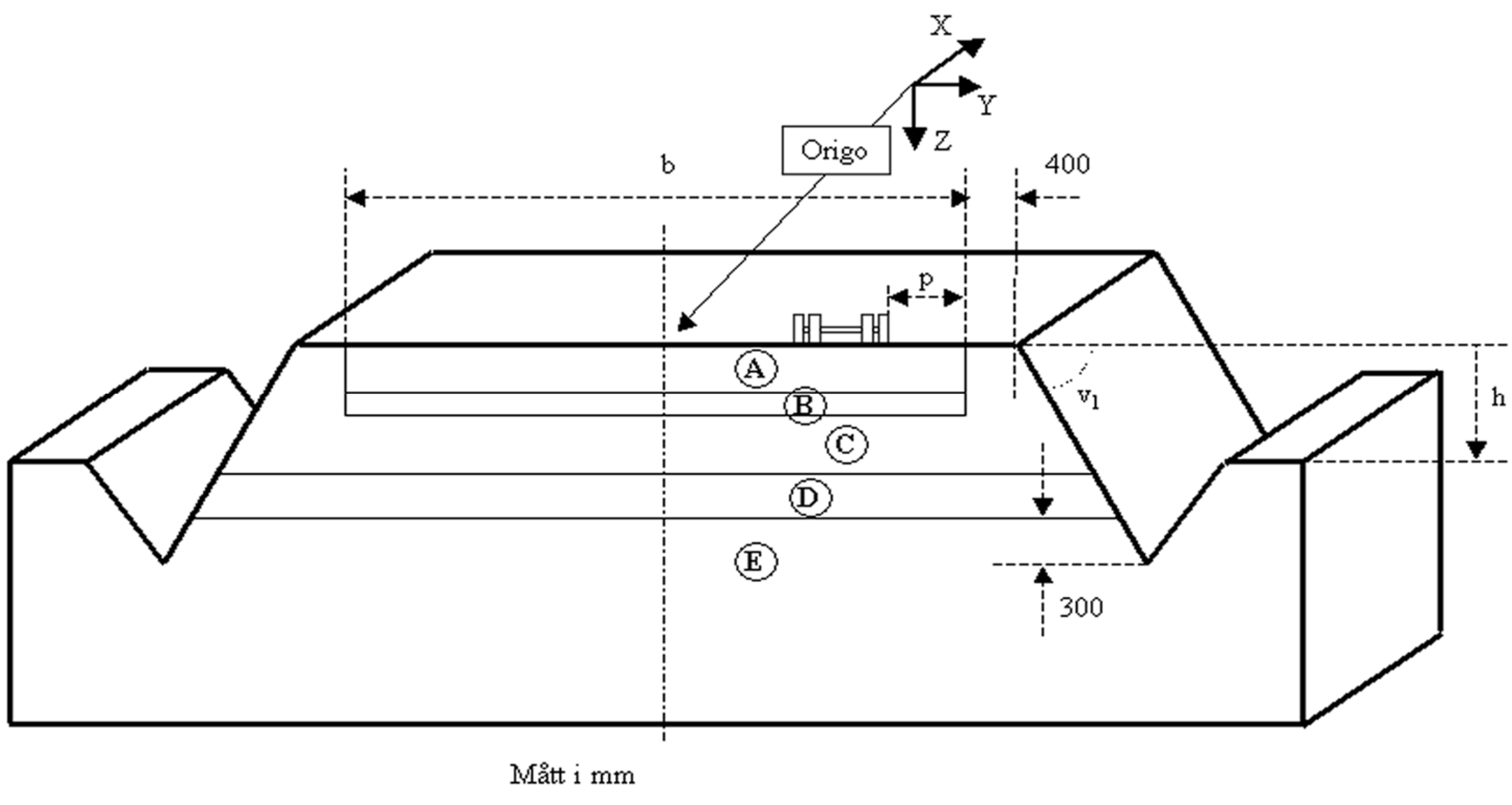


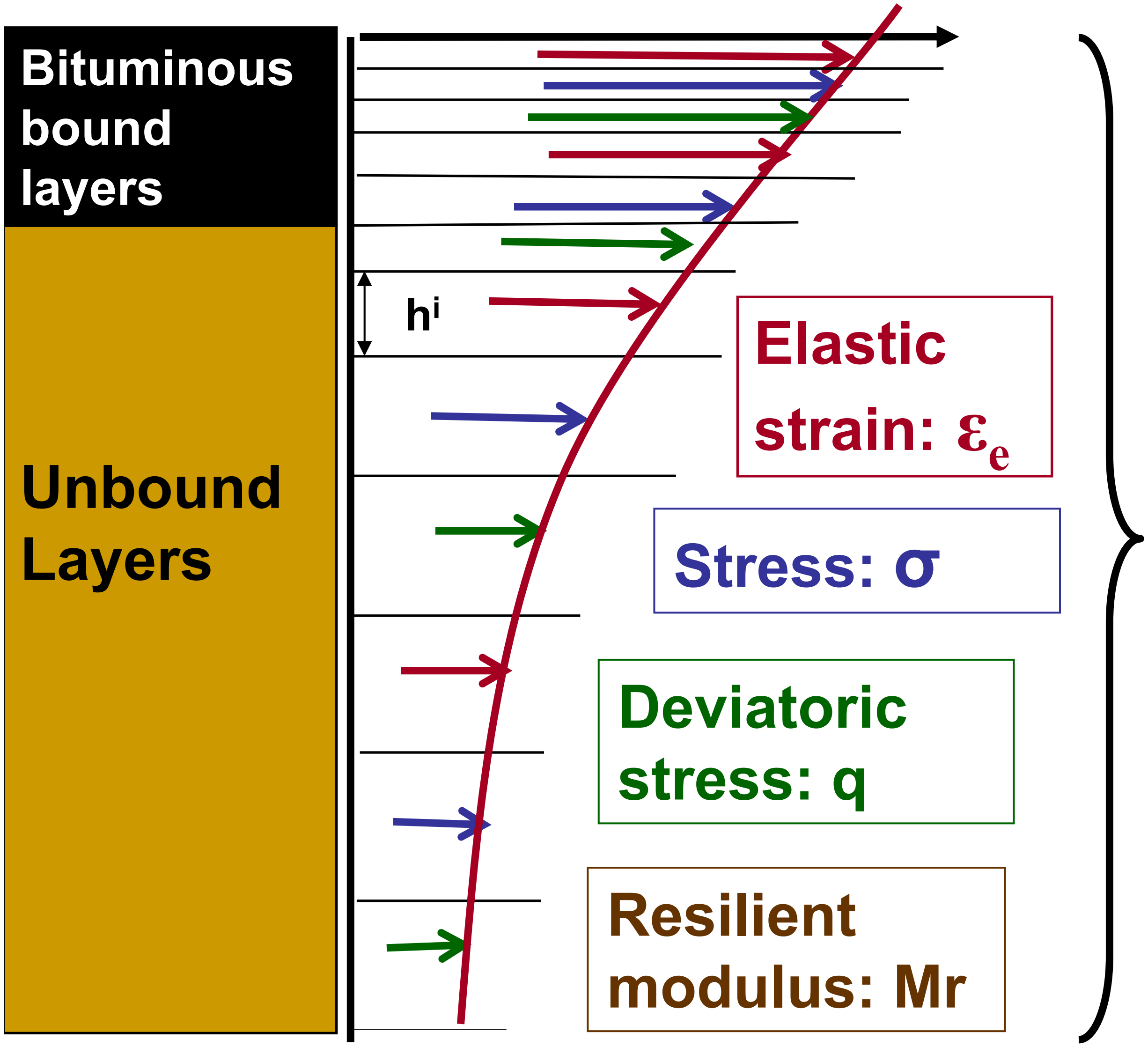
Calculate the correct elasticity modulus for each temperature interval in asphalt



VagFEM

Calculate stress, strain and resilient modulus with VagFEM

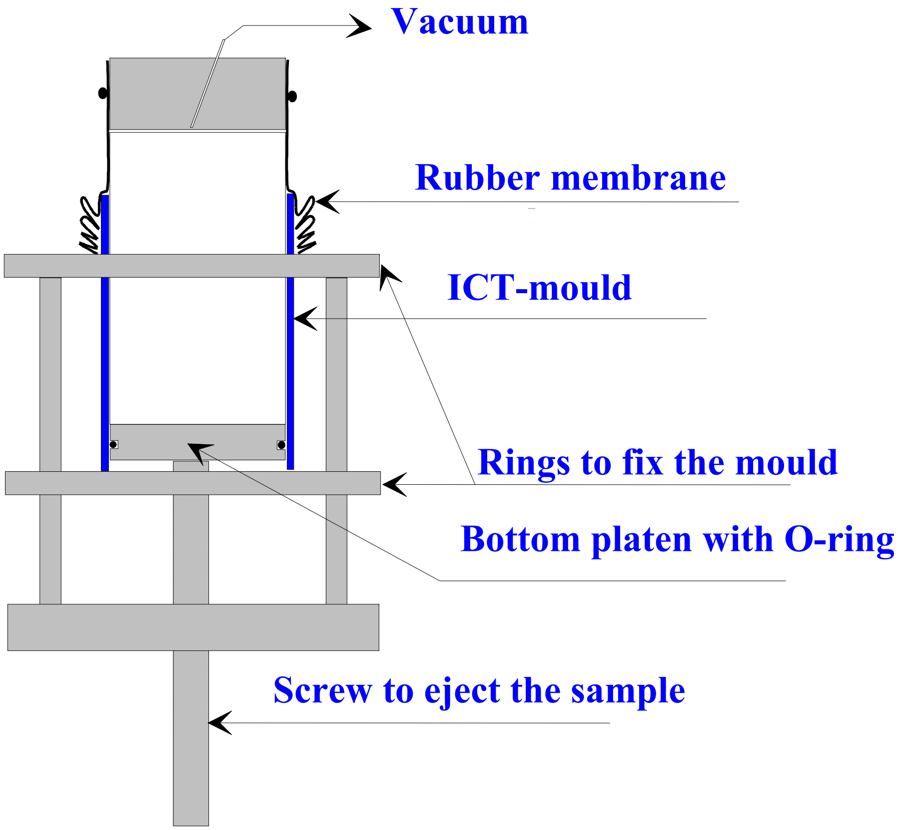


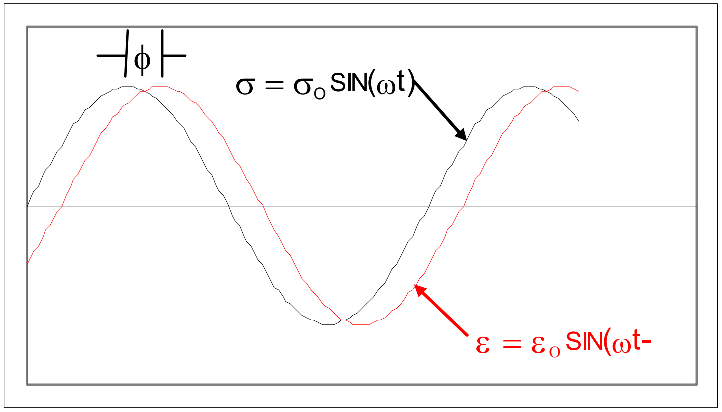


Input data for calculation of permanent deformations

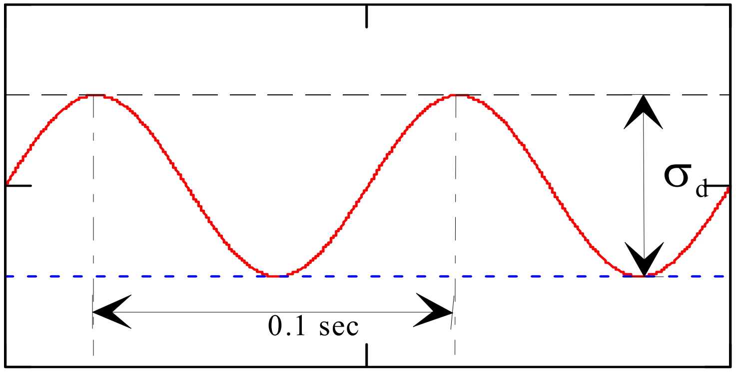
Elastic response, resilient modulus, as digital output data from VagFEM

Calculation of parameters from triaxial tests



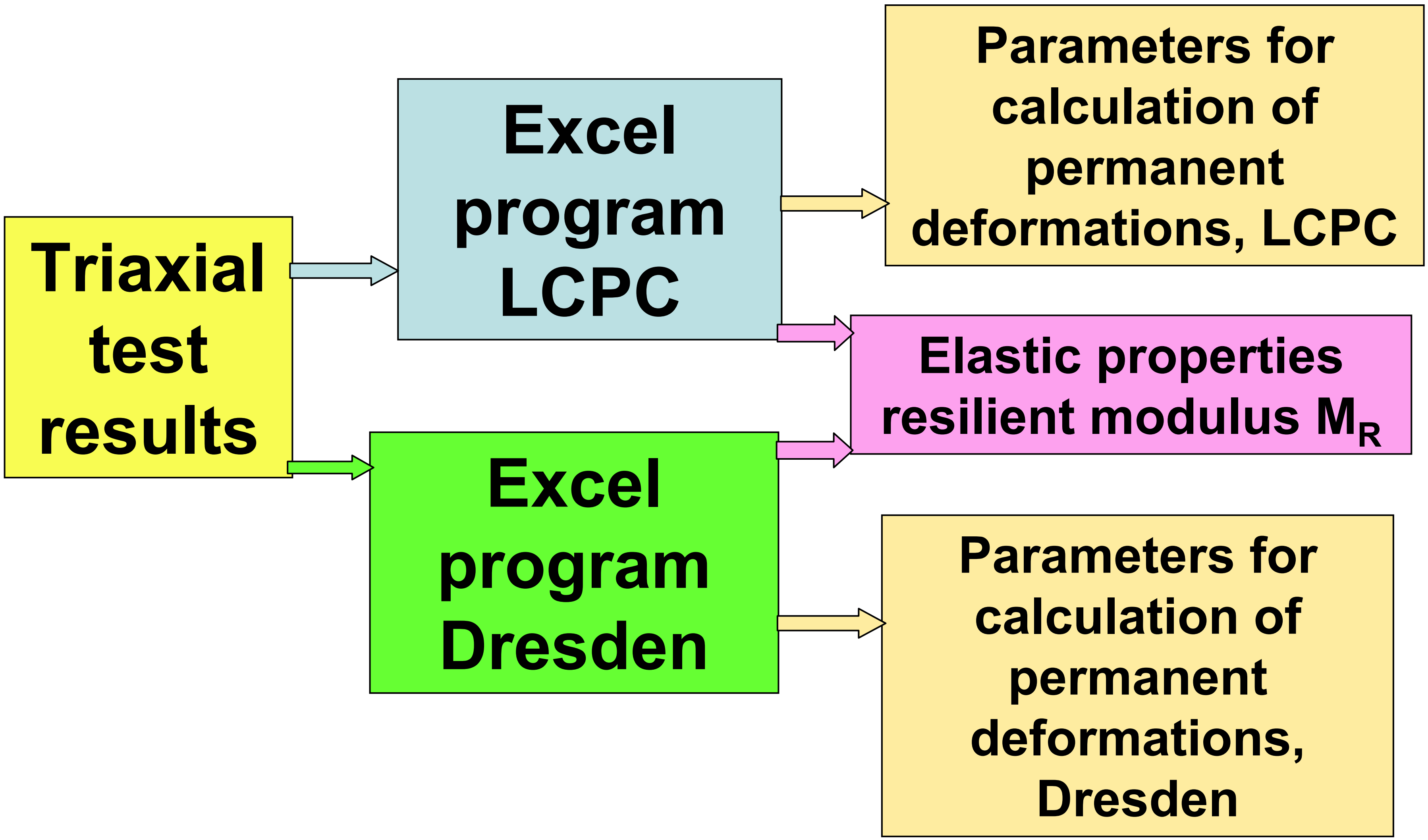


Asphalt material



Unbound material

Evaluation of triaxial tests



Calculate future rutting with VagFEM

Parameters for calculation of permanent deformations, LCPC

Parameters for calculation of permanent deformations, Dresden

Parameters for calculation of permanent deformations, Design guide, unbound mtrl

Parameters for calculation of permanent deformations, Design guide, asphalt mtrl

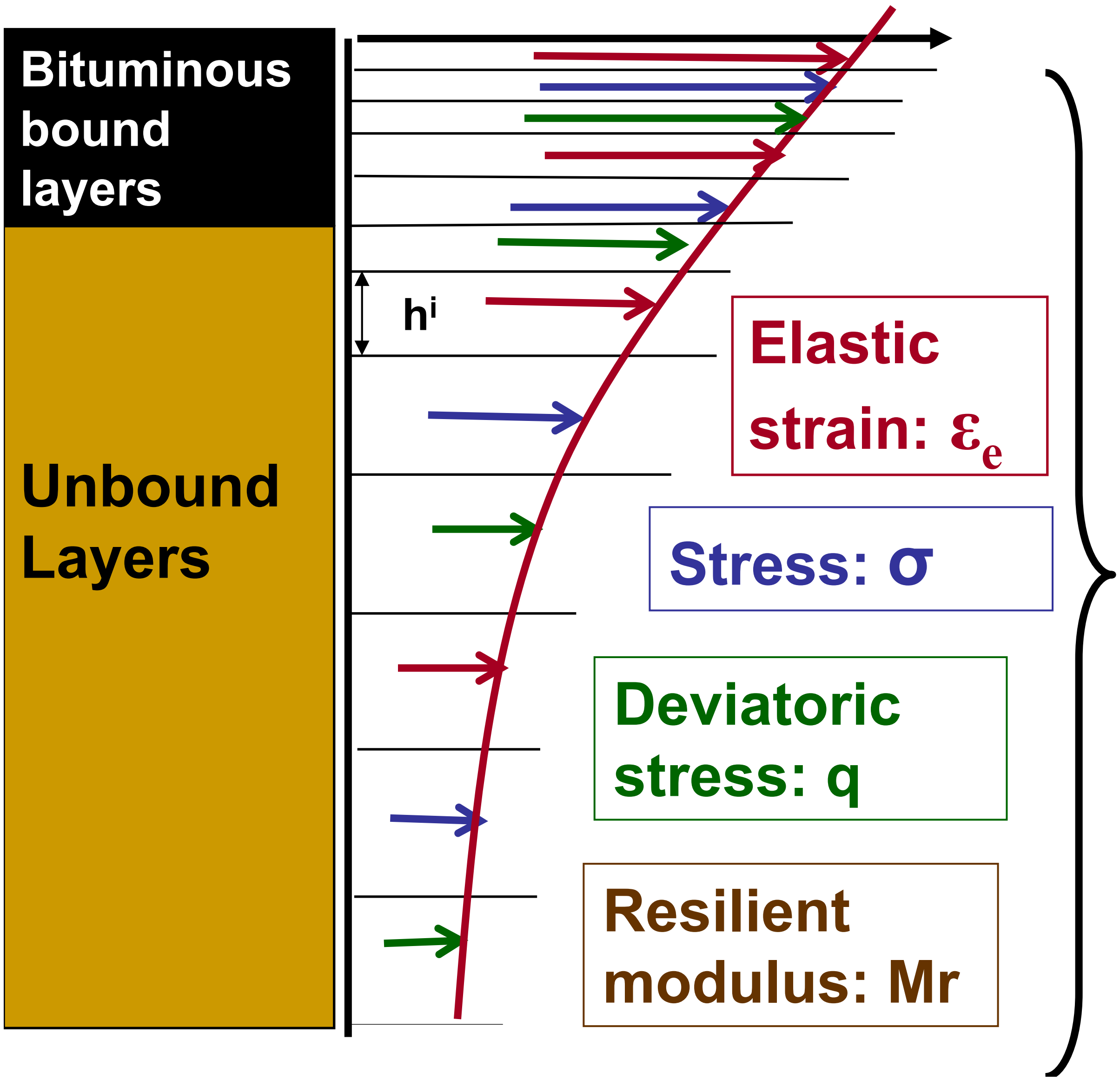
Elastic response, resilient modulus, as digital output data from VagFEM

Excel programs for calculation of future rutting

$$\varepsilon_1^p(N) = \varepsilon_{10}^p \cdot \left[1-\left(\frac{N}{N_0}\right)^{-B}\right] \cdot \left[\frac{L_{max}}{p_a}\right]^n \cdot \frac{1}{\left(m+\frac{s}{p_{max}}-\frac{q_{max}}{p_{max}}\right)}$$

$$\frac{\varepsilon_p}{\varepsilon_r} = a_1 \cdot N^{a_2} \cdot T^{a_3}$$

$$\varepsilon_p(N) = A \cdot \left(\frac{N}{1000}\right)^B + C\left(e^{D\frac{N}{1000}} - 1\right)$$



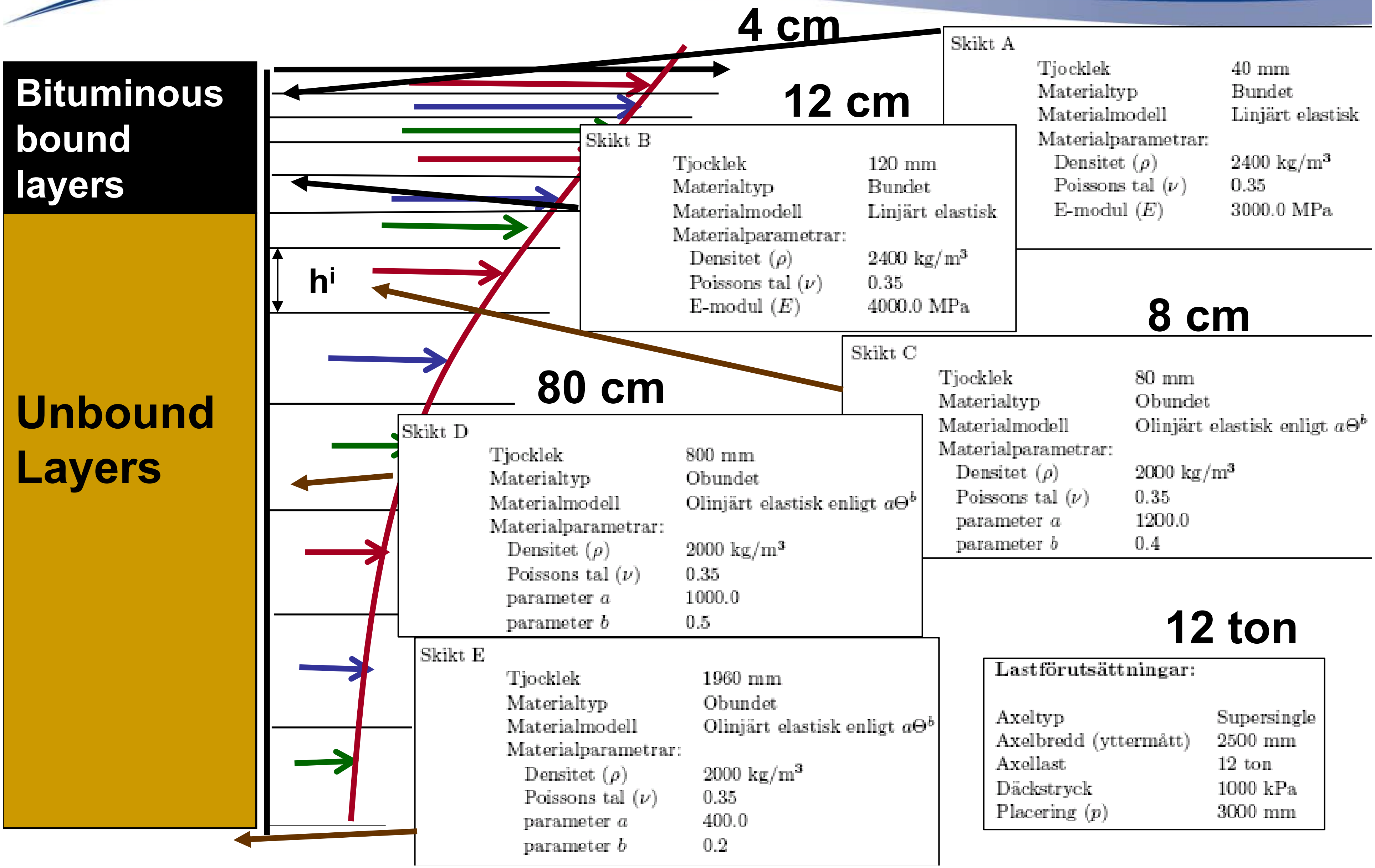
$$PD = \sum_{i=1}^{nsublayers} \varepsilon_p^i \cdot h^i$$

PD – Permanent Deformation

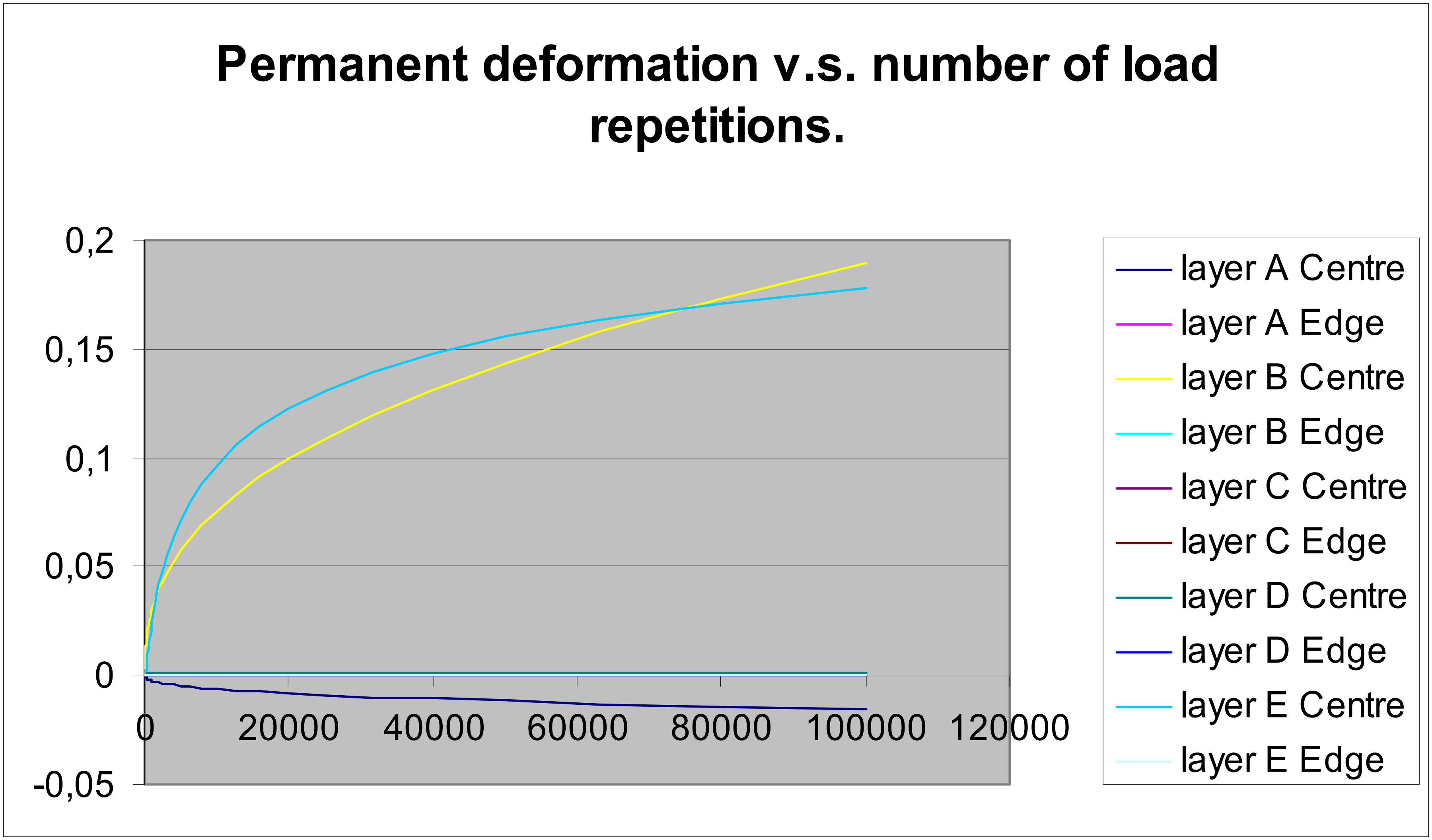
Nsublayers – Number of sublayers

ε_p^i – Total plastic strain in sublayer i

h^i – Thickness of sublayer i


4 cm
12 cm
8 cm
80 cm
12 ton
Bituminous bound layers
Unbound Layers
hⁱ
Skikt A
Tjocklek 40 mm
Materialtyp Bundet
Materialmodell Linjärt elastisk
Materialparametrar:
Densitet (ρ) 2400 kg/m³
Poissons tal (ν) 0.35
E-modul (E) 3000.0 MPa
Skikt B
Tjocklek 120 mm
Materialtyp Bundet
Materialmodell Linjärt elastisk
Materialparametrar:
Densitet (ρ) 2400 kg/m³
Poissons tal (ν) 0.35
E-modul (E) 4000.0 MPa
Skikt C
Tjocklek 80 mm
Materialtyp Obundet
Materialmodell Olinjärt elastisk enligt aΘᵇ
Materialparametrar:
Densitet (ρ) 2000 kg/m³
Poissons tal (ν) 0.35
parameter a 1200.0
parameter b 0.4
Skikt D
Tjocklek 800 mm
Materialtyp Obundet
Materialmodell Olinjärt elastisk enligt aΘᵇ
Materialparametrar:
Densitet (ρ) 2000 kg/m³
Poissons tal (ν) 0.35
parameter a 1000.0
parameter b 0.5
Skikt E
Tjocklek 1960 mm
Materialtyp Obundet
Materialmodell Olinjärt elastisk enligt aΘᵇ
Materialparametrar:
Densitet (ρ) 2000 kg/m³
Poissons tal (ν) 0.35
parameter a 400.0
parameter b 0.2
Lastförutsättningar:
Axeltyp Supersingle
Axelbredd (yttermått) 2500 mm
Axellast 12 ton
Däckstryck 1000 kPa
Placering (p) 3000 mm

Results from VagFEM



Vägverket

THANK YOU FOR YOUR ATTENTION

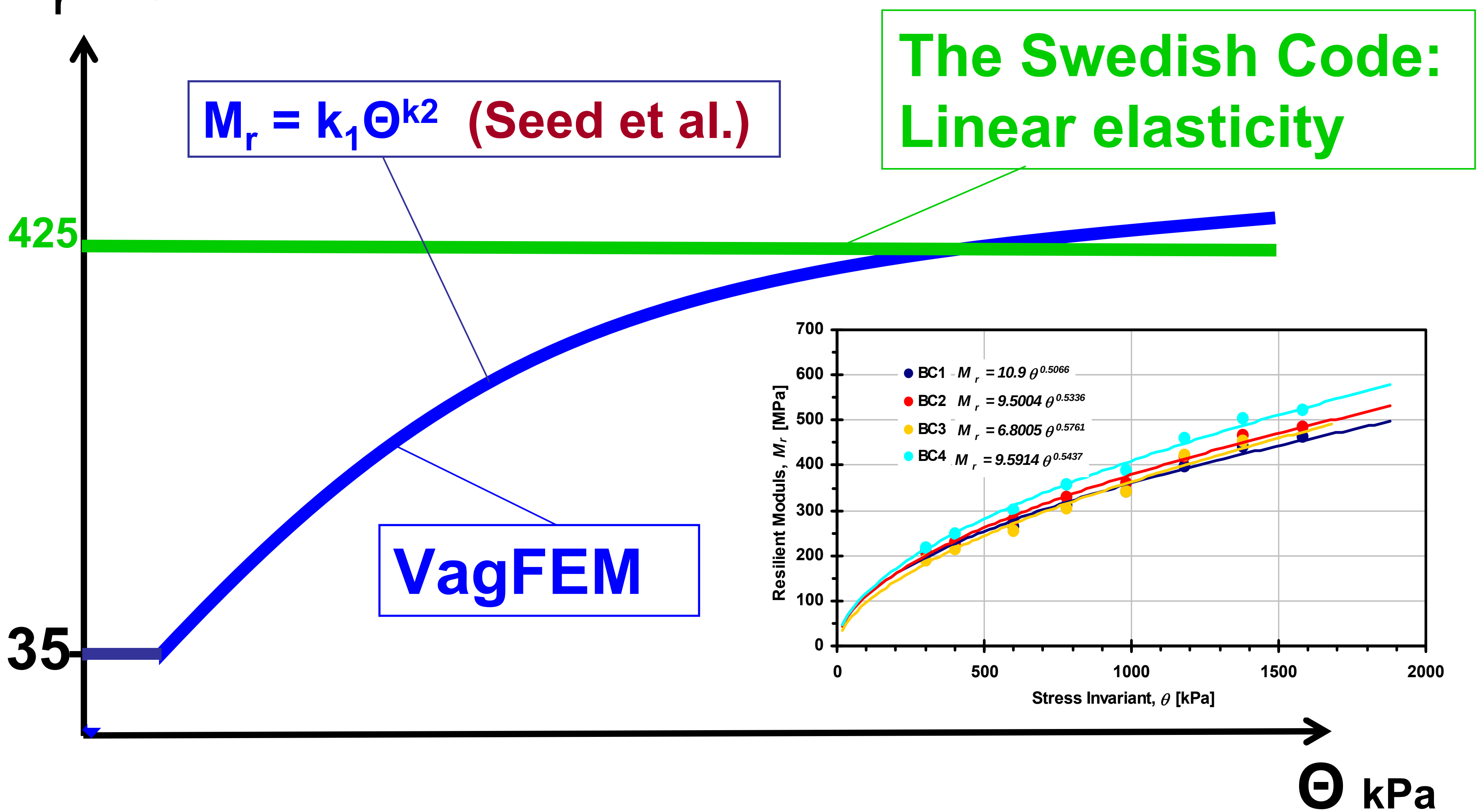
Anders Huvstig

Swedish Road Administration (SRA)

MATERIAL MODELS
unbound layers

Unbound layer: Simulated E-modulus

M_r MPa

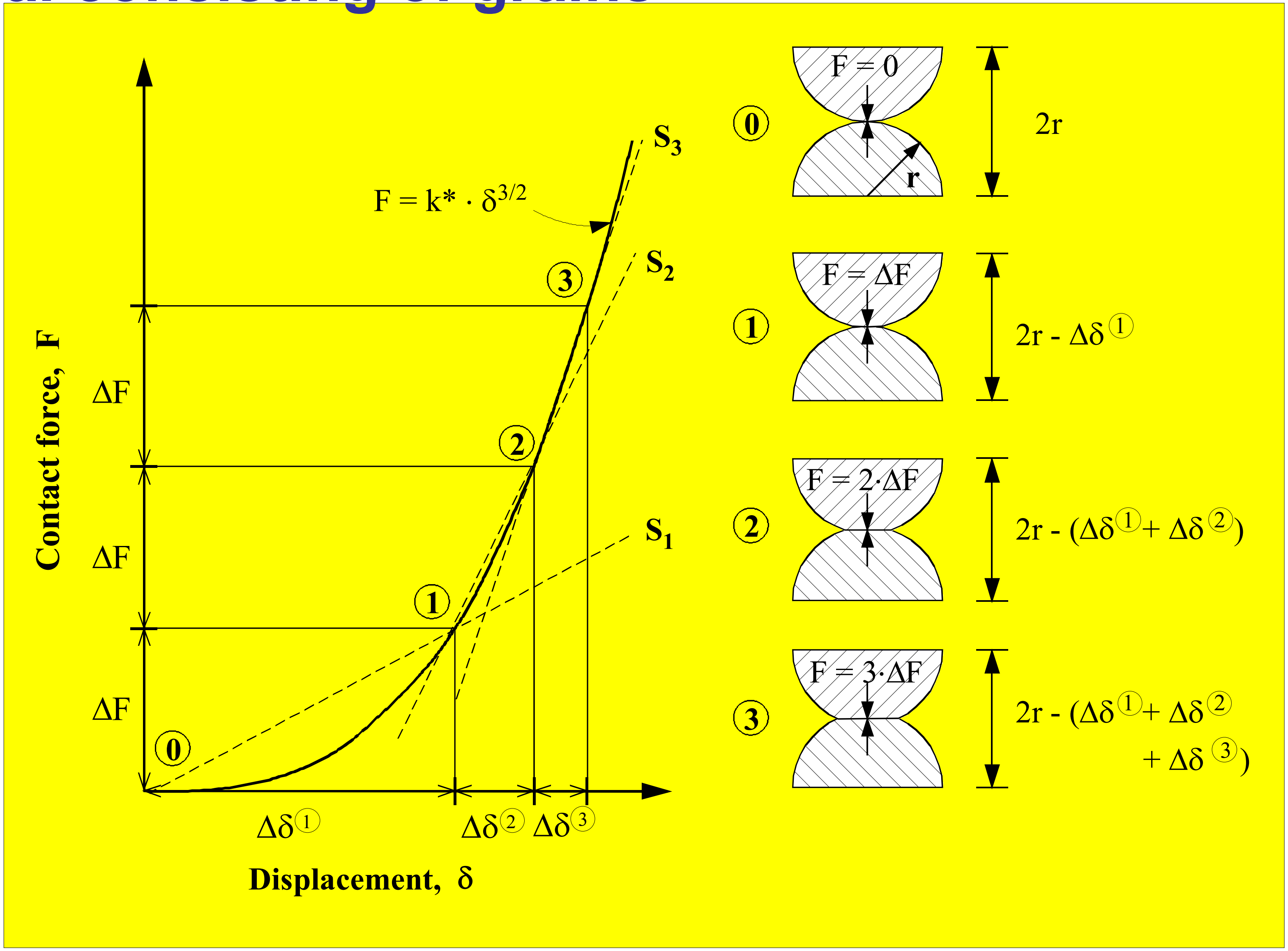


Different material gives different resilient modulus

Materiale	Resilientmodul (MPa)			
	θ=100 kPa	θ=200 kPa	θ=300 kPa	θ=400 kPa
Hovinmoen grus 0 – 32 mm	174	242	293	373
Hovinmoen knust grus 0 – 32 mm, orig.	141	210	264	353
Hovinmoen knust grus 0 – 32 mm, NGI gradering	178	260	326	432
Hedrum knust fjell 0 – 32 mm,	230	337	422	560
Steinskogen knust fjell 0 – 32 mm	222	320	397	521
Visnes knust fjell 0 – 32 mm	298	461	596	821

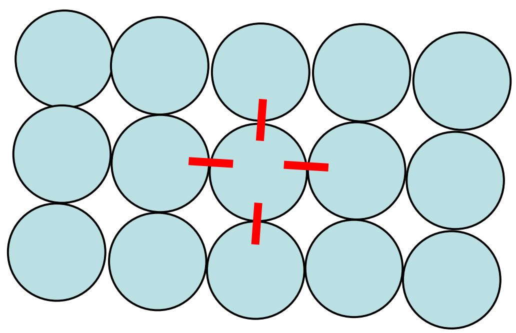
Exemple from Norway and Finland

Material consisting of grains

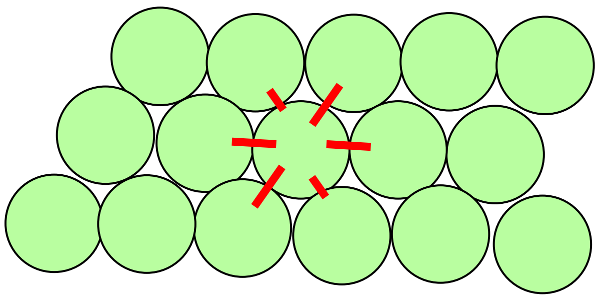


P Kolisoja

The grains gets more contact surfaces when they are pressed together

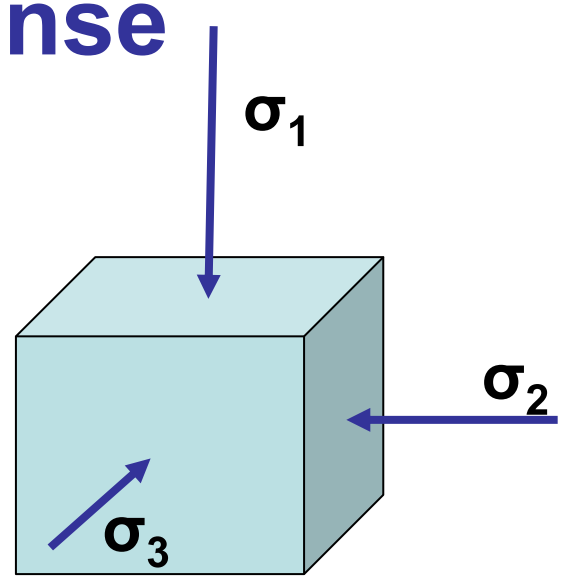


Loose compacted material



Hard compacted material

Unlinear elastic response



$$M_r = k_1 (\sigma_1 + \sigma_2 + \sigma_3)^{k2}$$

$$M = k_1 \Theta^{k2}$$ **(Seed et al.)**

$$\nu = A + B(\sigma_1/\sigma_3) + C(\sigma_1/\sigma_3)^2 + D(\sigma_1/\sigma_3)^3$$

$$M = k_1 p_0 (\Theta/p_0)^{k2}$$

Calculation of rutting

Triaxial test

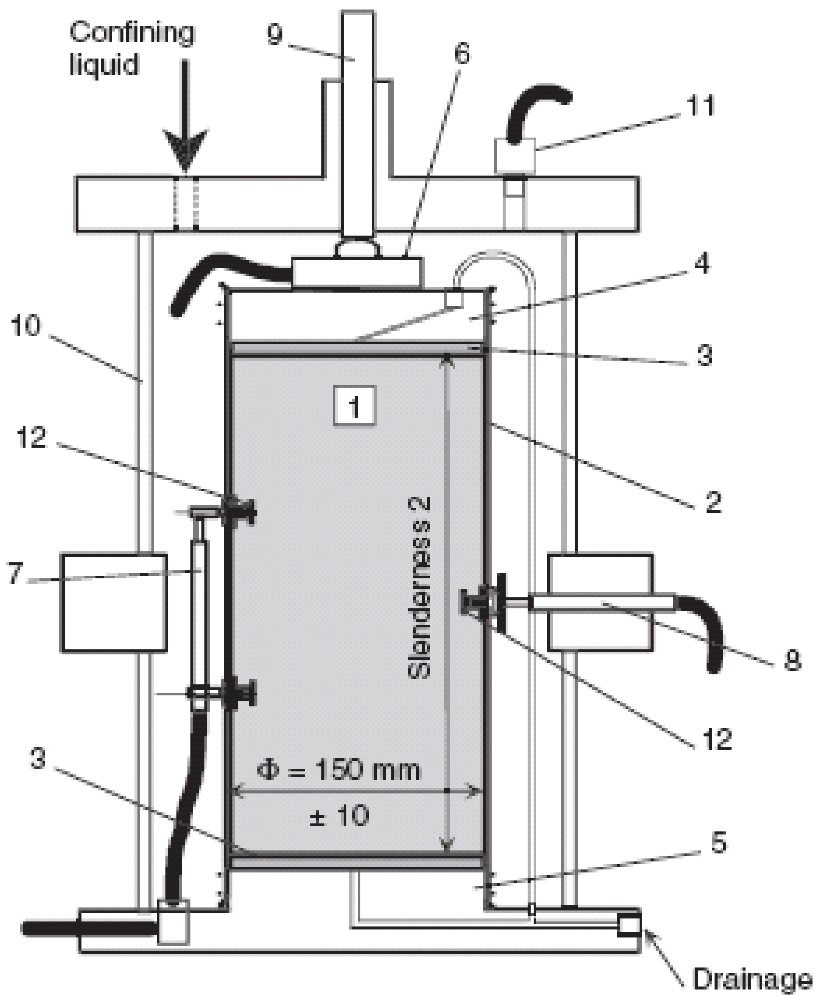


Fig. 1 - The triaxial cell of the repeated load triaxial apparatus.

1. *Specimen.*
2. *Membrane.*
3. *Porous disc.*
4. *Cell top.*
5. *Base.*
6. *Force sensor.*
7. *Axial strain measurement device.*
8. *Radial strain measurement device.*
9. *Loading ram.*
10. *Triaxial cell casing.*
11. *Pressure sensor.*
12. *Displacement transducer fixings.*

Cyclic loadings

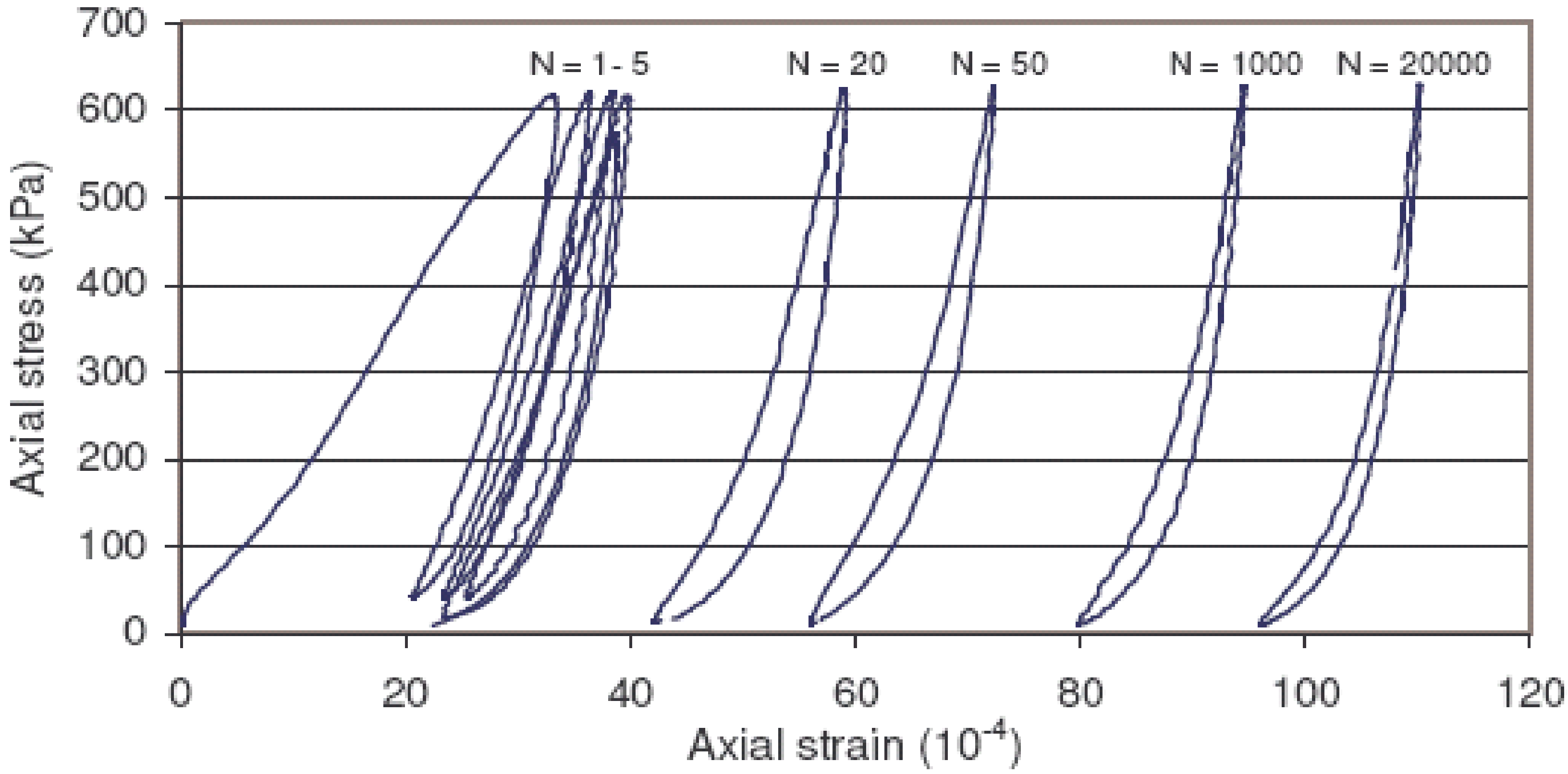
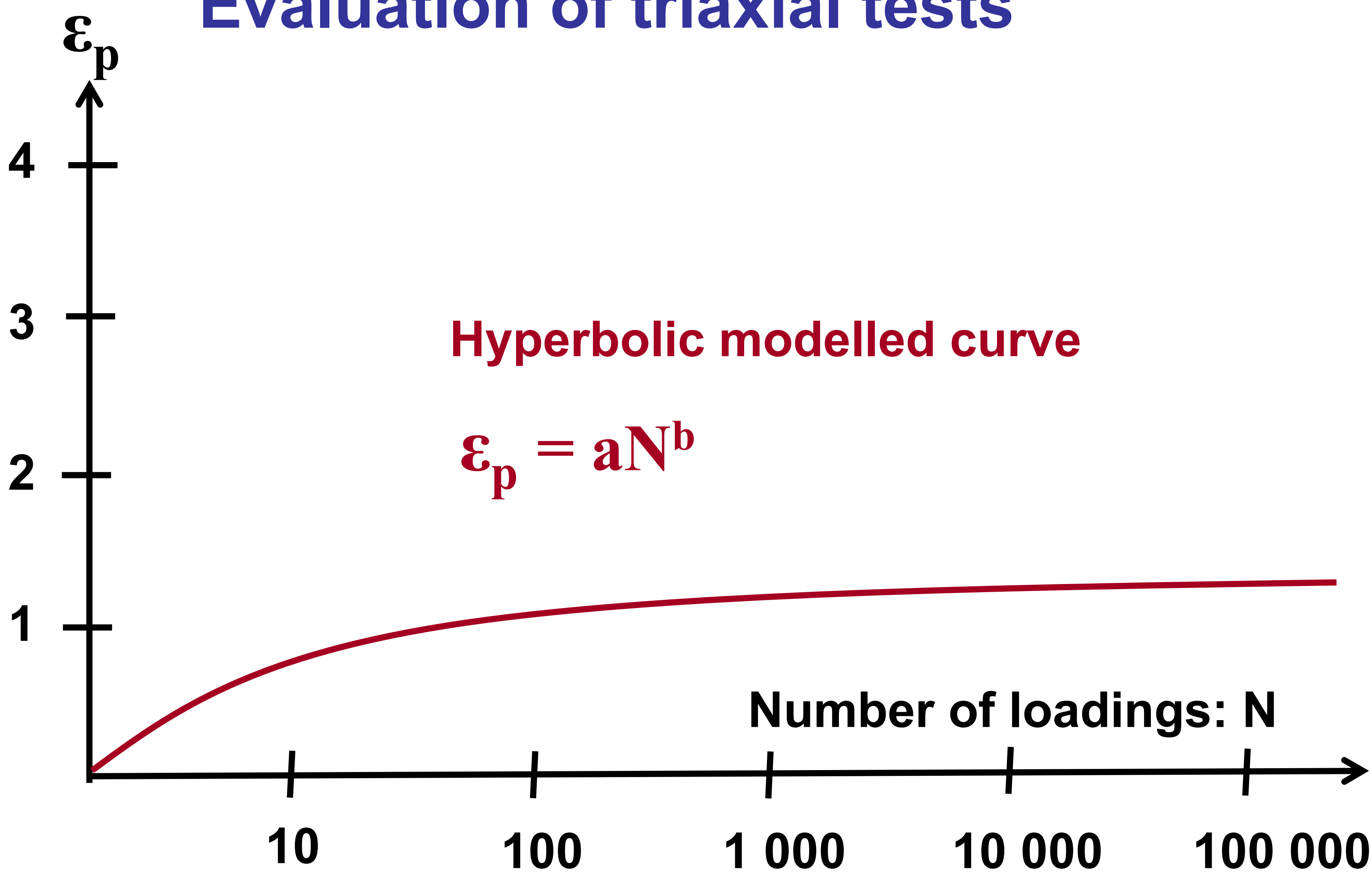
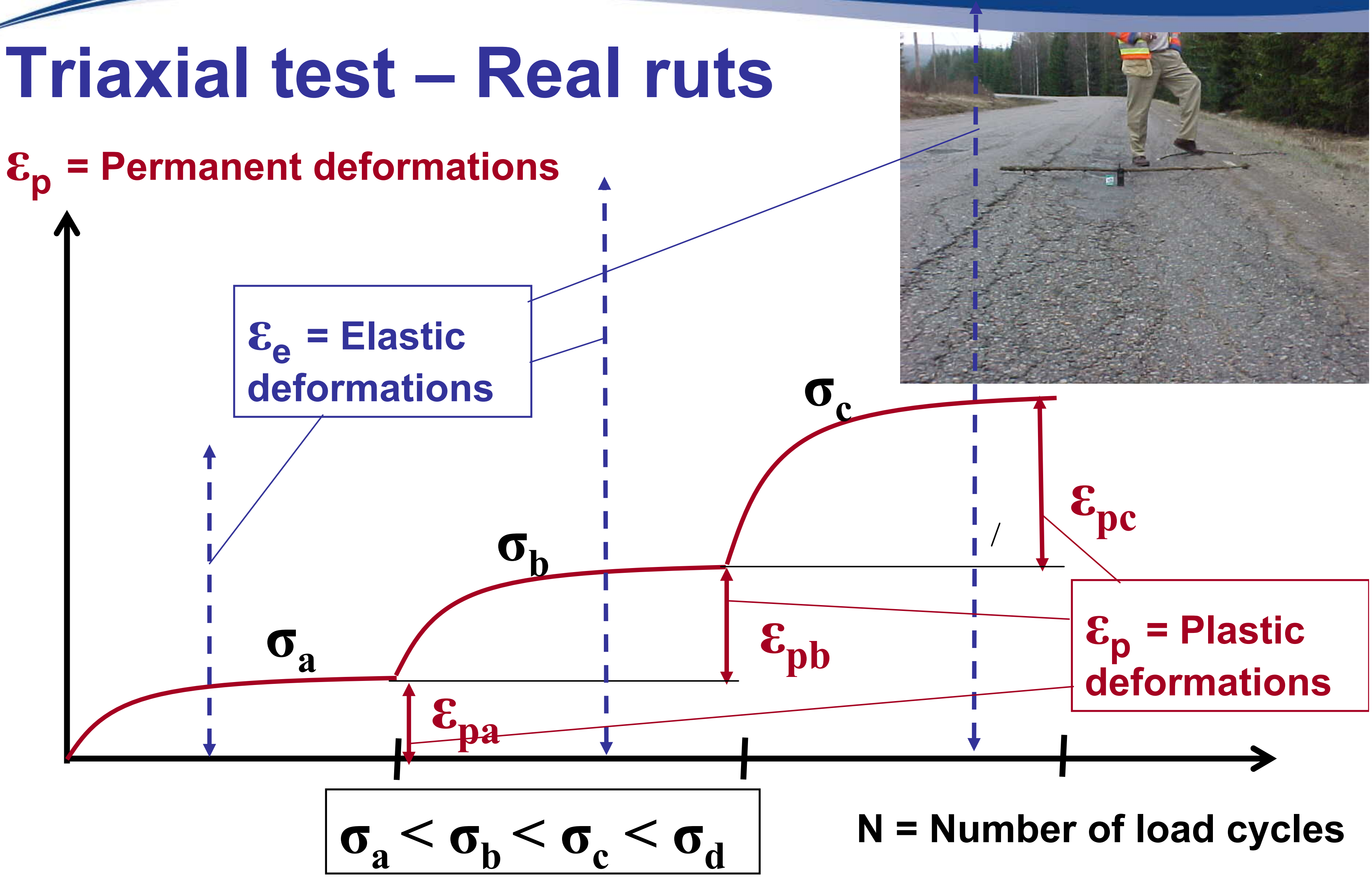


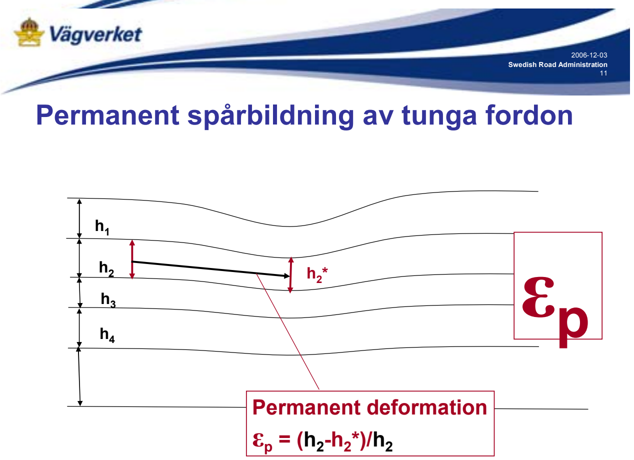
Figure 1. Axial stress – axial strain cycles obtained in a cyclic triaxial test on a UGM.

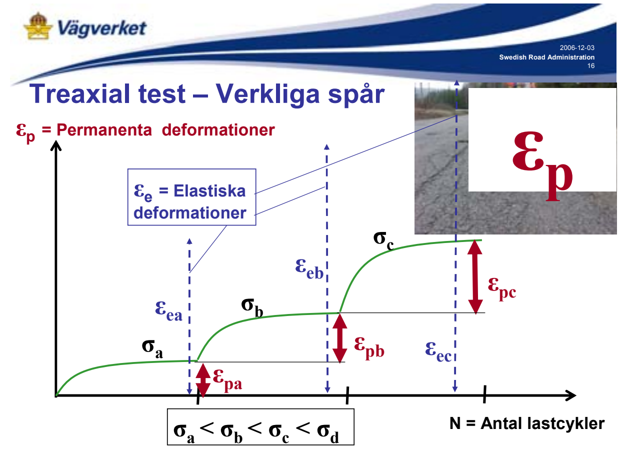
Evaluation of triaxial tests



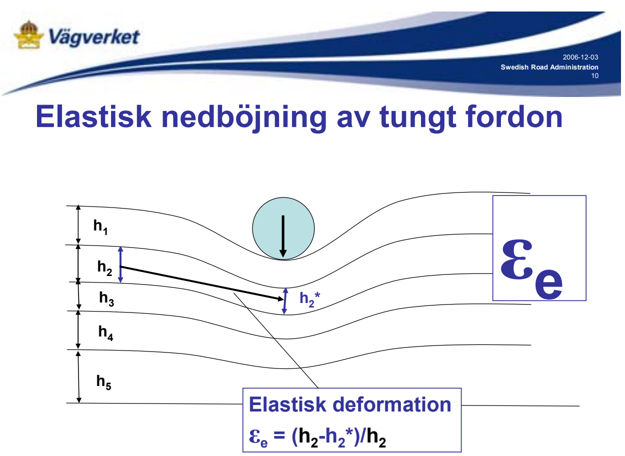
Triaxial test – Real ruts

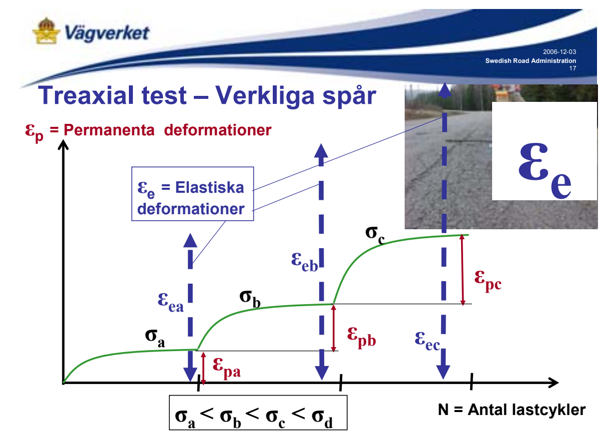






Real ruts $\dfrac{\varepsilon_p}{\varepsilon_e} = \dfrac{\varepsilon_p}{\varepsilon_e}$ Triaxial test



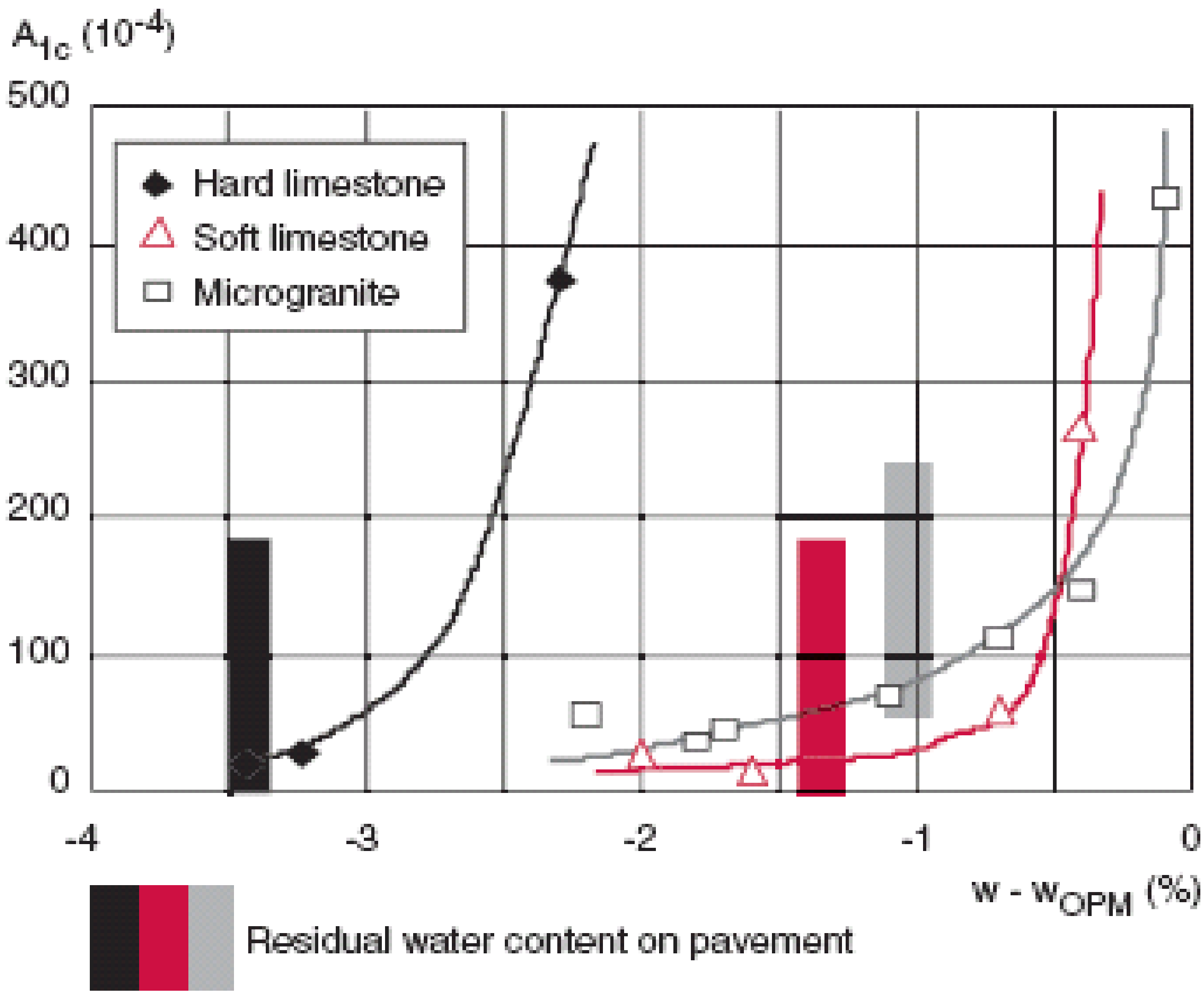


MATERIAL MODELS

Rutting in unbound materials

SAMARIS

Permanent deformations depending on moisture content



Evaluation of triaxial test

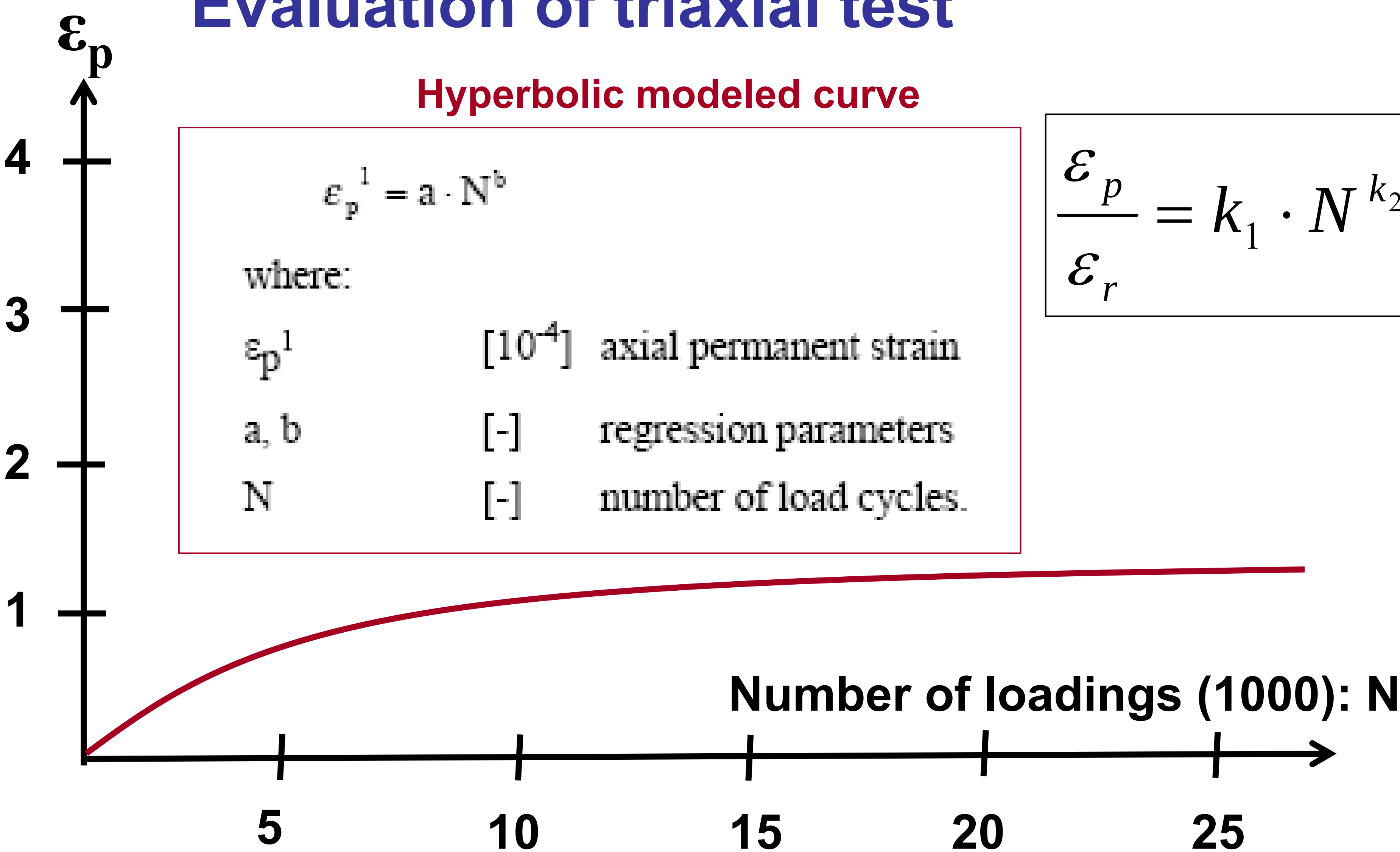
Hyperbolic modeled curve

$$\varepsilon_p^{\,1} = a \cdot N^b$$

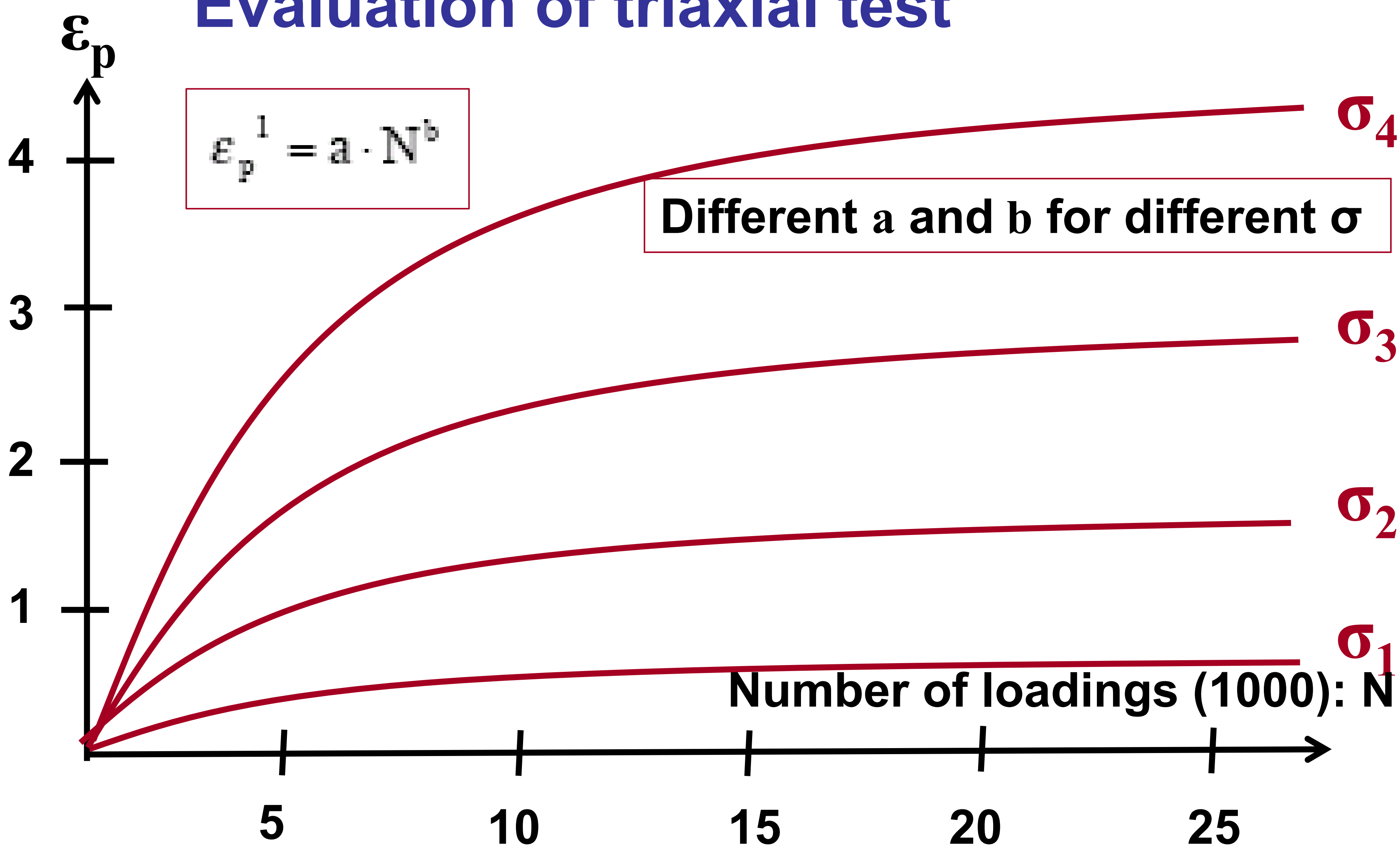
where:

$\varepsilon_p^{\,1}$	$[10^{-4}]$	axial permanent strain
a, b	[-]	regression parameters
N	[-]	number of load cycles.

$$\frac{\varepsilon_p}{\varepsilon_r} = k_1 \cdot N^{k_2}$$



Evaluation of triaxial test



Calculation of permanent deformations – LCPC

$$\varepsilon_1^p(N) = \varepsilon_{10}^p \cdot \left[1 - \left(\frac{N}{N_0}\right)^{-B}\right] \cdot \left[\frac{L_{max}}{p_a}\right]^n \cdot \frac{1}{\left(m + \frac{s}{p_{max}} - \frac{q_{max}}{p_{max}}\right)}$$

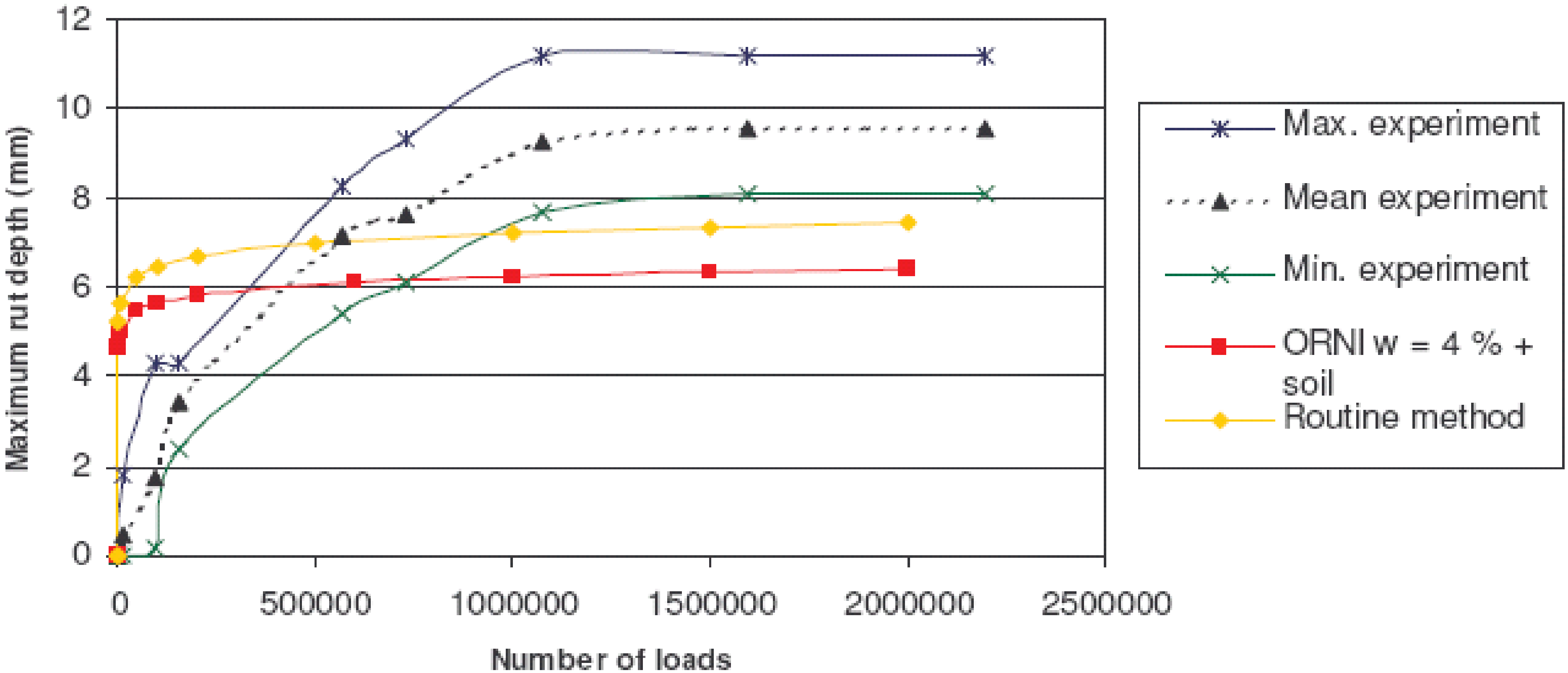
ε_1^p : permanent axial strain; N : number of load cycles;
p_{max}, q_{max} : maximum values of the mean normal stress p and deviatoric stress q;

$$L_{max} = \sqrt{p_{max}^2 + q_{max}^2}$$

Samaris

P_a : reference pressure equal to 100 kPa;
ε_1^{p0}, B, n model parameters;
m,s parameters of the failure line of the material, of equation q = m.p+s;
(from experience, m=2.5 to 2.6 and s=20 kPa)

Result: Prediction of permanent deformation, rutting

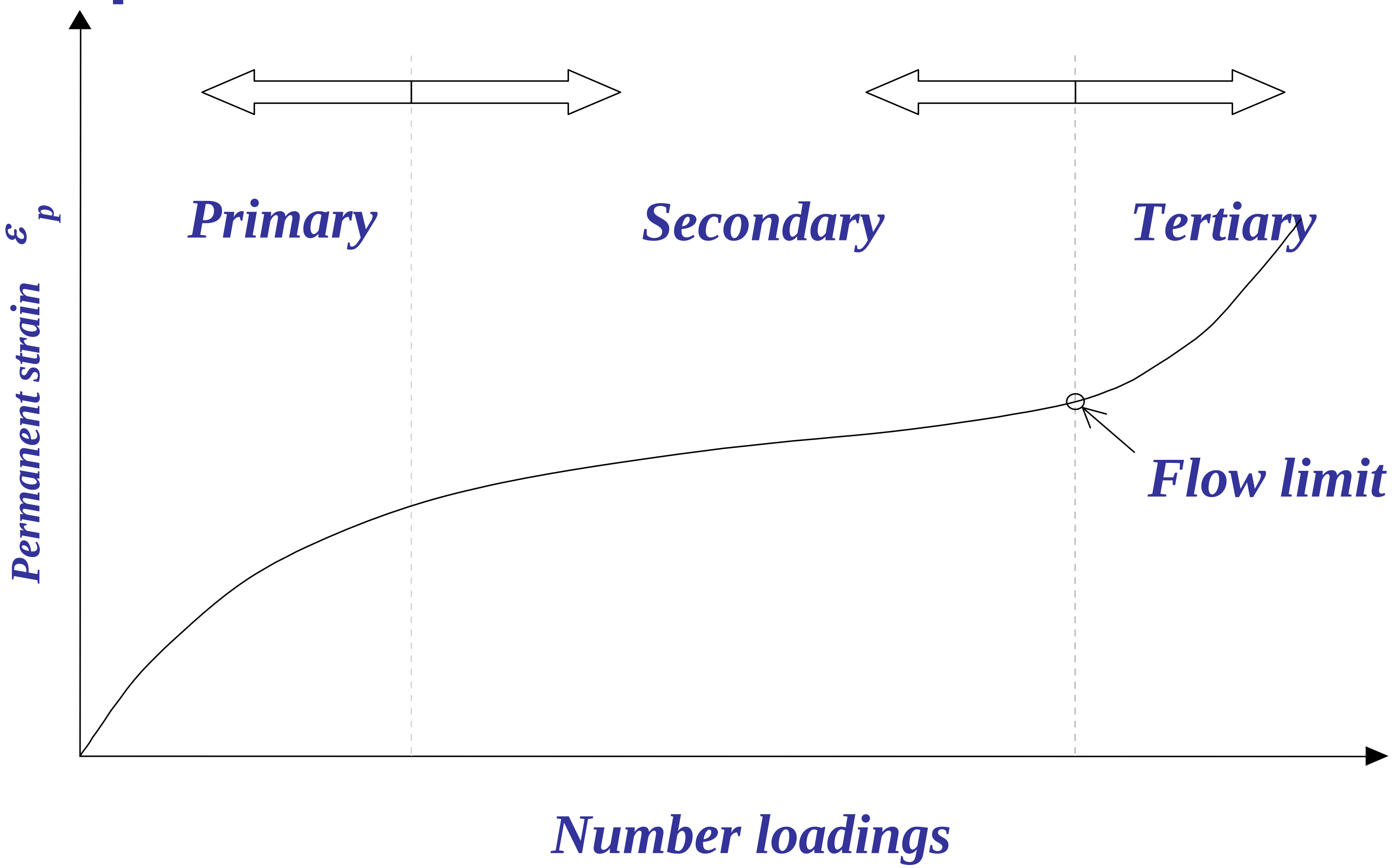


MATERIAL MODELS

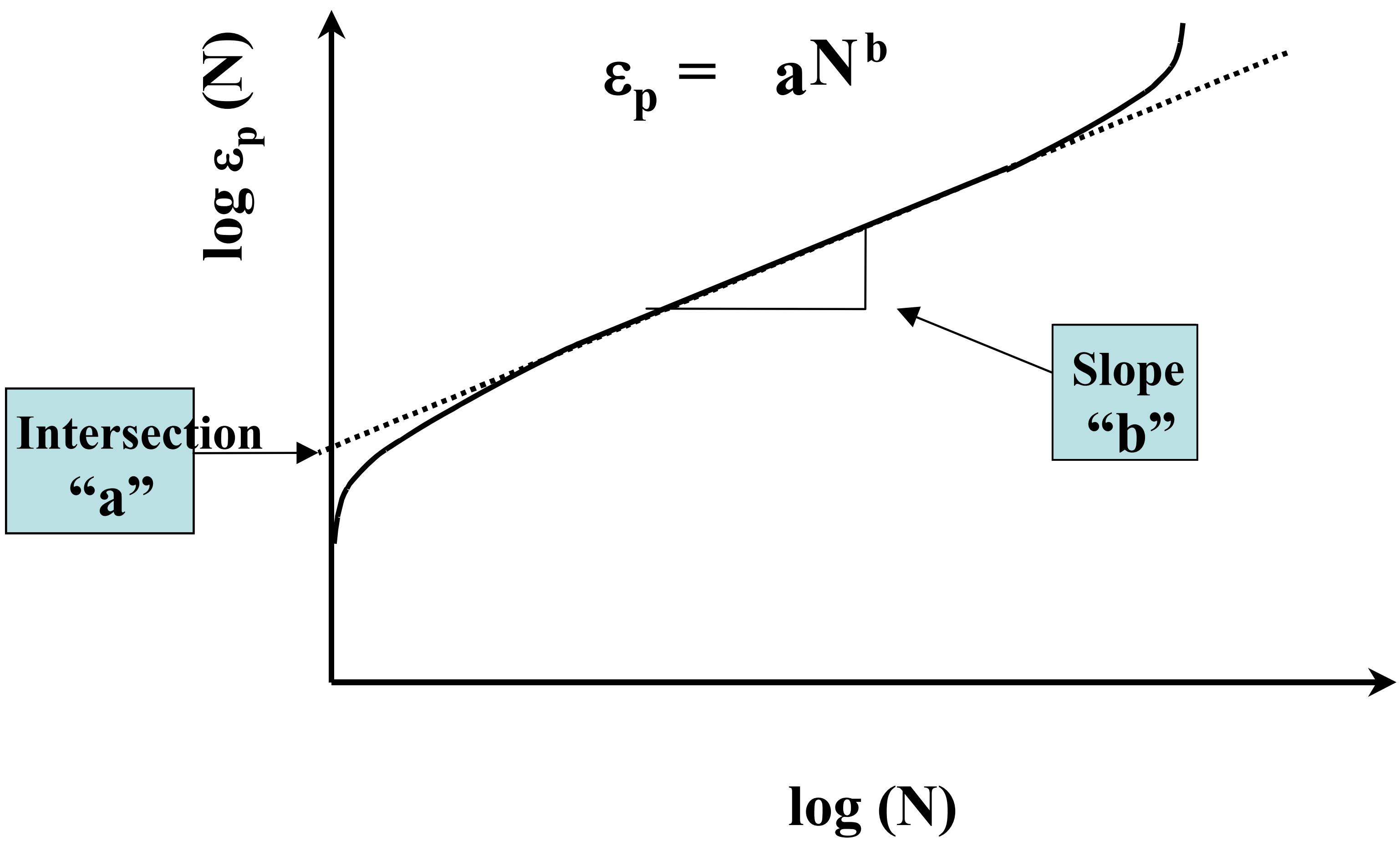
Rutting in bituminous bound materials

Design Guide

Development of permanent deformations at typical periodic load



Permanent deformation test; Parameters



Modelling permanent deformation

Asphalt layer – Design Guide

$$\frac{\varepsilon_p}{\varepsilon_r} = a_1 \cdot N^{a_2} \cdot T^{a_3}$$

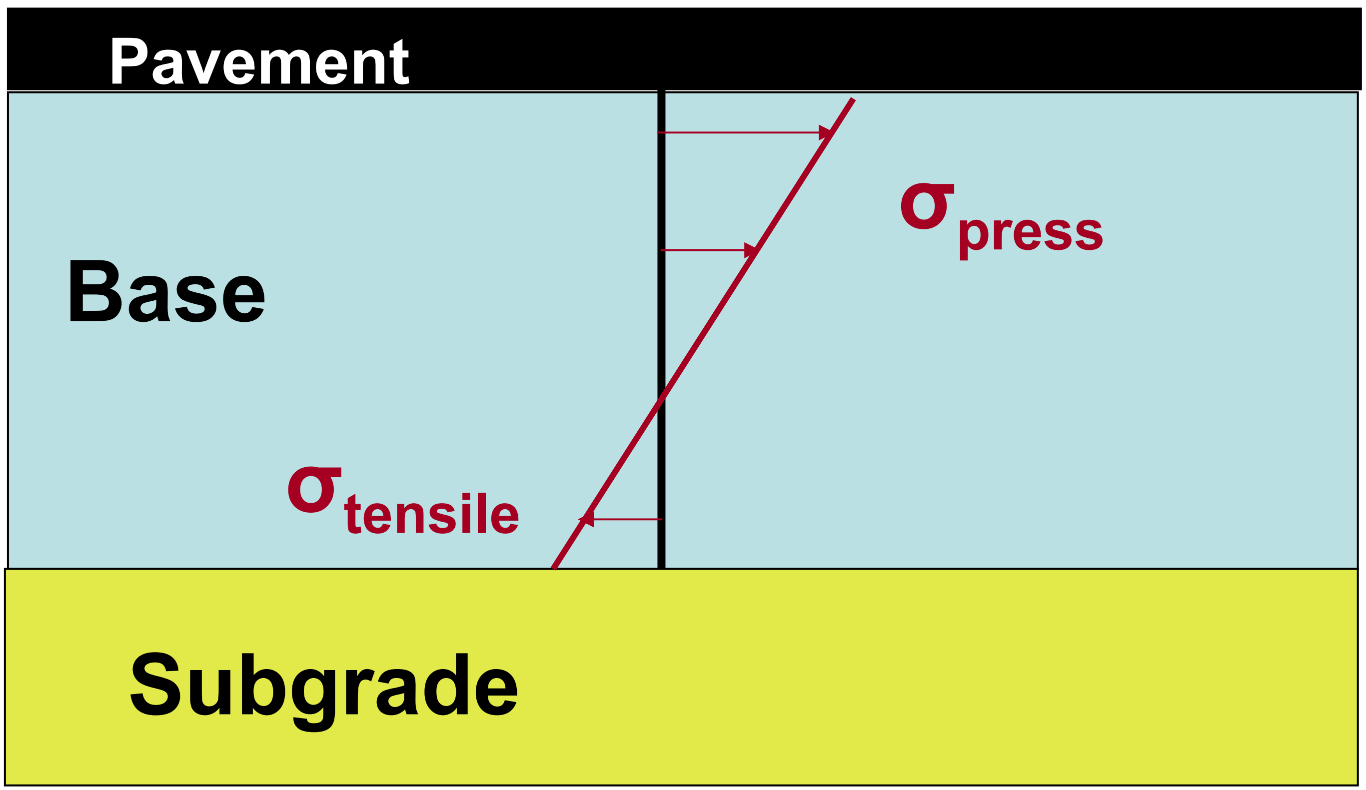
ε_p – Accumulated plastic strain at N repetitions of load
ε_r – Resilient strain of the asphalt material
N – Number of load repetitions
T – Temperature (10°C)
a_i – Non-linear regression coefficients (from NCHRP 1-37A)

Future development

NordFoU

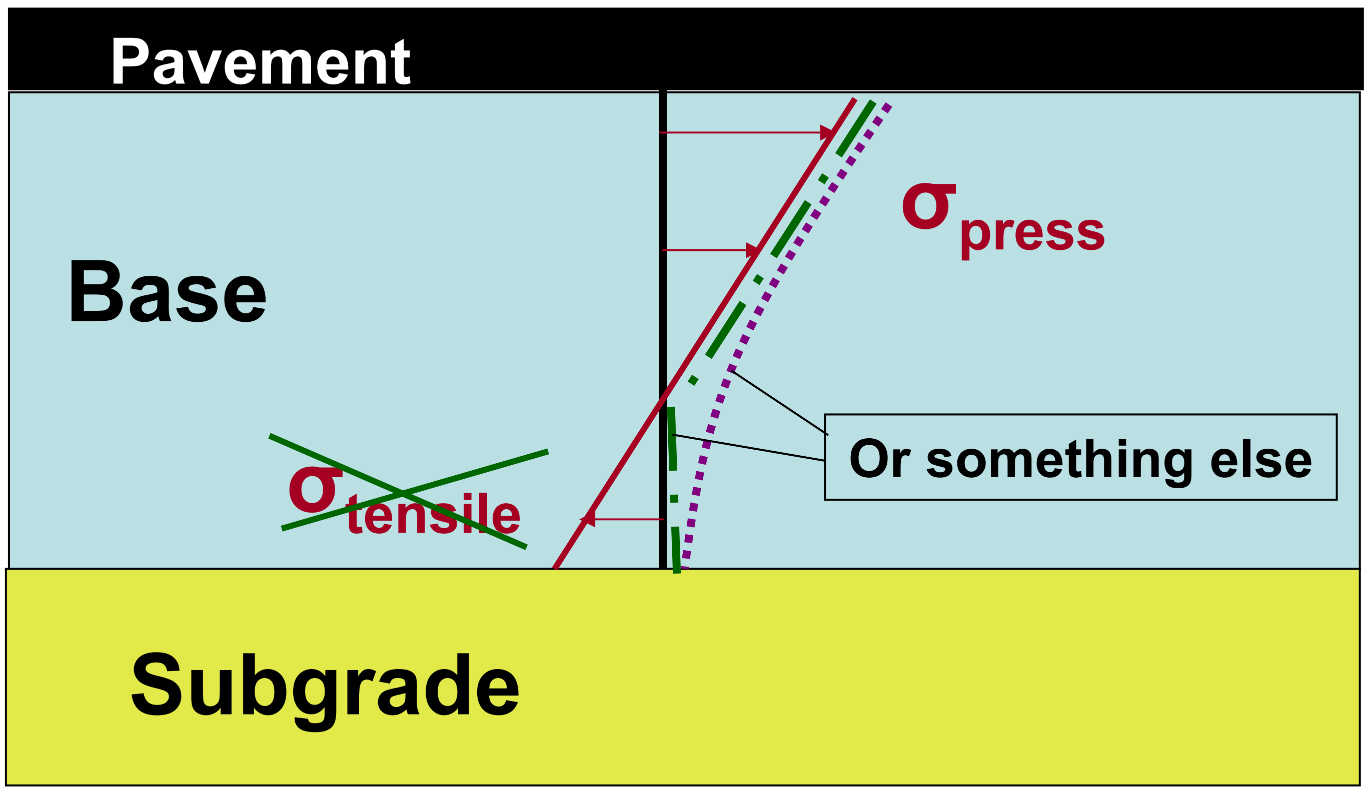
Sweden, Norway, Denmark and Island

Tensile stress in the bottom of unbound layers?

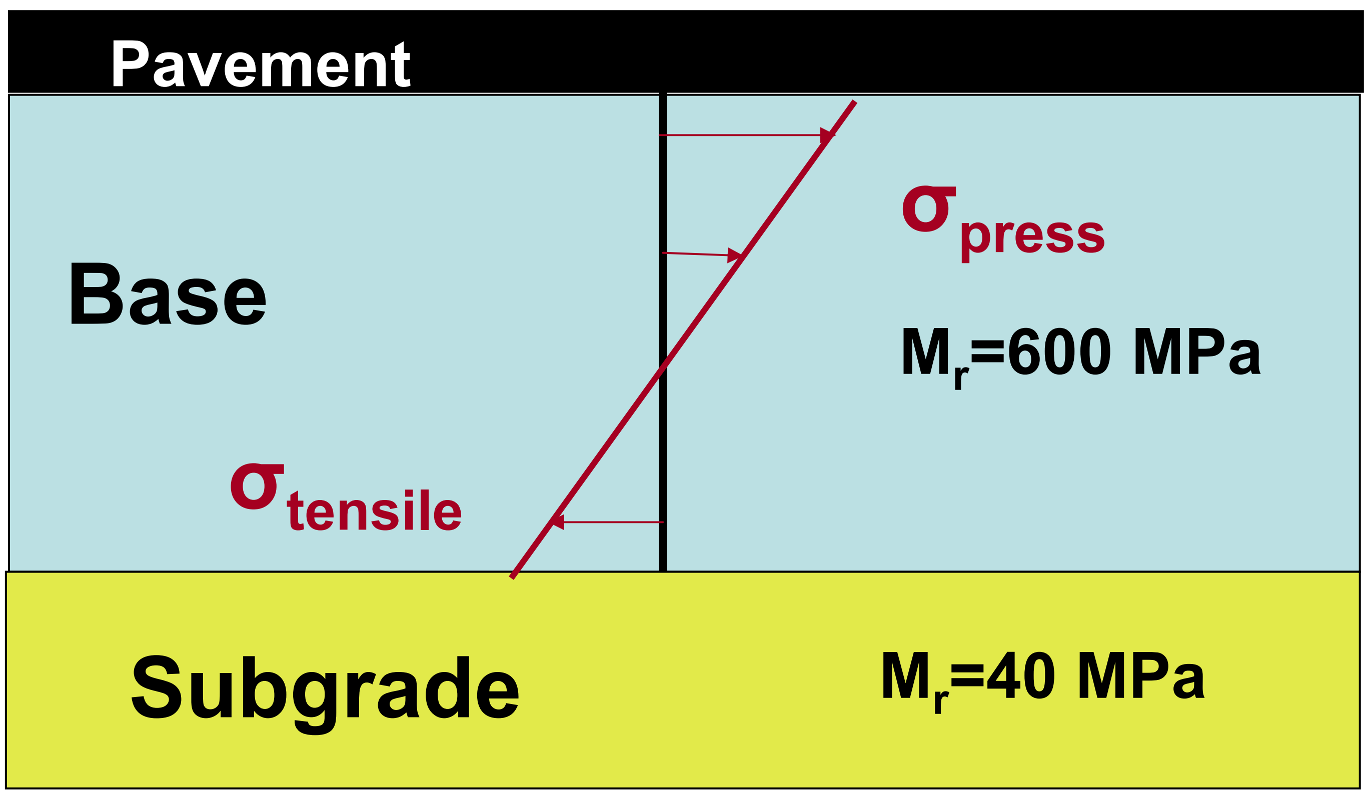


Tensile stress in the bottom of unbound layers?

Which is the real stress distibution?

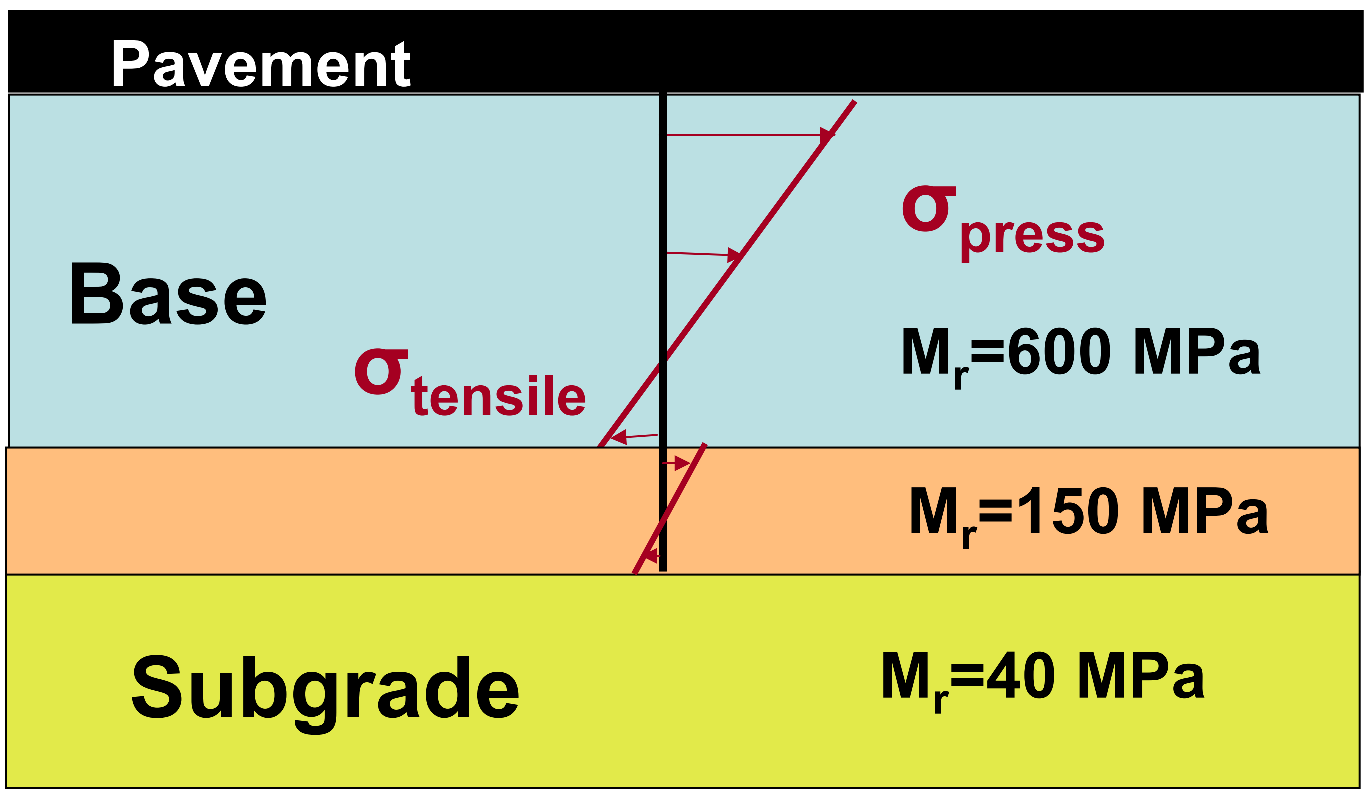


Unbound layers with large difference in resilient modulus?

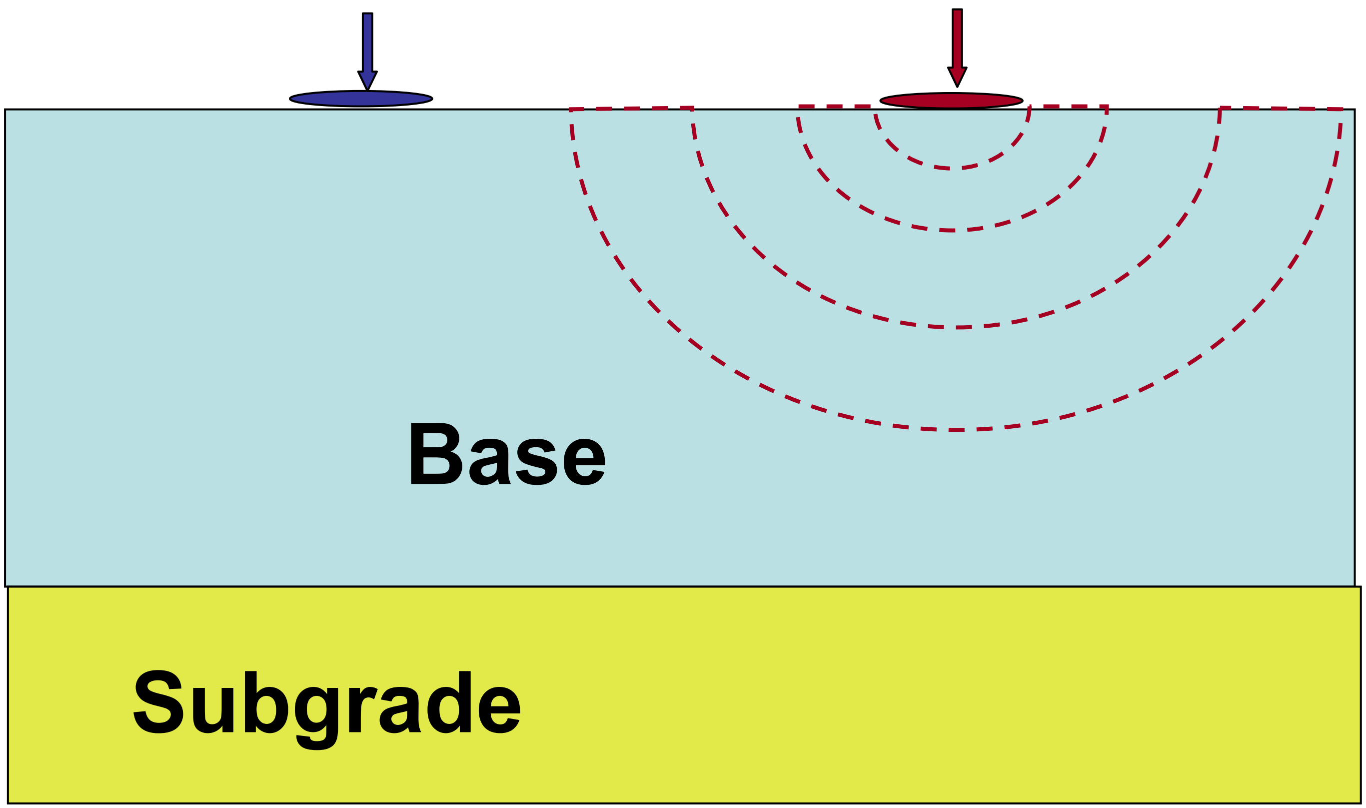


Unbound layers with large difference in resilient modulus?

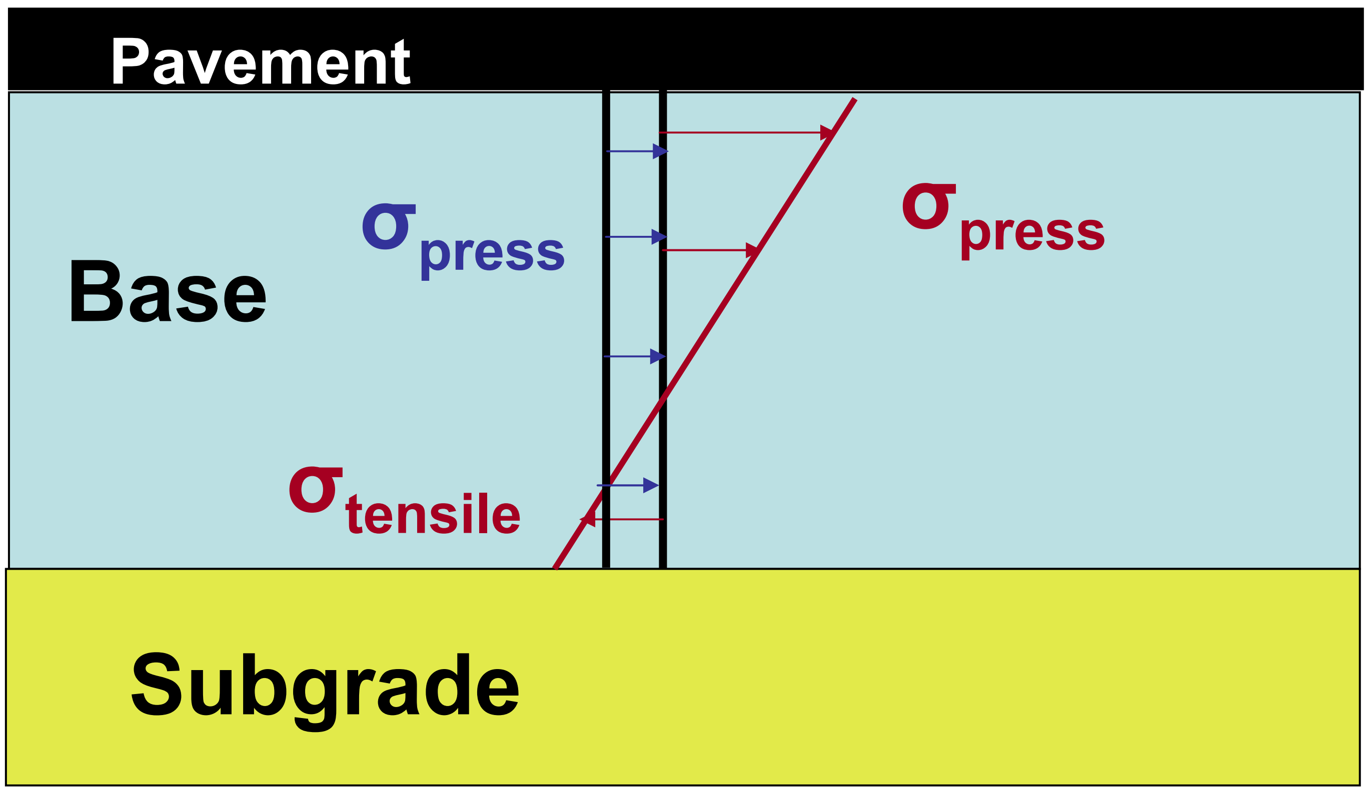
Old experience: Insert a layer with medium resilient modulus!



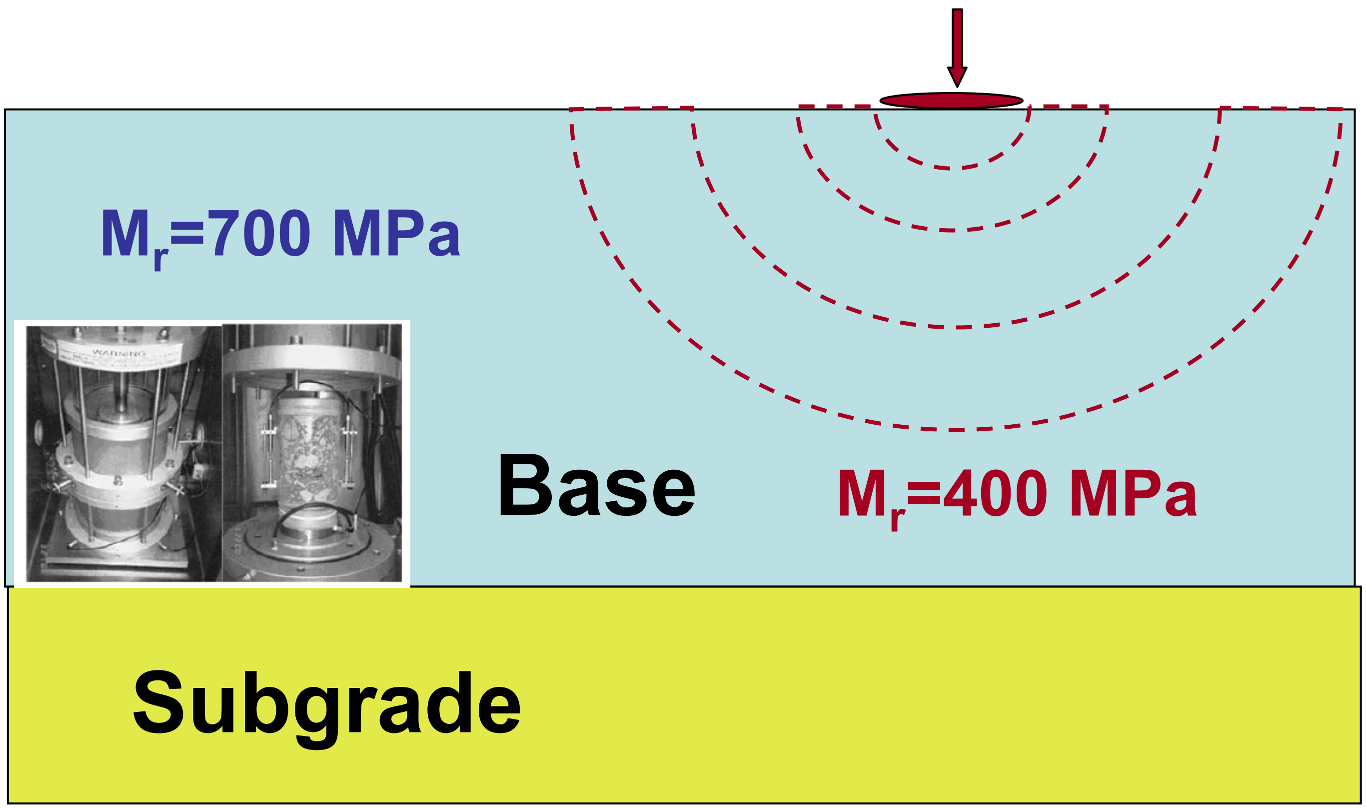
Difference/connection between static and dynamic resilient modulus?



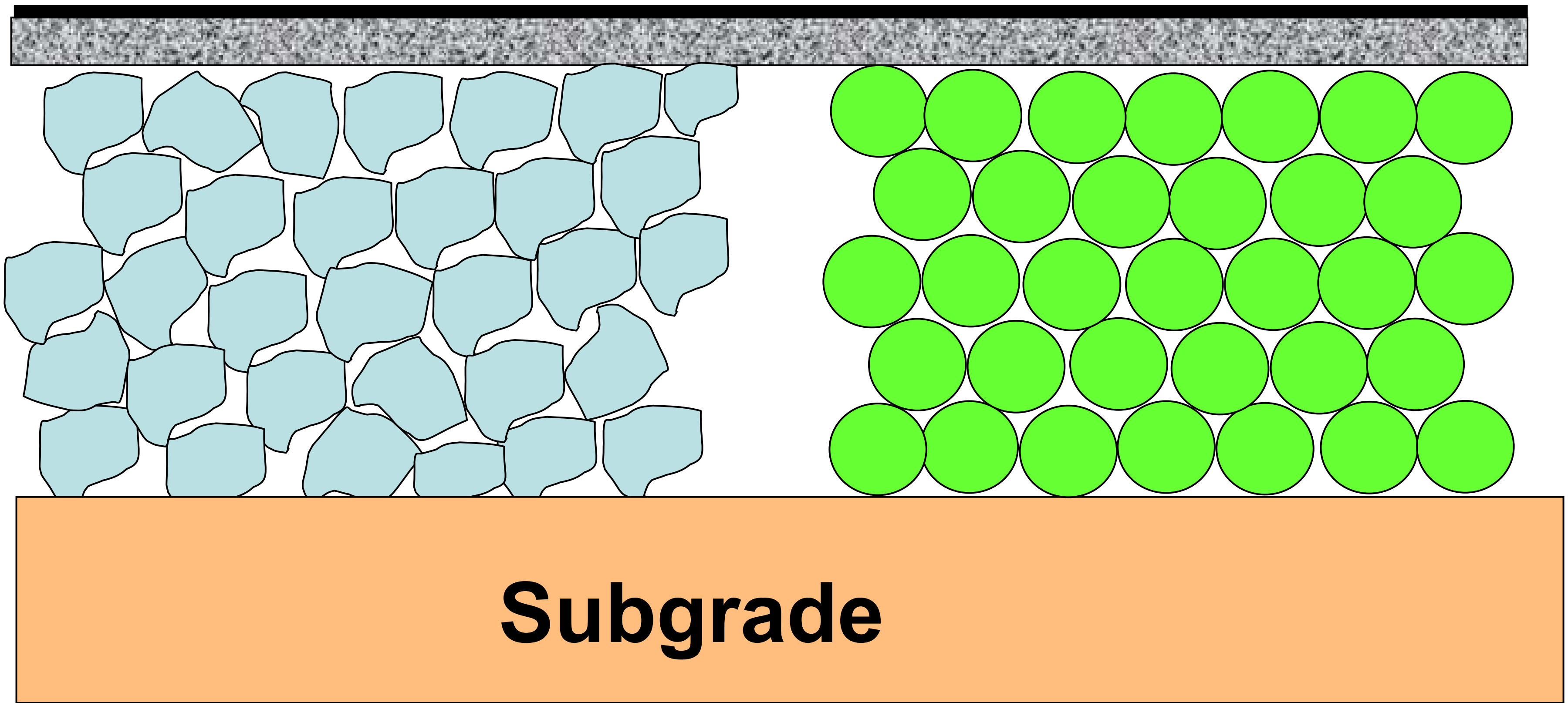
Horisontal stress depending on compaction and traffic ?



Difference/connection between resilient modulus measured with triaxial test and on site with plate loading etc.?



Material models different for crushed and uncrushed material?



Why does high plate loading values give small rutting?

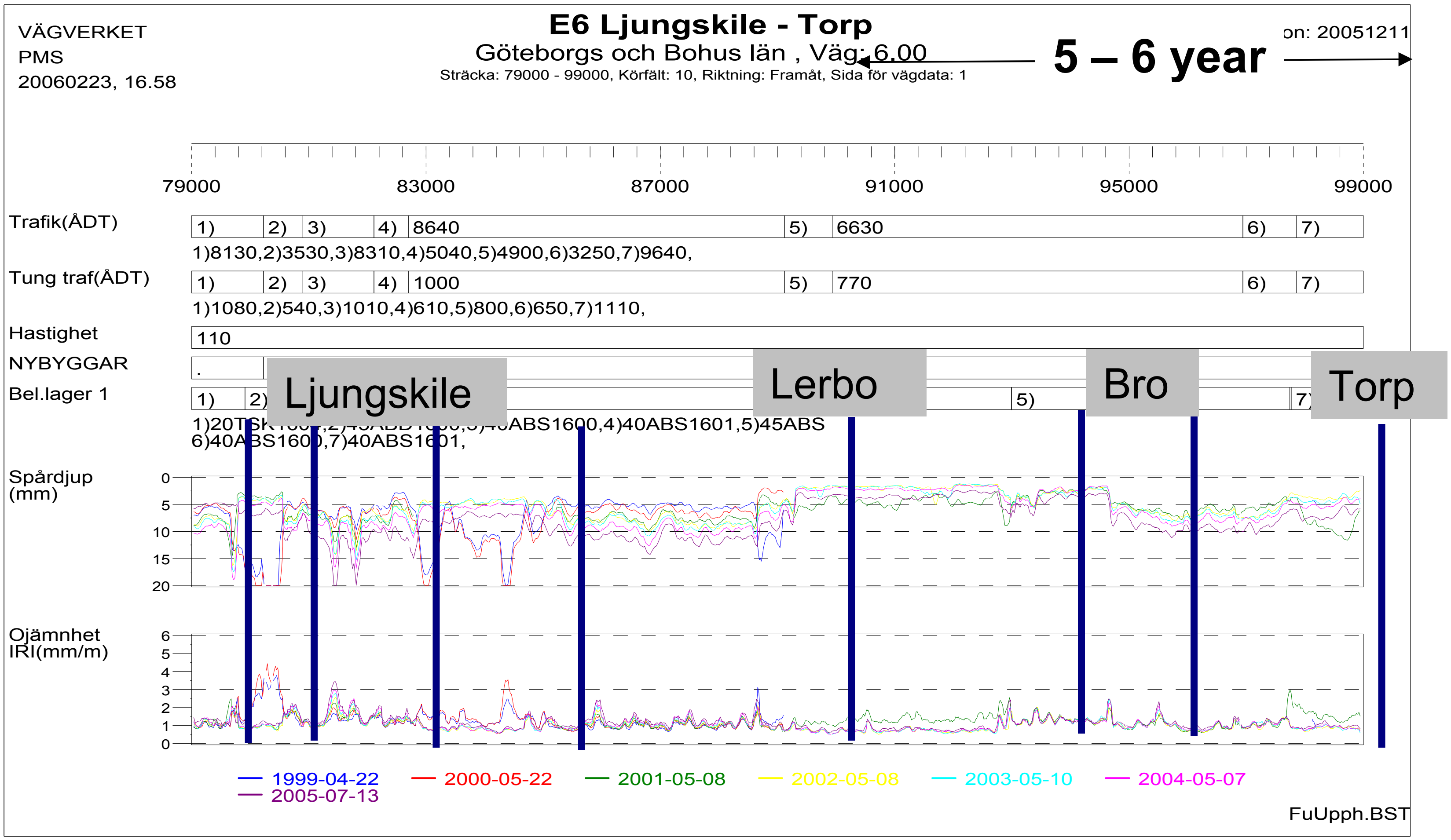
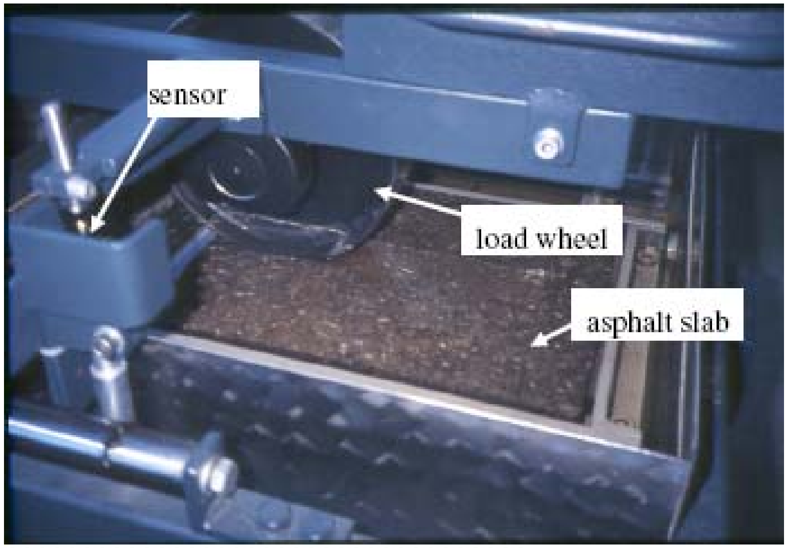


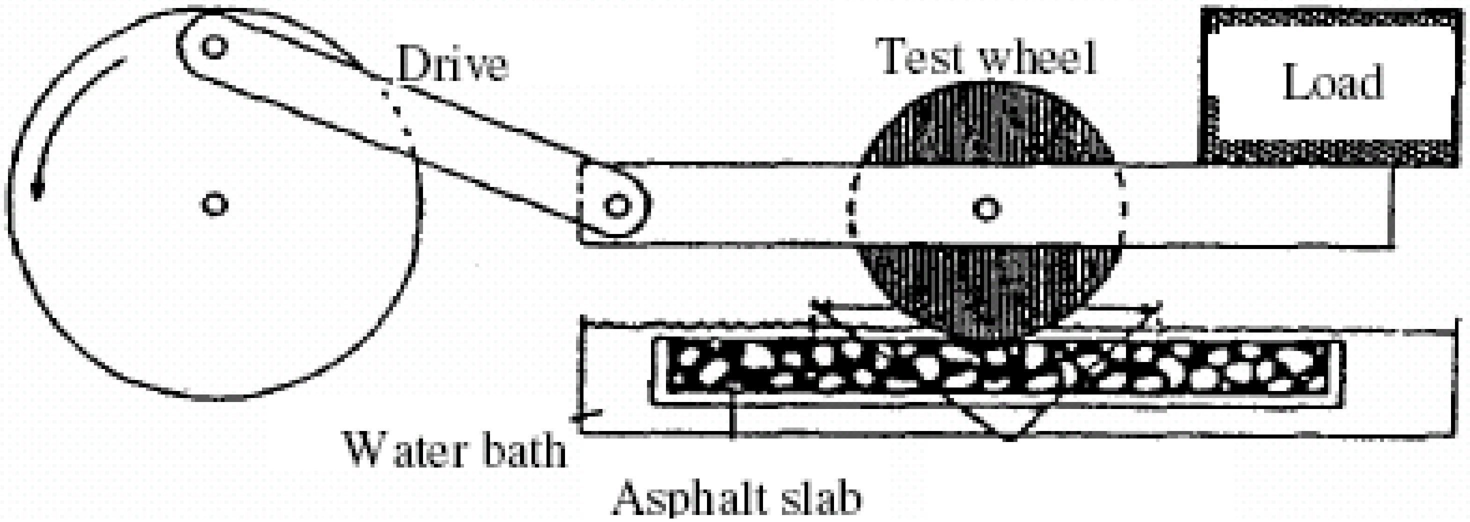
Plate loading: ca 90 MPa 250 – 500 MPa ca 150 MPa

Connection between aggregate characteristics etc. and permanent rutting?

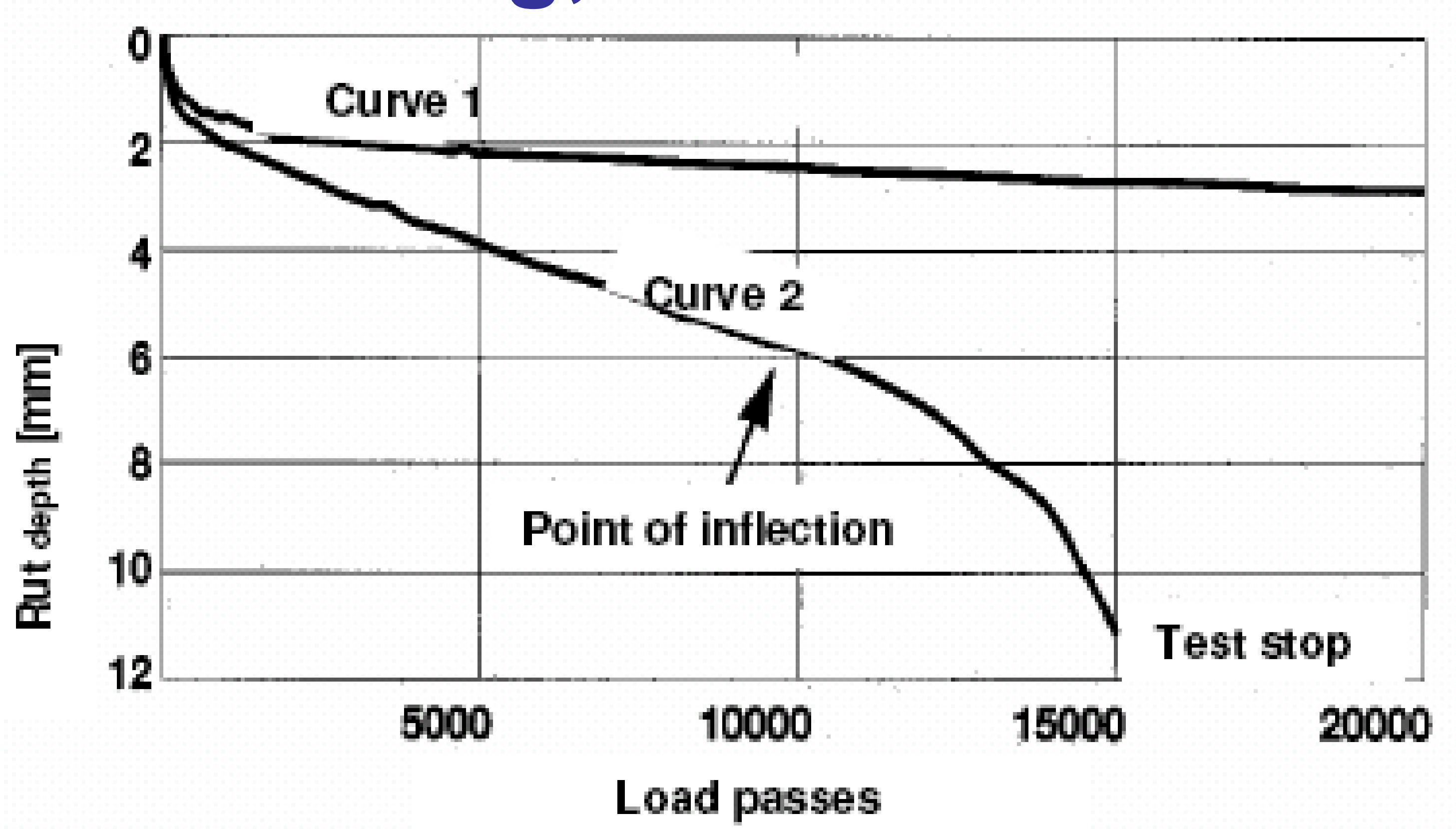
- Grain maximum size
- Aggregate gradation
- Rock material, Geology
- Moisture content

Wheel Tracking Test





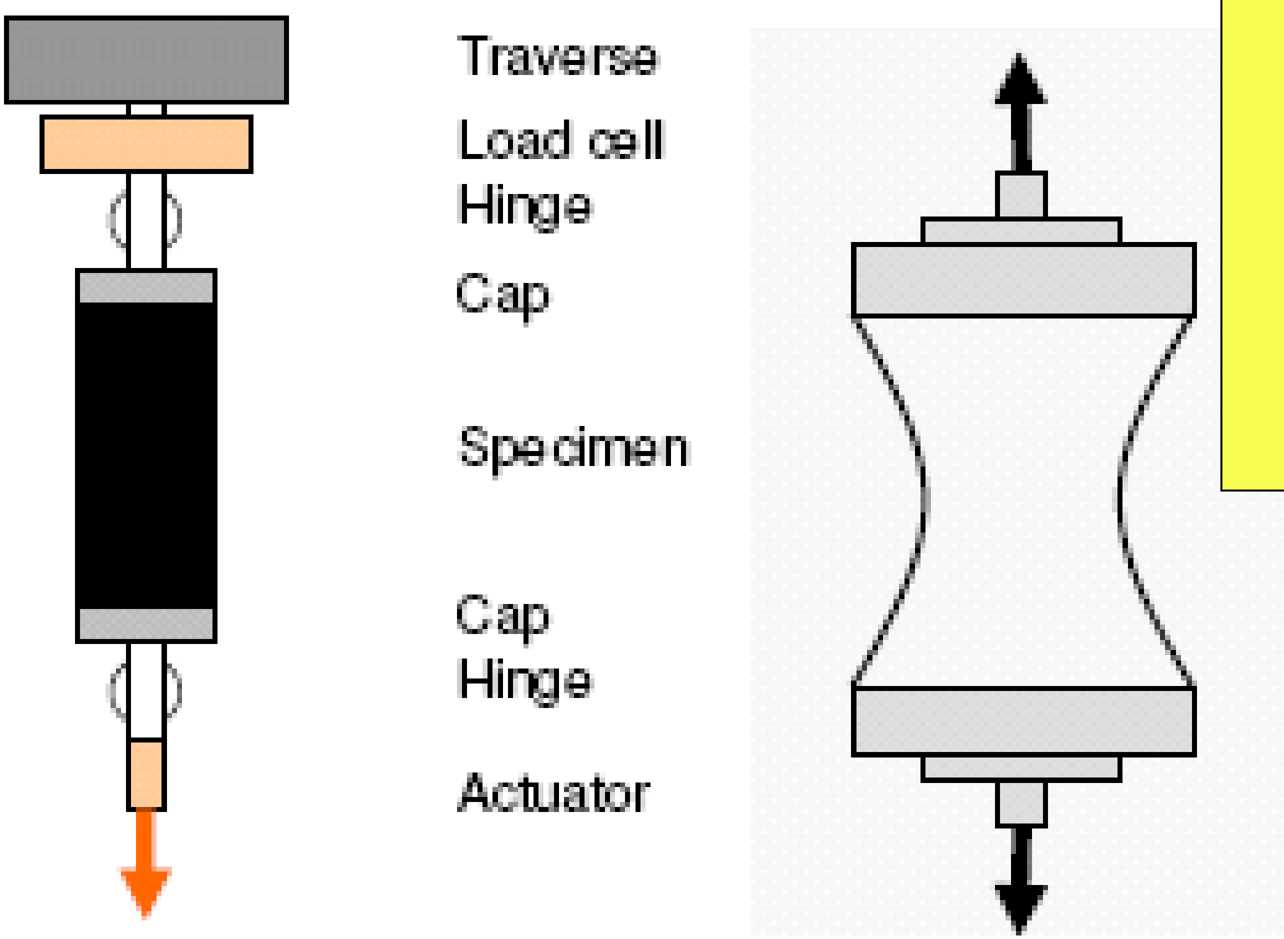
Wheel tracking; Result



Is it possible to backcalculate parameters from Wheel track tests in order to get parameters for calculation of permanent deformations in asphalt?

Uniaxial tensile testing

Connection between tensile strength and fatigue?

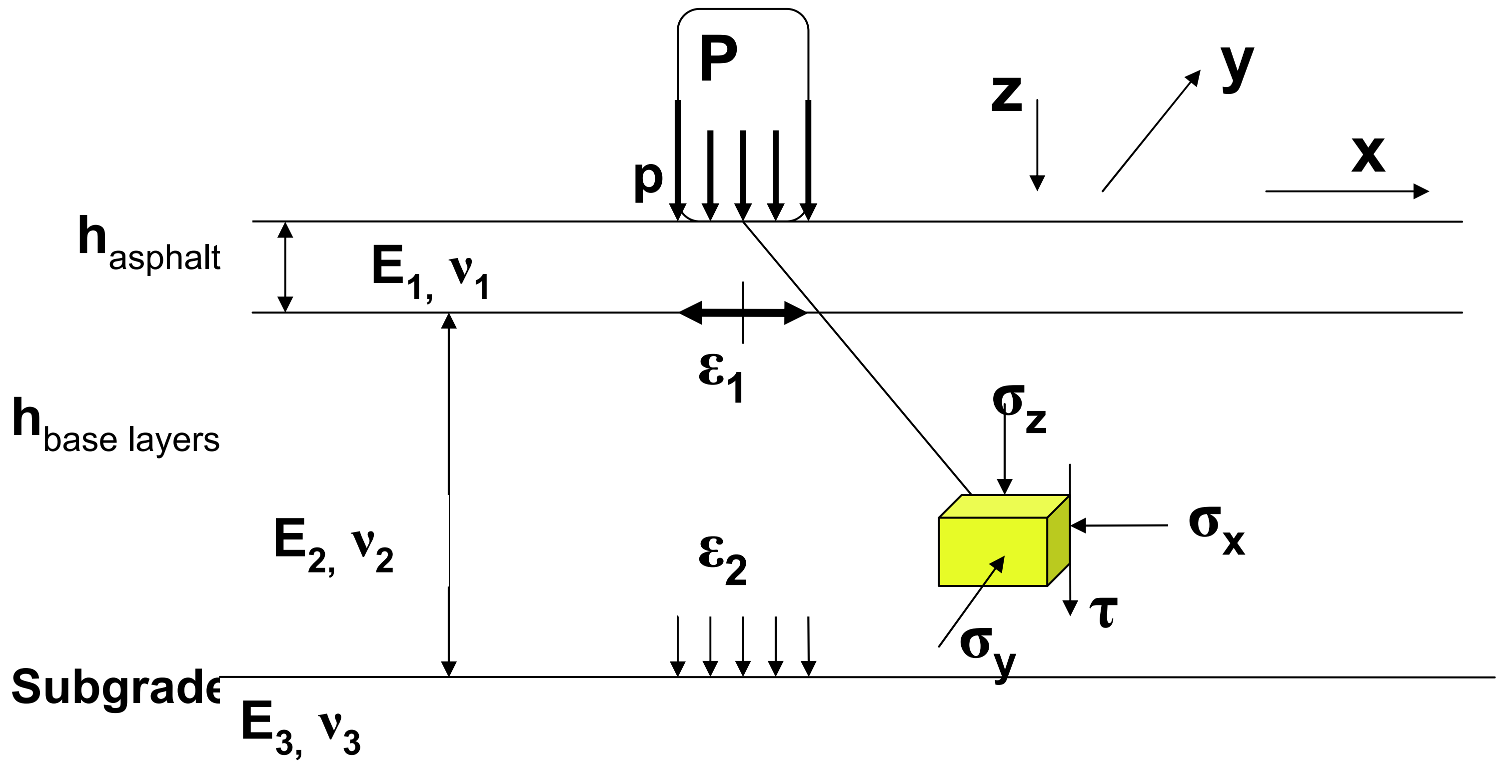


Effect of stabilisation

So, why do we not use this knowledge, test methods and models?

Mechanistical background

Linear elastic multilayer models



P = Wheel load
p = Wheel pressure

E = Elasticity moduli
ν = Poissons figure

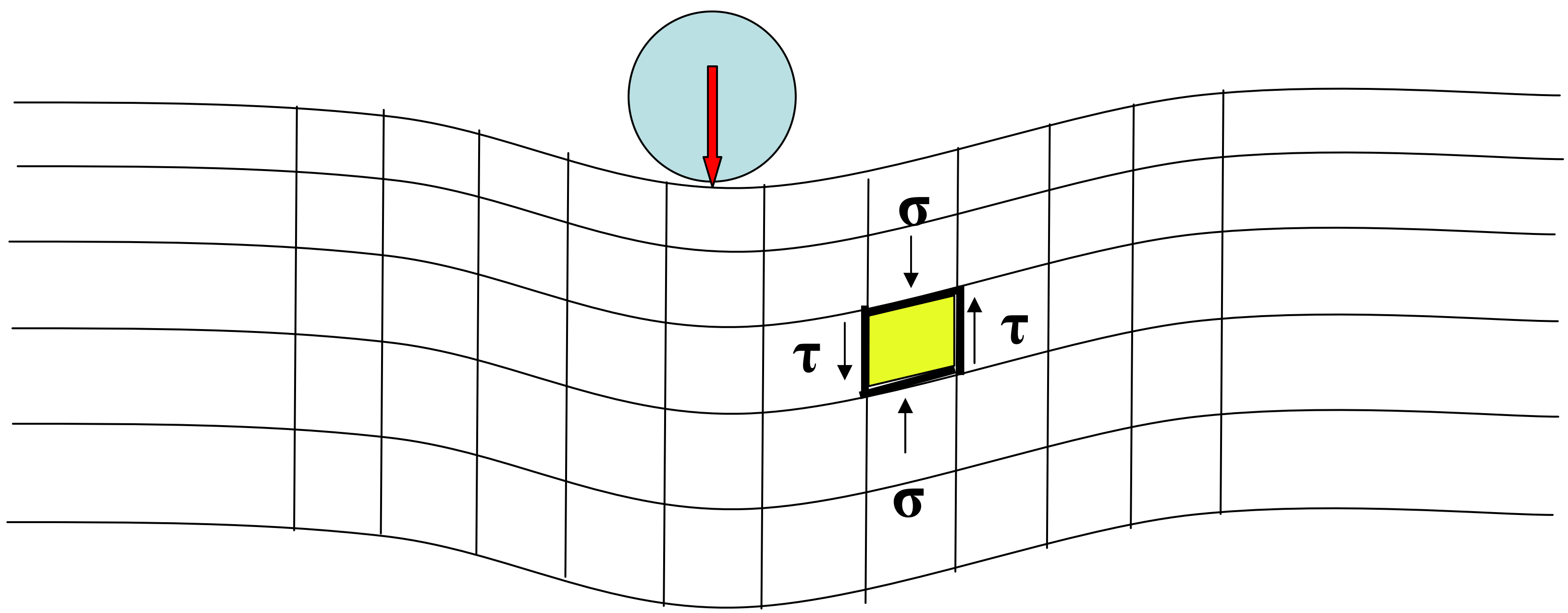
ε_1 = Strain in bottom asphalt layer
ε_2 = Strain on subgrade

MULTILAYER MODELS

Prerequisites:

- **The material is linear elastic**
- **The material can take tensile stress, even if it is wrong (unbound material)**
- **The material has no weight**
- **The material has infinite extension in all directions**

FINIT ELEMENT MODELS (FEM)



Every little part must be in stress equilibrim and deform in such a way that all pieces fits together.

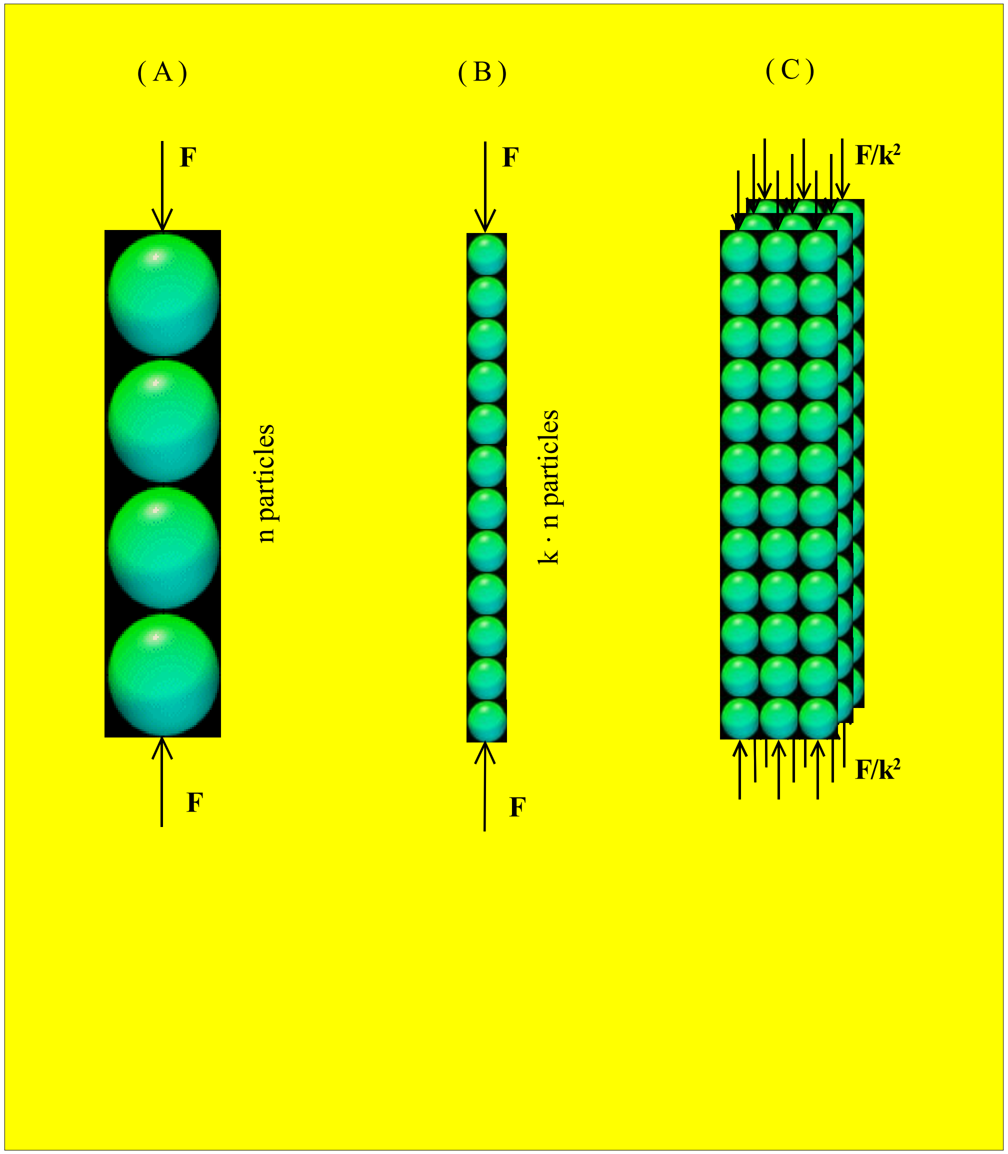
FINIT ELEMENT MODELS (FEM)

Prerequisites:

- Different material models could be used
- The material can take tensile stress or not (unbound material)
- The weight of the material could be included in the calculations
- The real geometry of the road can be simulated

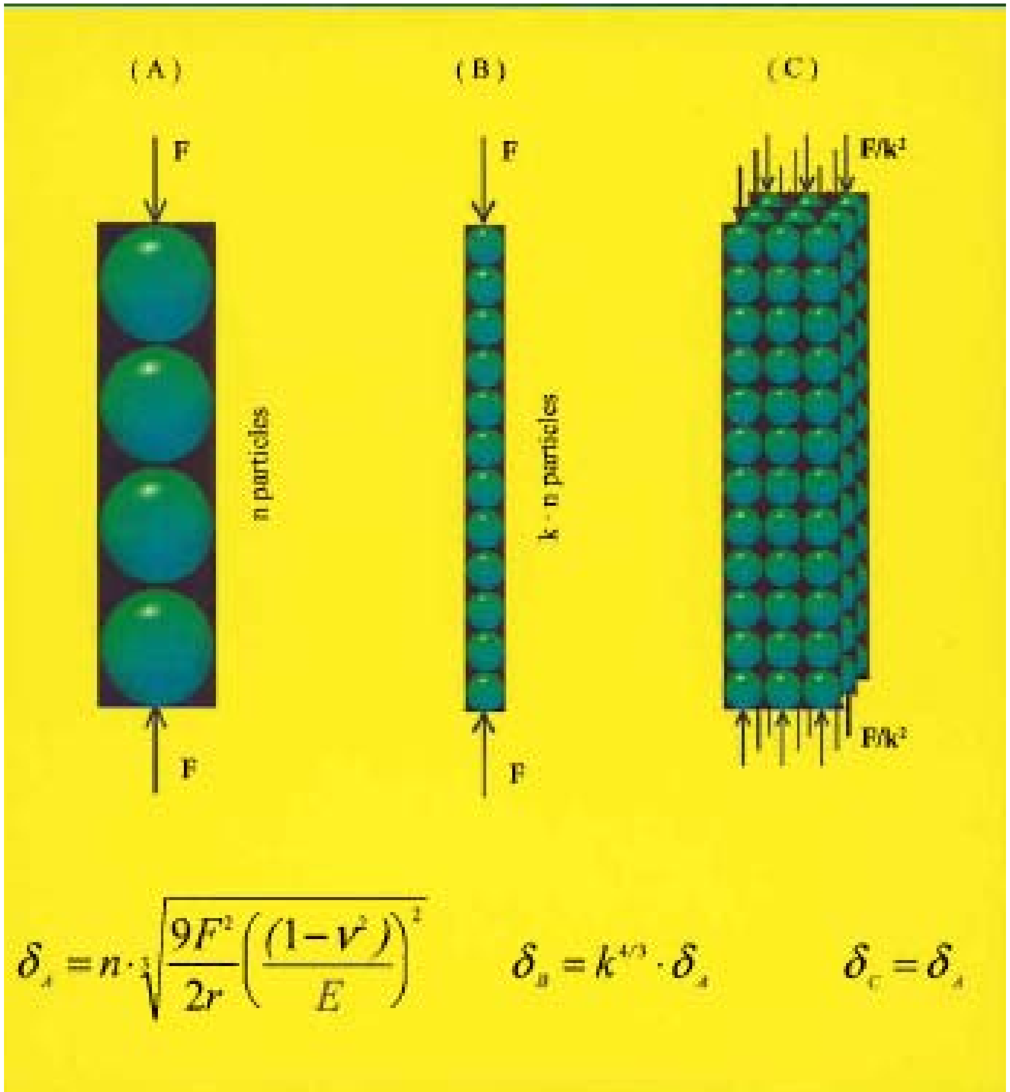
SOME MECHANISTICAL FACTORS

Aggregate size

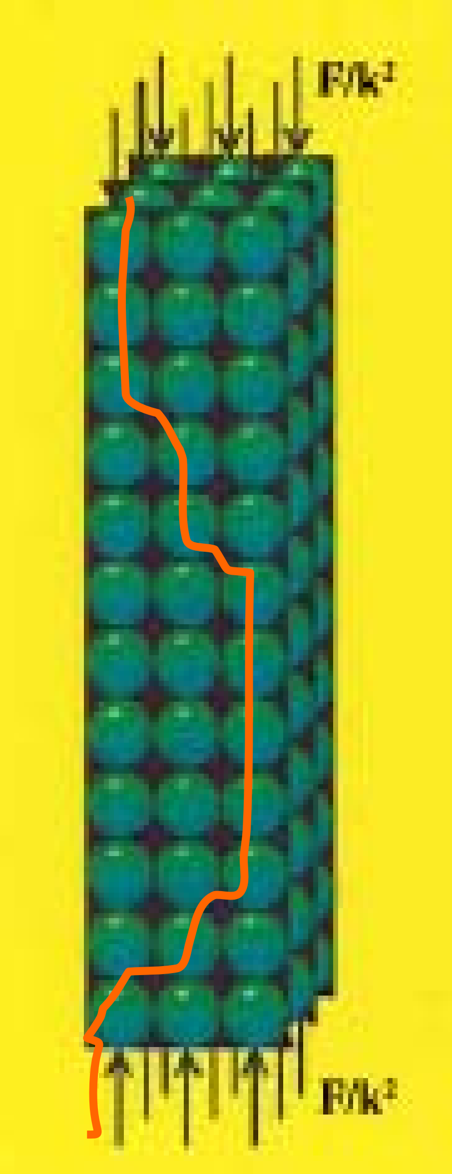


P Kolisoja

Influence from aggregate size

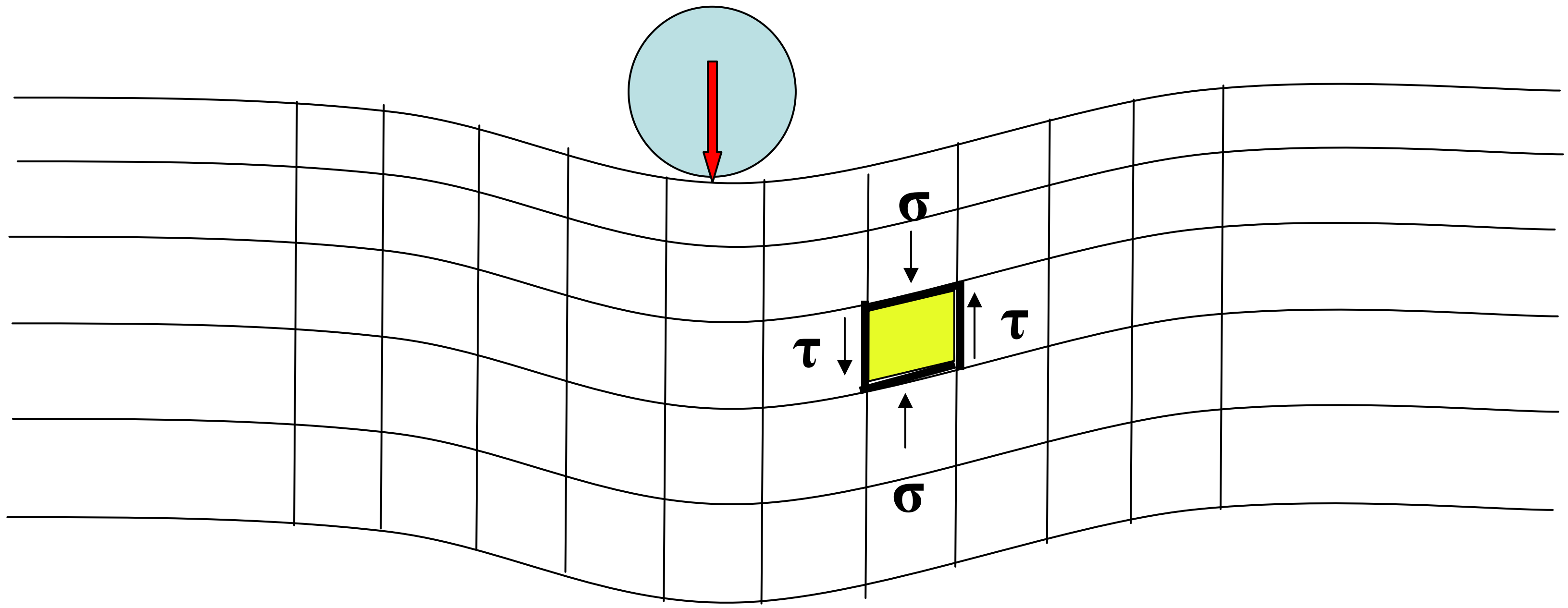


$$\delta_A = n \cdot \sqrt[3]{\frac{9F^2}{2r}\left(\frac{(1-\nu^2)}{E}\right)^2} \qquad \delta_B = k^{4/3} \cdot \delta_A \qquad \delta_C = \delta_A$$

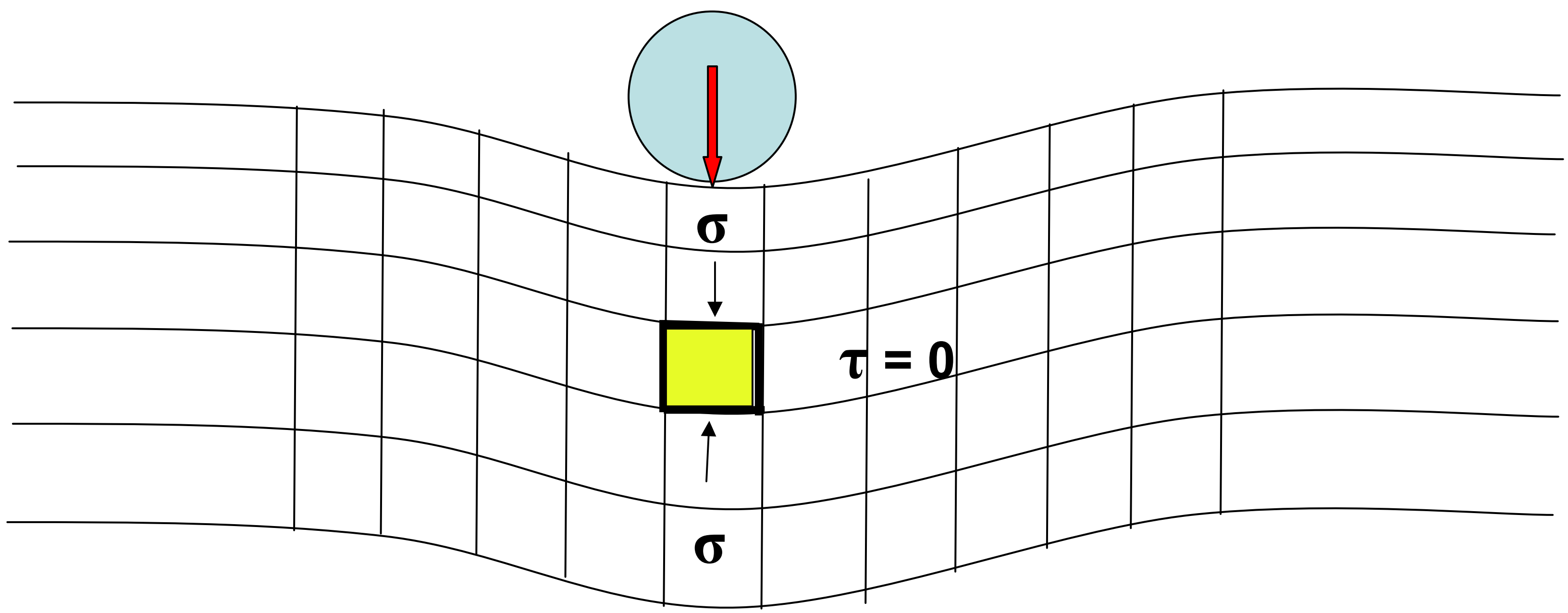


P Kolisoja

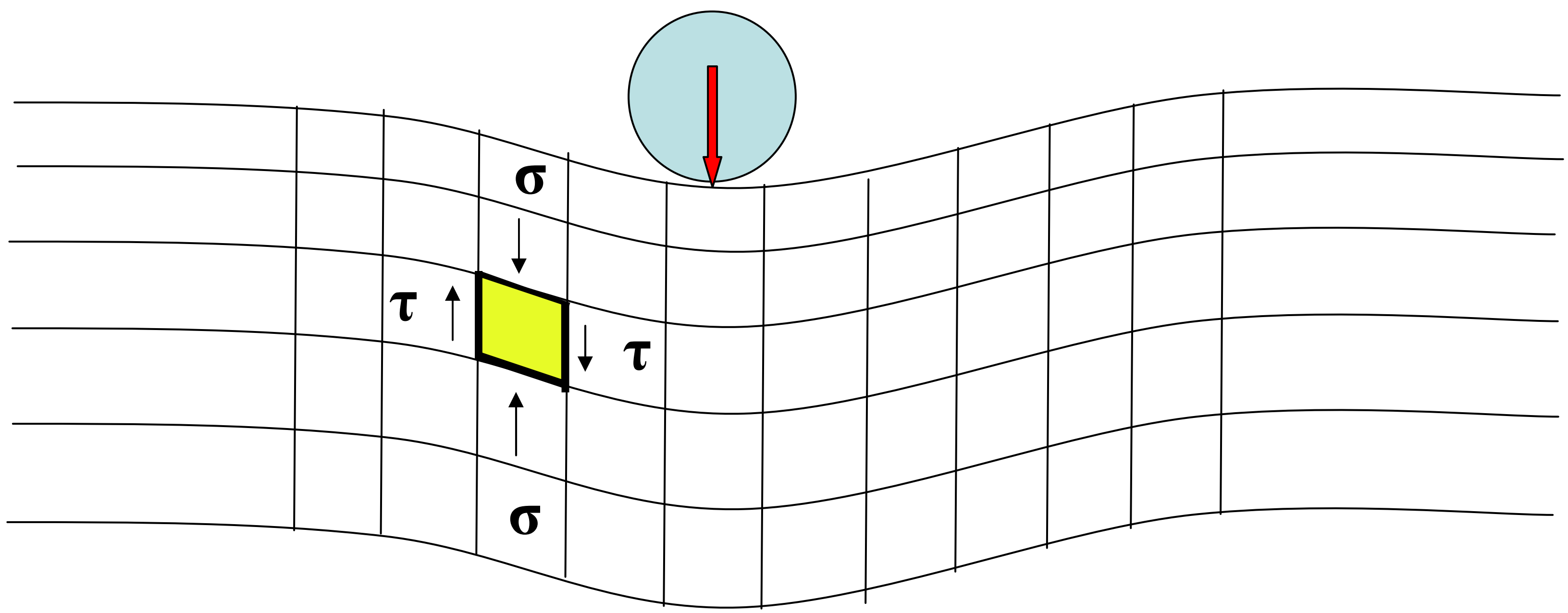
Reversed direction of shear stress



Reversed direction of shear stress

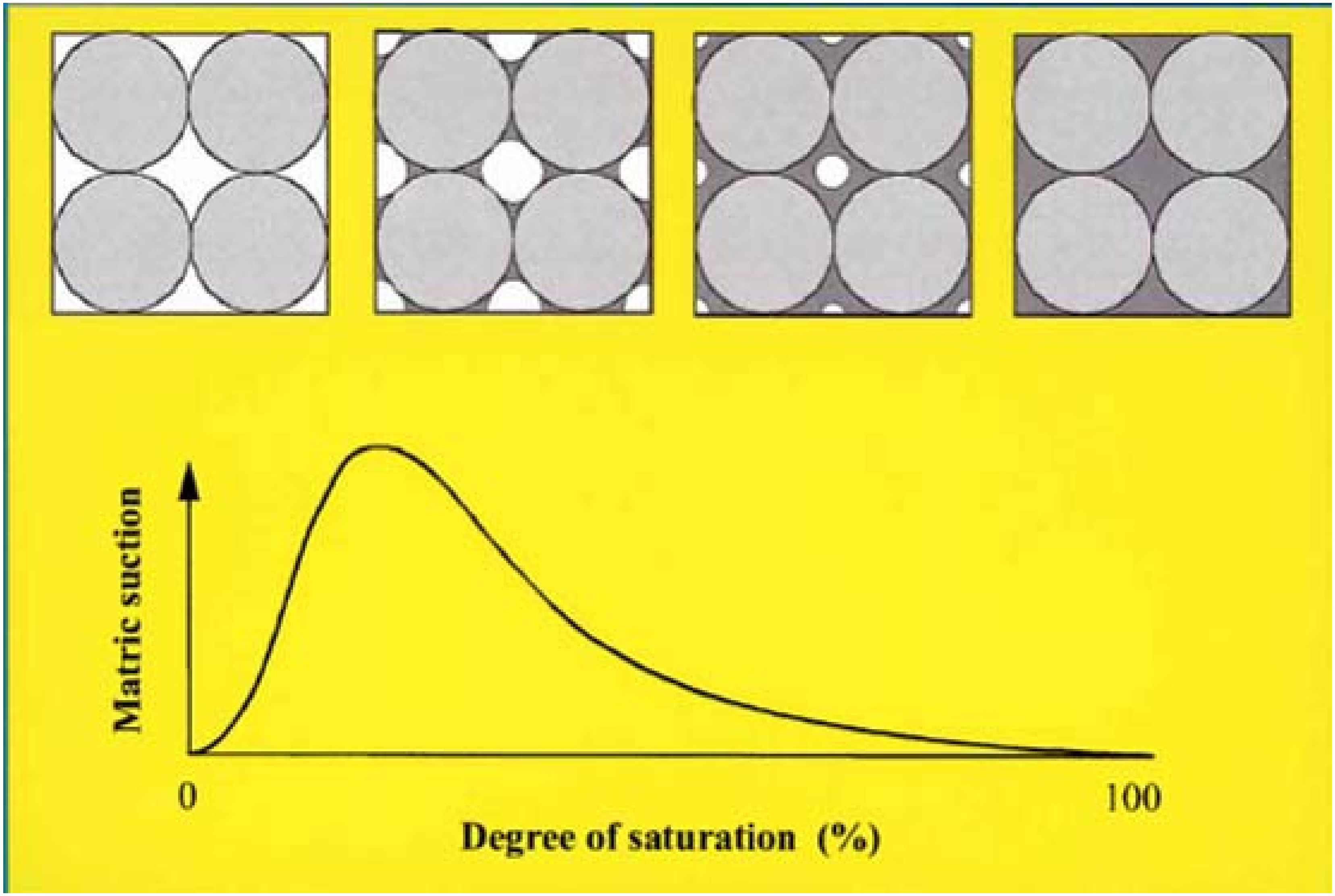


Reversed direction of shear stress

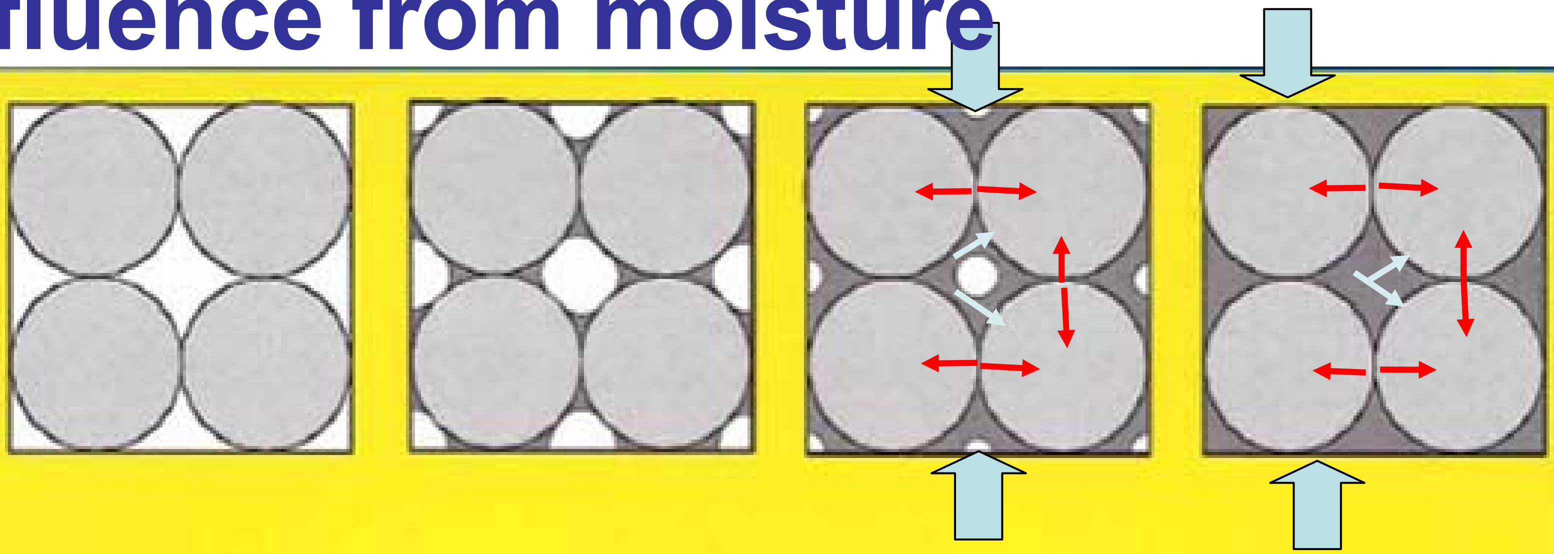


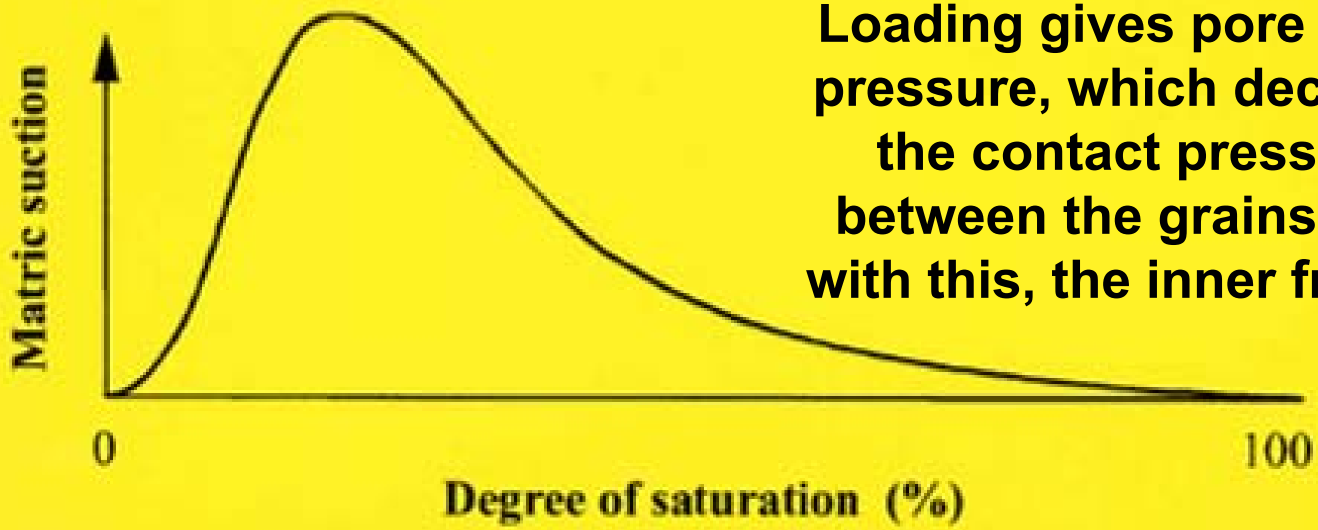
Large influence on permanent deformations

Influence from moisture



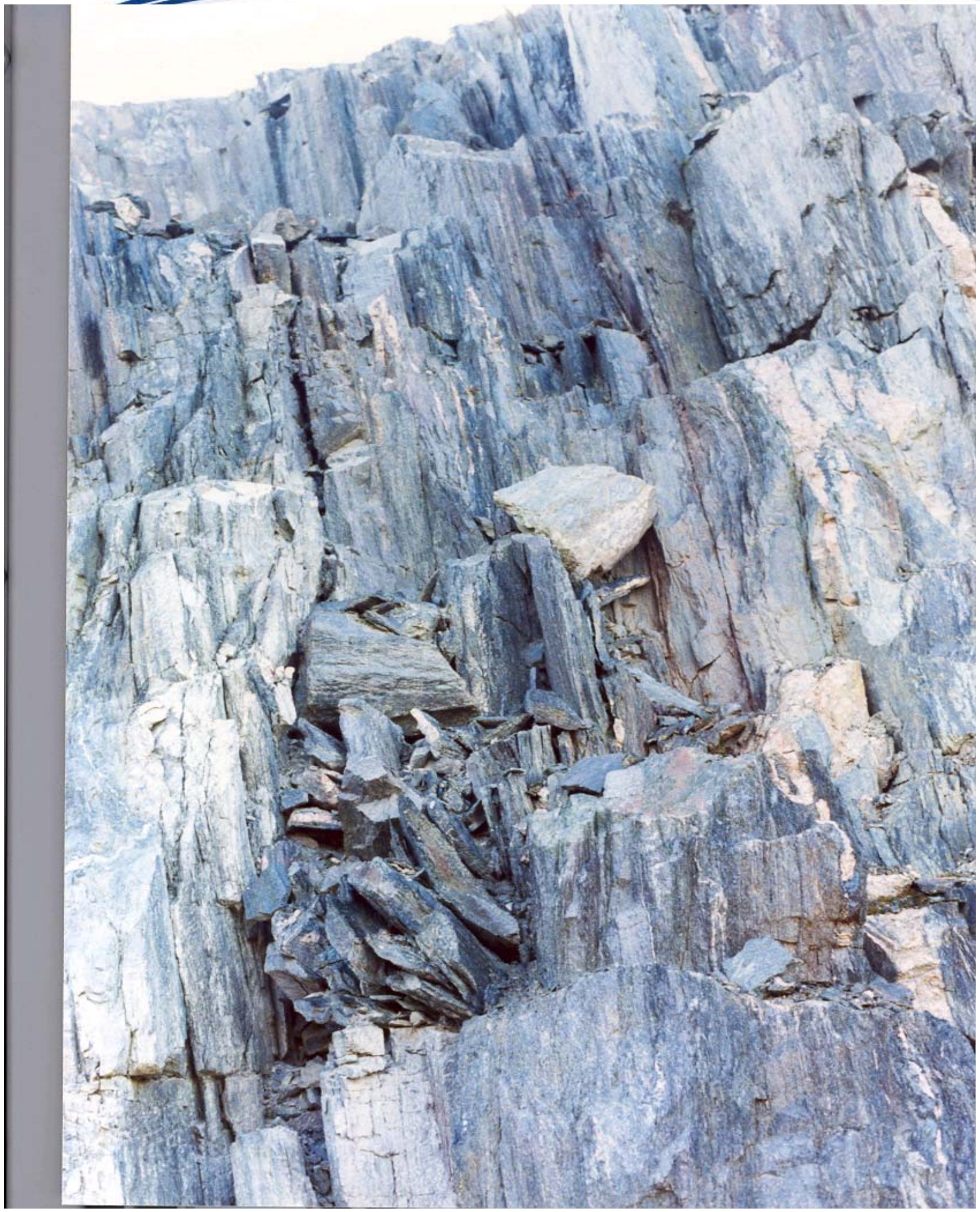
Influence from moisture





Loading gives pore water pressure, which decrease the contact pressure between the grains, and with this, the inner friction

DURABILITY
Unbound layers



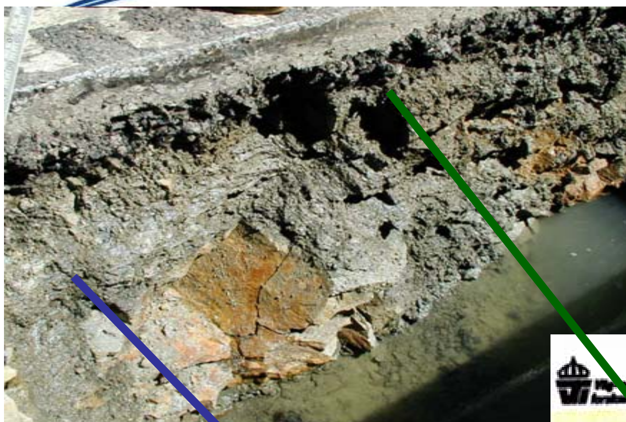
Rock material, fitness for the use as base material

Decomposed rock in a rock excavation

The fitness of the rock material for the use as base material

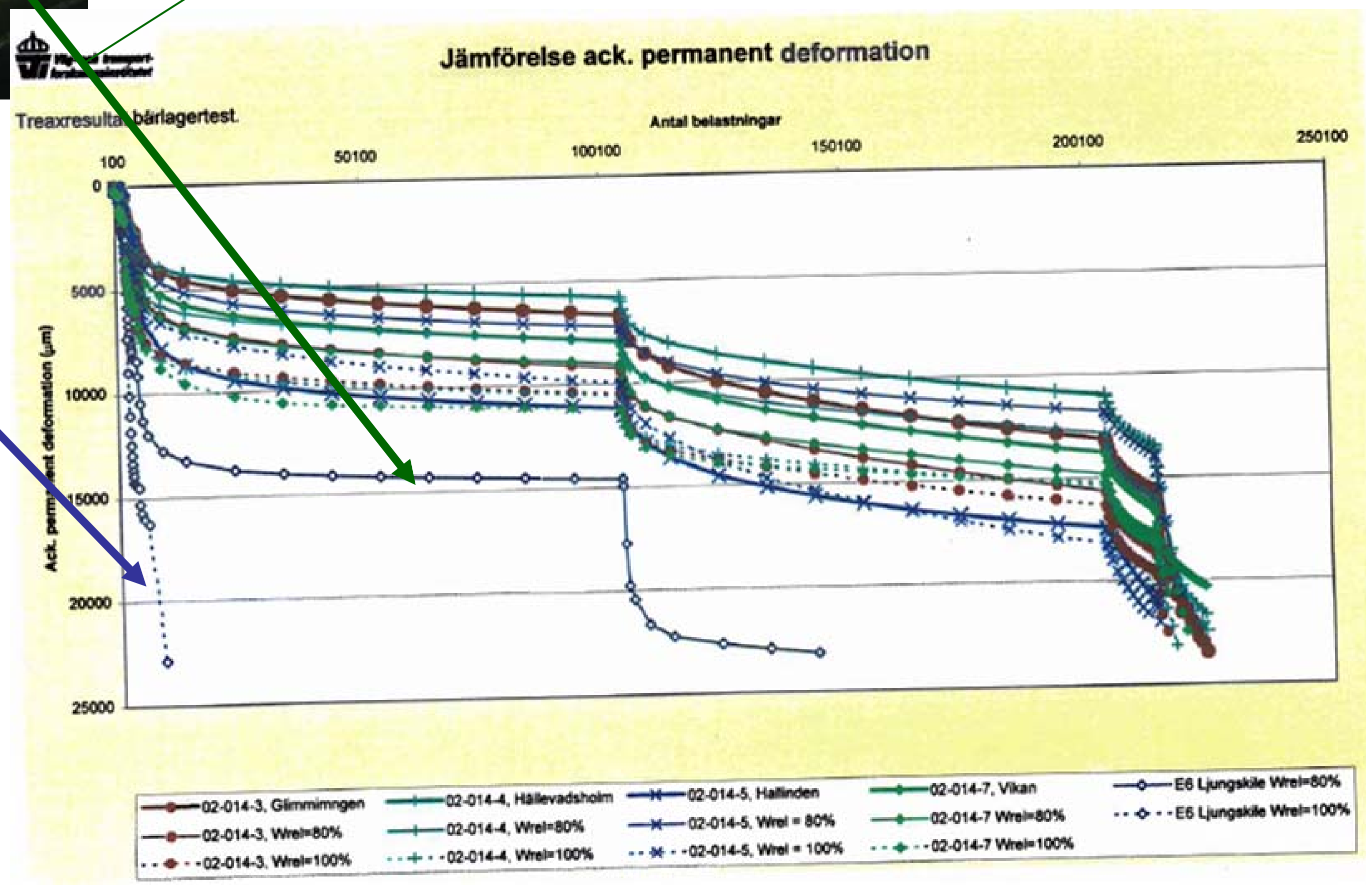
Base material of rock, which has decomposed in a road under trafic

Triaxial test on different materials



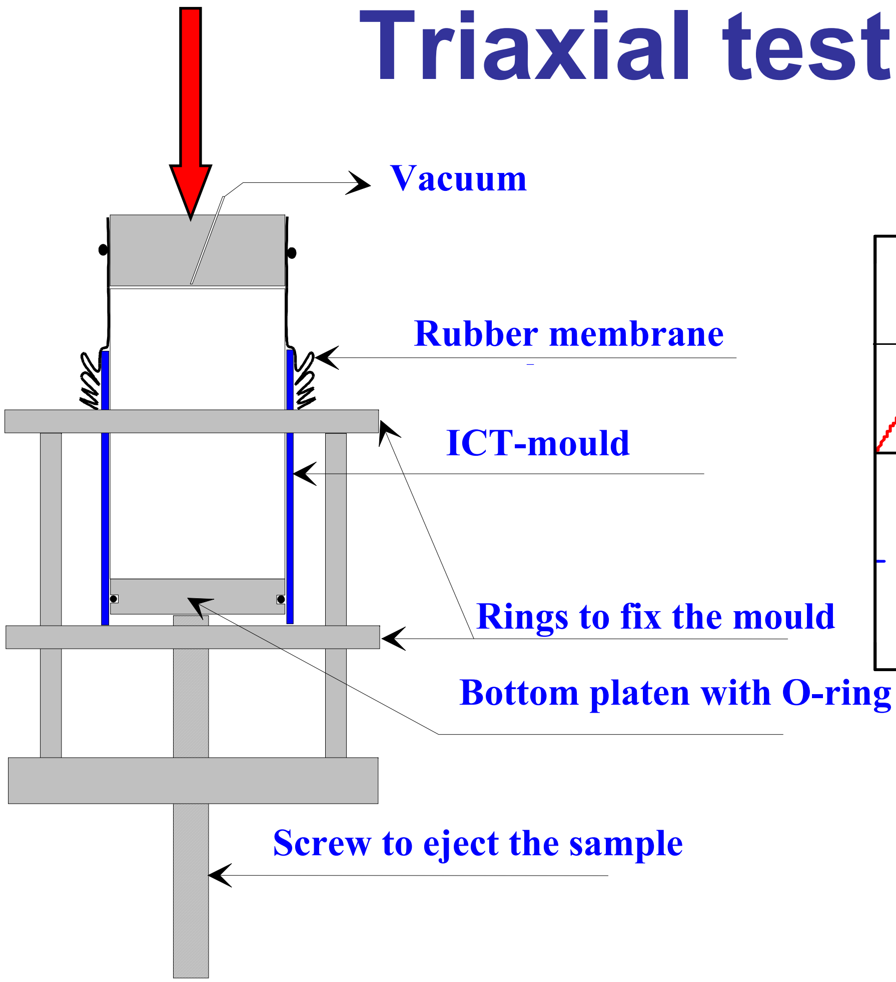
Dry

Humid

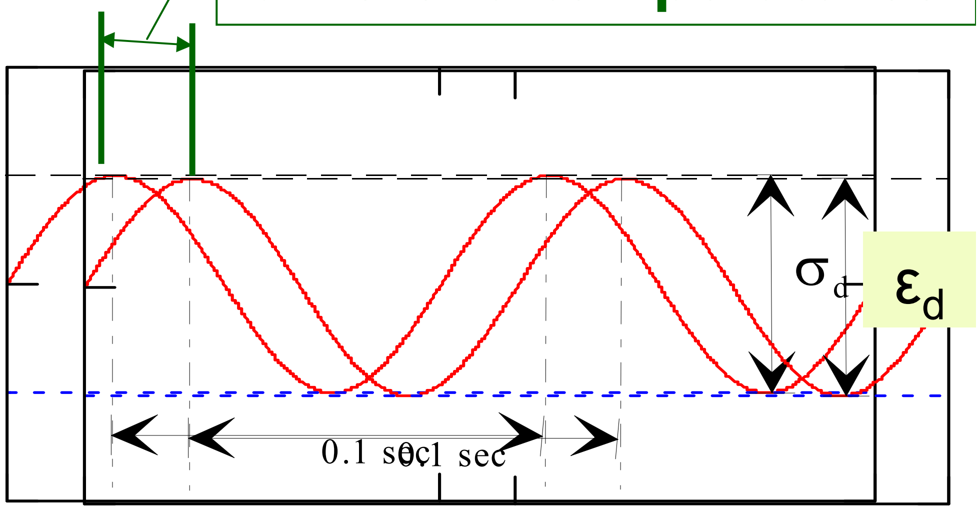


TEST METHODS
bituminous bound layers

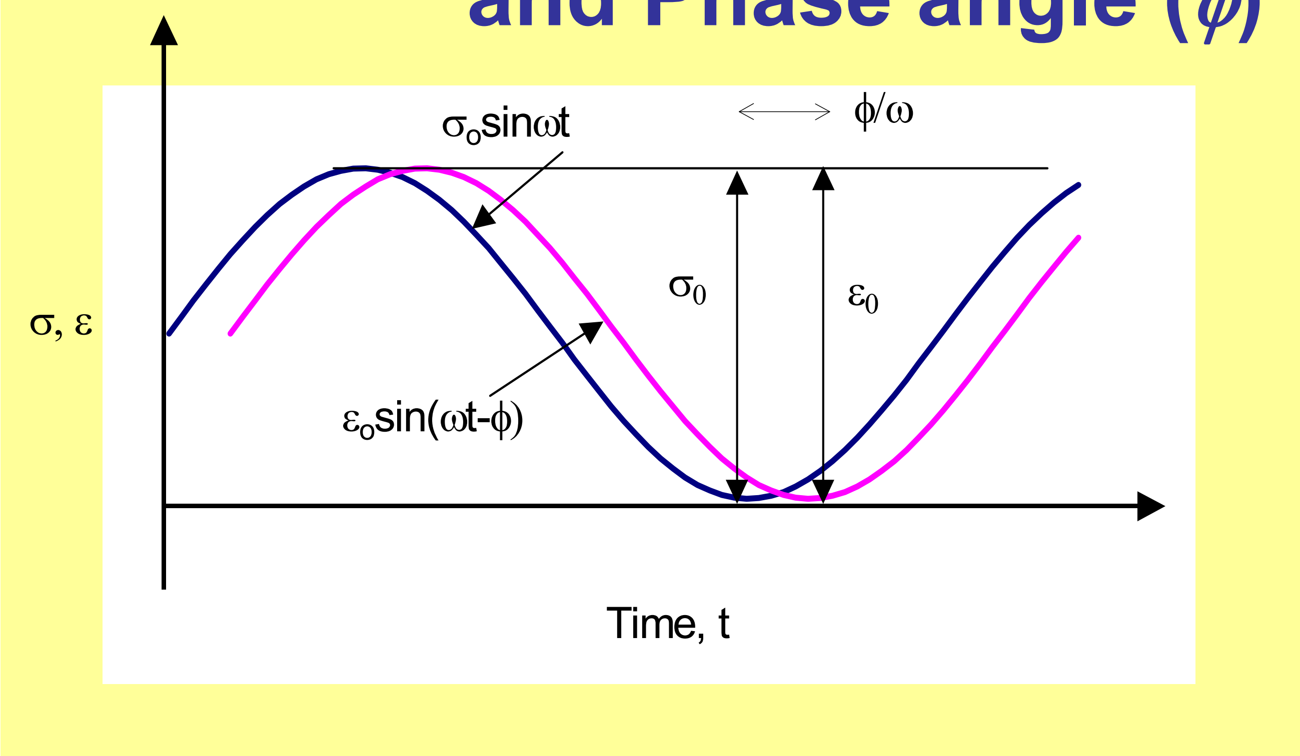
Triaxial test



Phase displacement at different temperatures



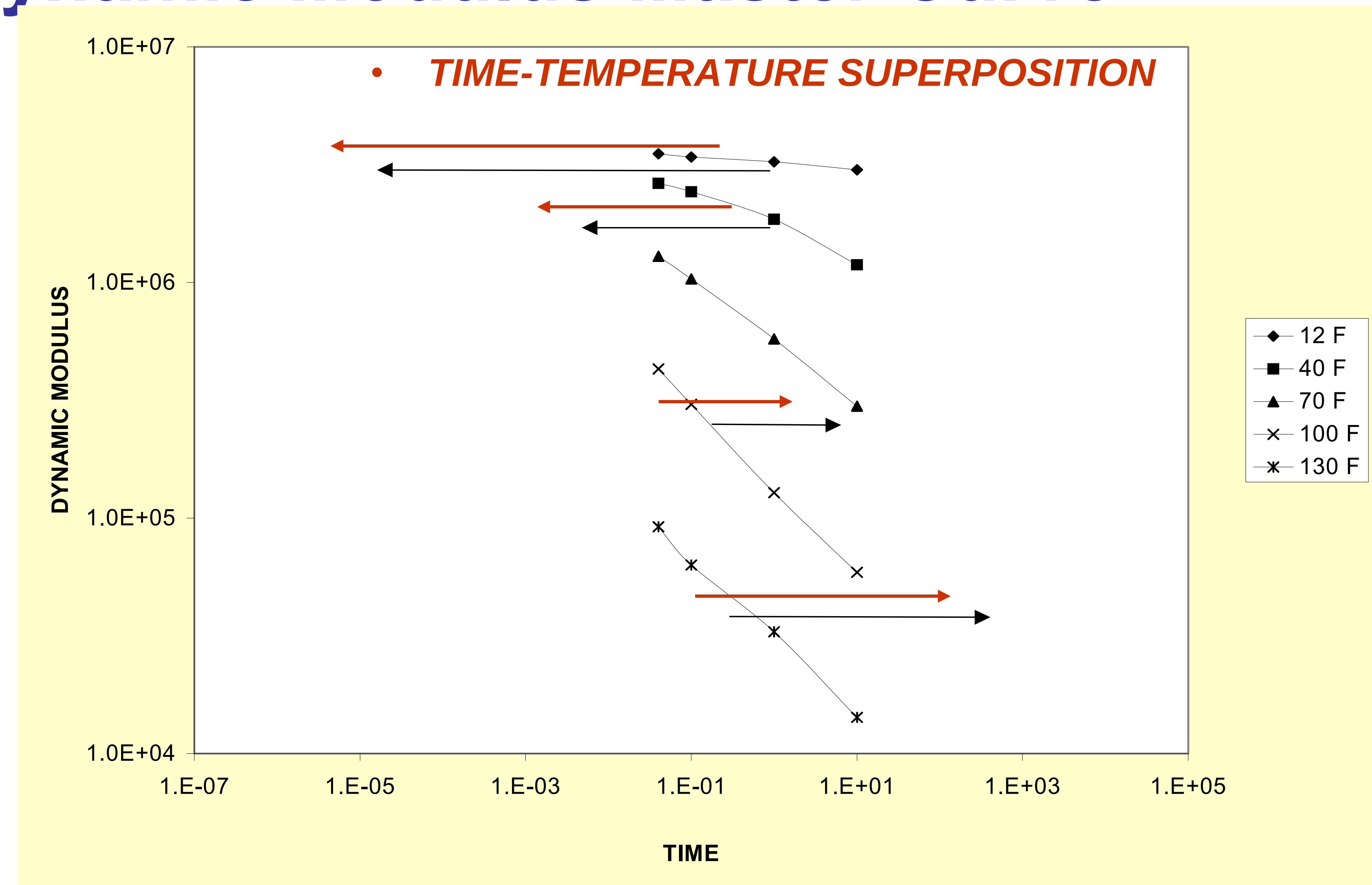
Compressive Dynamic Modulus (|E*|) and Phase angle (ϕ)



$$|E^*| = \frac{\sigma_0}{\varepsilon_0}$$

$$\phi = \omega t_i$$

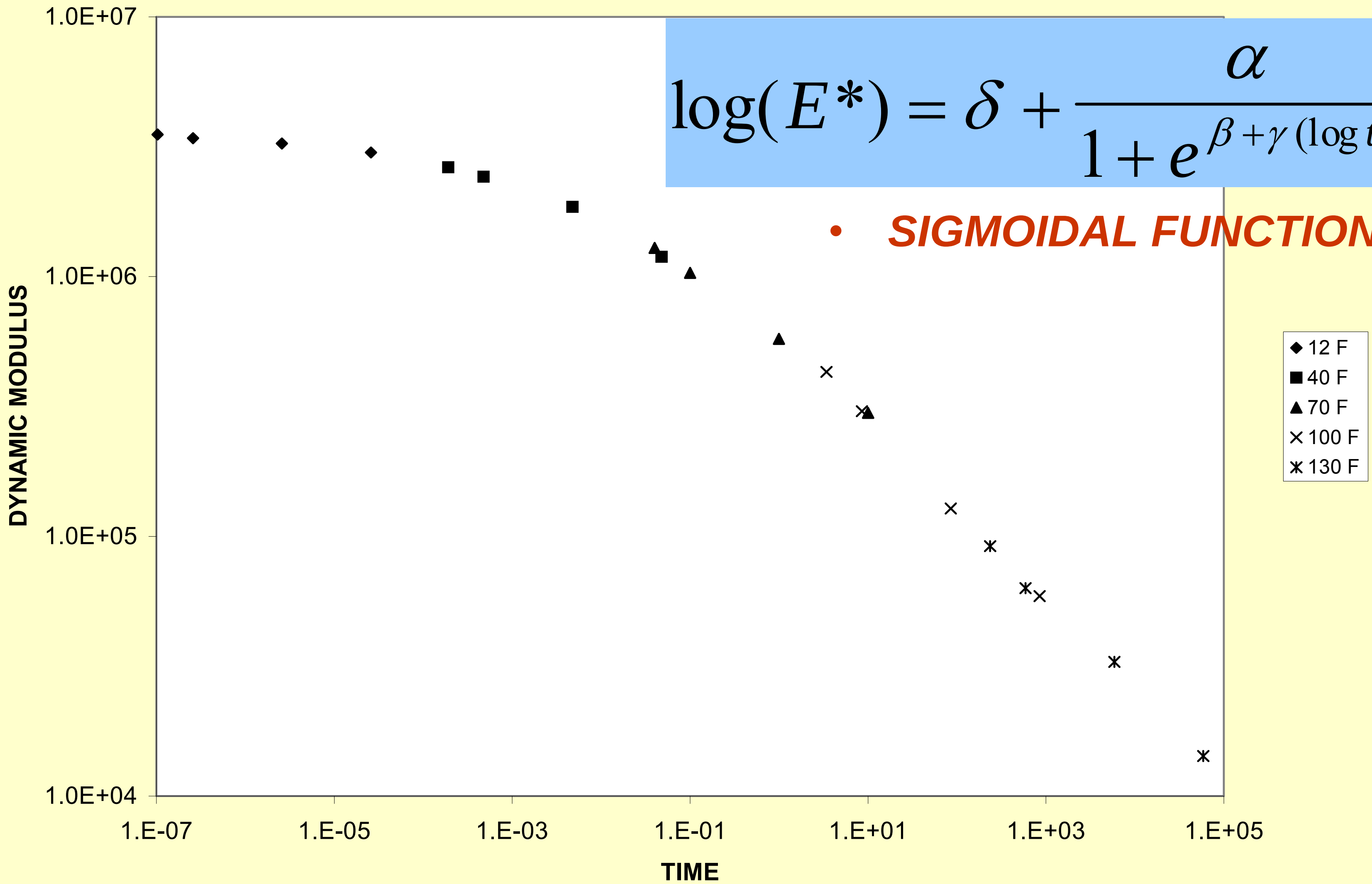
Dynamic Modulus Master Curve



Dynamic Modulus Master Curve

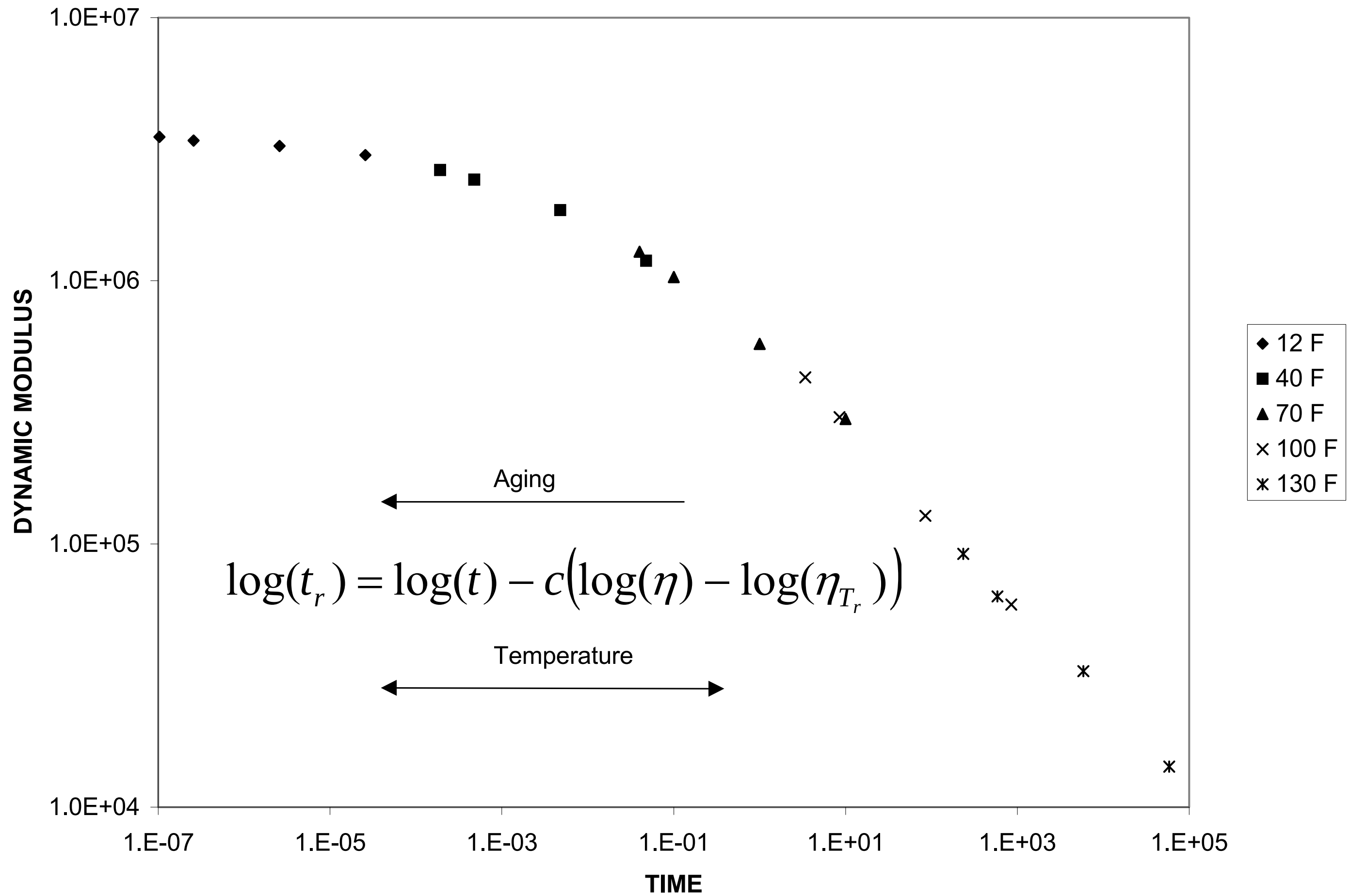
$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma(\log t_r)}}$$

- *SIGMOIDAL FUNCTION*



DYNAMIC MODULUS MASTER CURVE

- **TIME-TEMPERATURE AGE SUPERPOSITION**



$$\log(t_r) = \log(t) - c\left(\log(\eta) - \log(\eta_{T_r})\right)$$

Dynamic Modulus Master Curve

- **MASTERCURVE EQUATION**

MODULUS AS A FUNCTION OF REDUCED TIME

$$\log(E^*) = \delta + \frac{\alpha}{1 + e^{\beta + \gamma(\log t_r)}}$$

FOUR MIXTURE DEPENDENT PARAMETERS

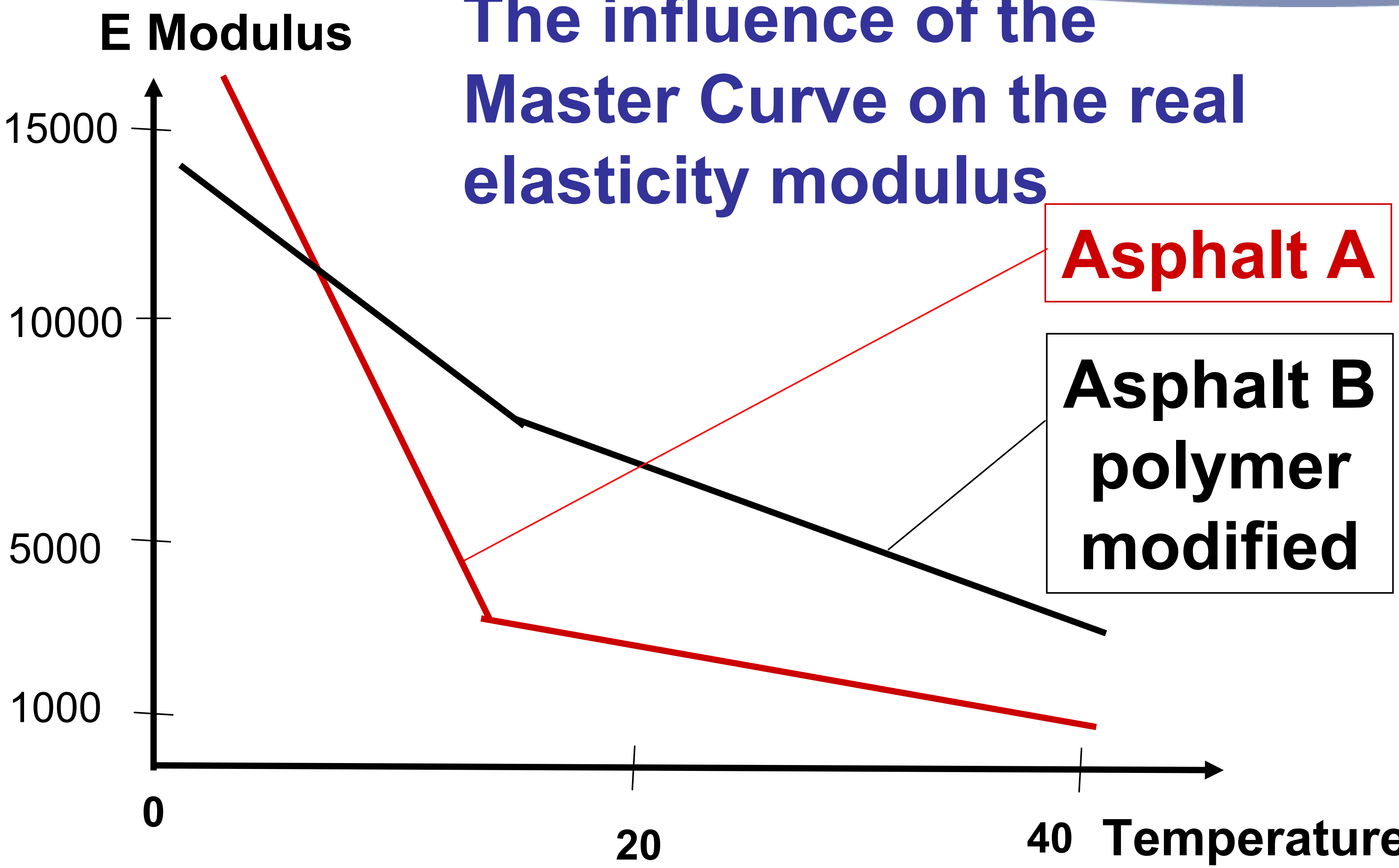
- o **REDUCED TIME**

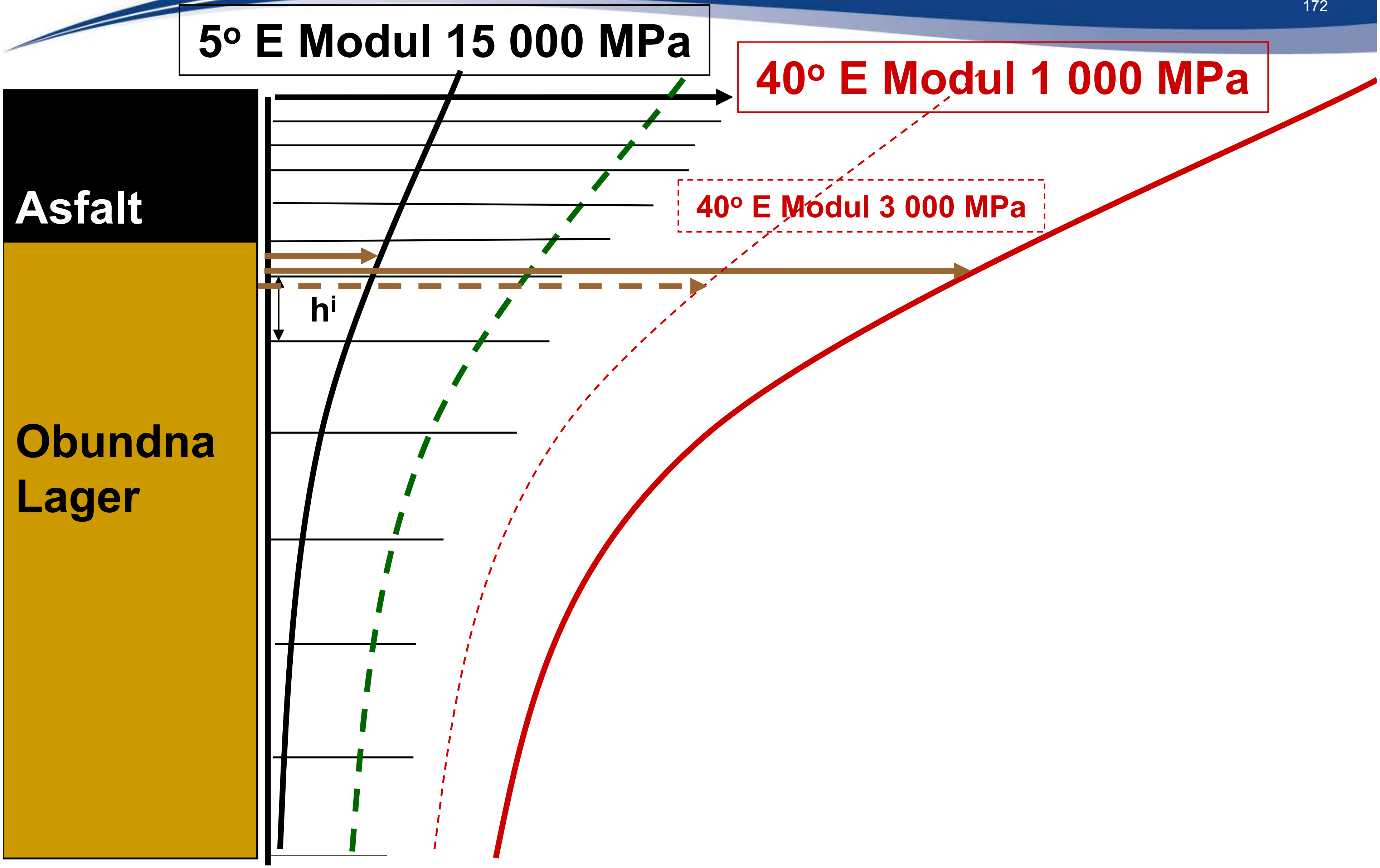
TIME-TEMPERATURE-AGE SUPERPOSITION

$$\log(t_r) = \log(t) - c\left(\log(\eta) - \log(\eta_{T_r})\right)$$

Expressed as a function of binder viscosity (stiffness) to include both temperature and age effects

The influence of the Master Curve on the real elasticity modulus

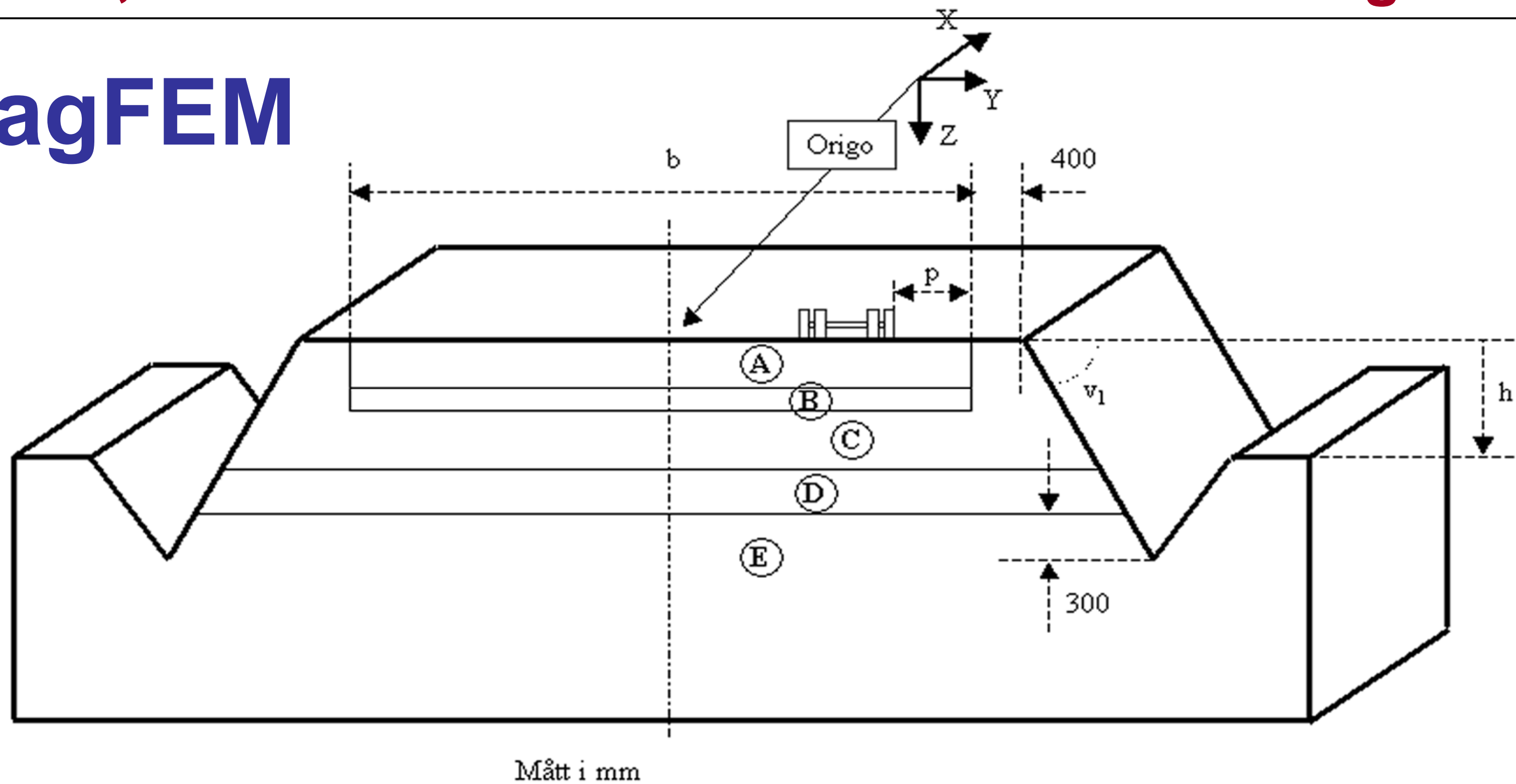



5° E Modul 15 000 MPa
40° E Modul 1 000 MPa
40° E Modul 3 000 MPa
Asfalt
Obundna
Lager
hi

USER FRIENDLY PROGRAMS

VagFEM is a 3D finite element program, built on ABAQUS, and run in a large computer. The result is coming back as a PDF-file inside 20 minutes. The input data is very easy to handle, it could be done in 3 minutes on a working site.

VagFEM



Inre släntlutning		1:2	
Höjd omgivande mark		50	[mm]
SKIKT A	Typ	Bundet linjärt	
	Tjocklek	110	[mm]
SKIKT B	Typ	Asfaltsgrus linjärt	
	Tjocklek	130	[mm]
SKIKT C	Typ	Obundet linjärt	
	Tjocklek	400	[mm]
SKIKT D	Typ	Inget	
	Tjocklek	600	[mm]
SKIKT E	Typ	Obundet linjärt	
Lasthantering		Axel med super-single hjul	
Axellast		10 ton	
Däcktryck		1200	[kPa]
Placering		600	[mm]

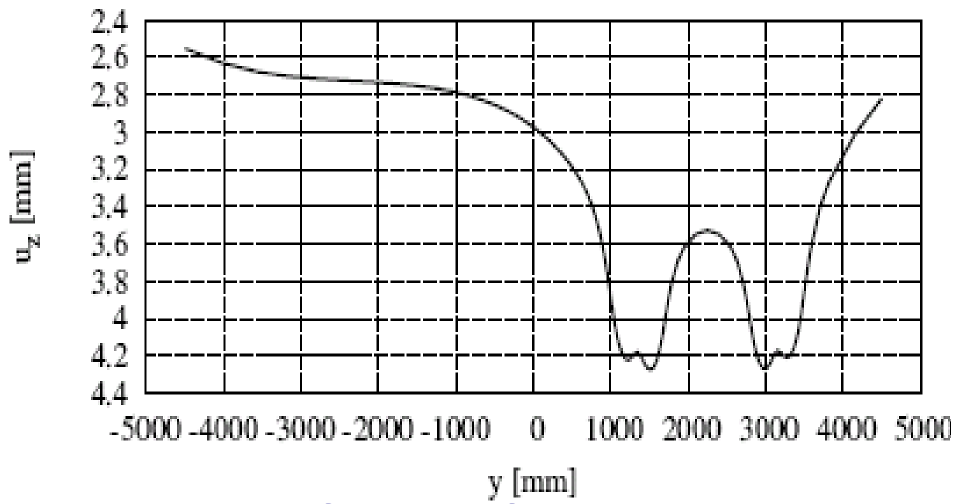
Fortsätt till nästa steg | Återställ | Hjälp

SKIKT A		Bundet linjärt		Tjocklek 110 [mm]
	Densitet	2000	[kg/m^3]	
	Poissons tal	0.35	[1]	
	Elasticitetsmodul	10000	[MPa]	
SKIKT B		Asfaltsgrus linjärt		Tjocklek 130 [mm]
	Densitet	2000	[kg/m^3]	
	Poissons tal	0.35	[1]	
	Elasticitetsmodul	9000	[MPa]	
SKIKT C		Obundet linjärt		Tjocklek 400 [mm]
	Densitet	2000	[kg/m^3]	
	Poissons tal	0.35	[1]	
	Elasticitetsmodul	1000	[MPa]	
SKIKT D		Inget		Tjocklek 0 [mm]
SKIKT E		Obundet linjärt		
	Densitet	2000	[kg/m^3]	
	Poissons tal	0.35	[1]	
	Elasticitetsmodul	1000	[MPa]	

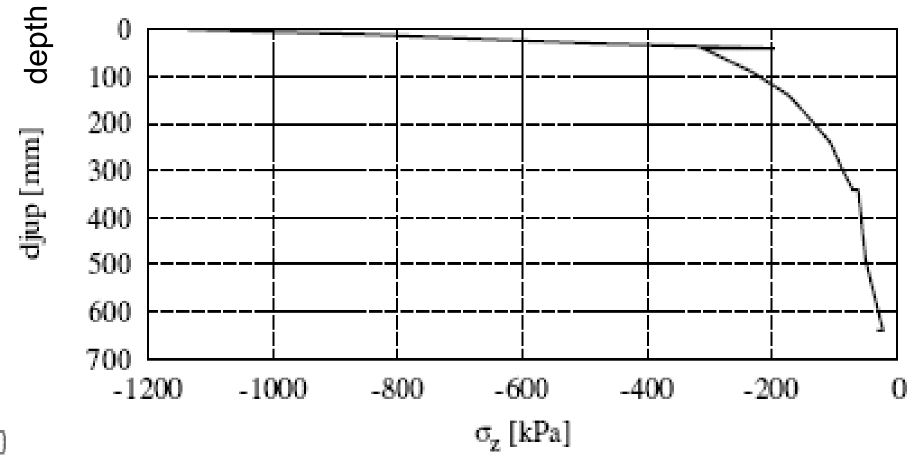
Komplett resultatfil ☐

Generera fil för permanent deformation ☐

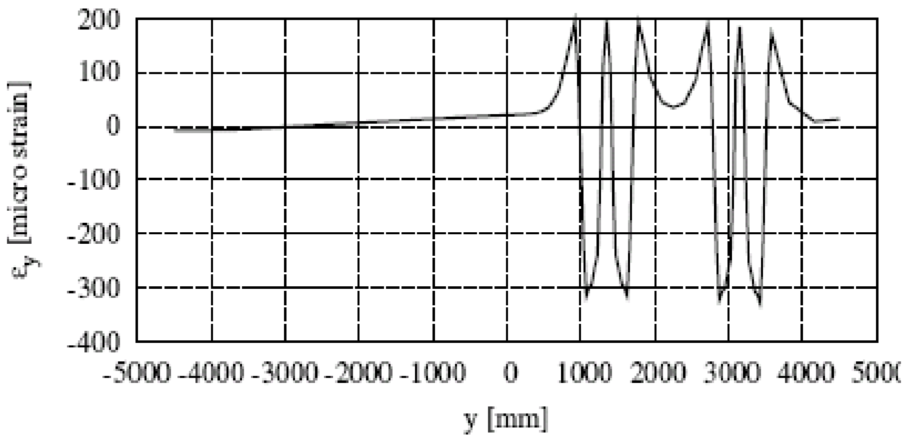
Starta beräkningen | Tillbaka till föregående steg | Hjälp



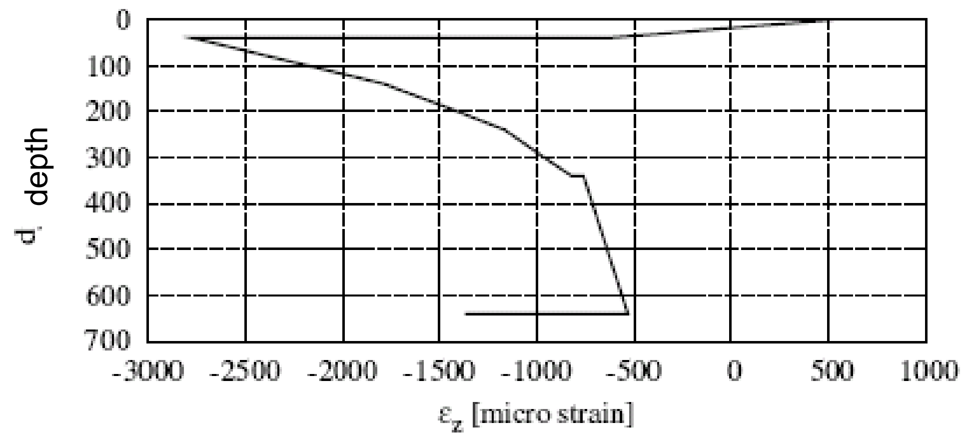
Road surface deflection



Stress as a function of the depth under the wheel



Strain in the lower surface of asphalt pavement



Strain as a function of the depth under the wheel

Projekt: Testprojekt

Namn på beräkningen: Ber 2

SKIKT C

Typ: Obundet linjärt

Tjocklek: 125 [mm]

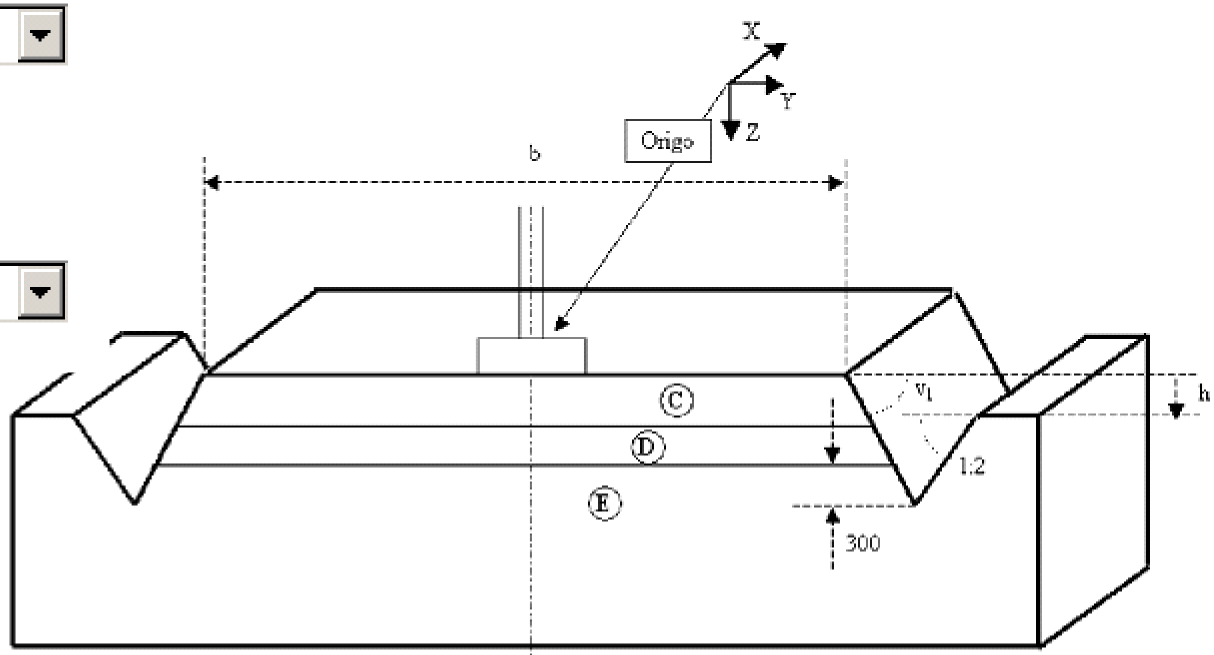
SKIKT D

Typ: Inget

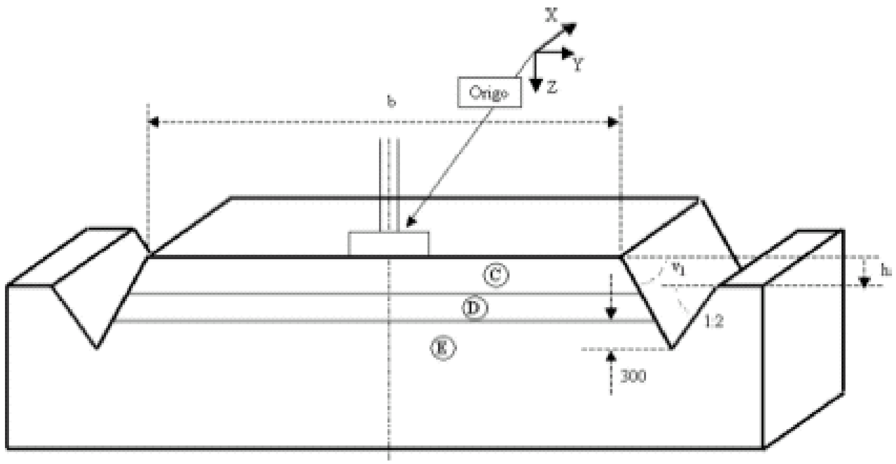
Tjocklek: [mm]

SKIKT E

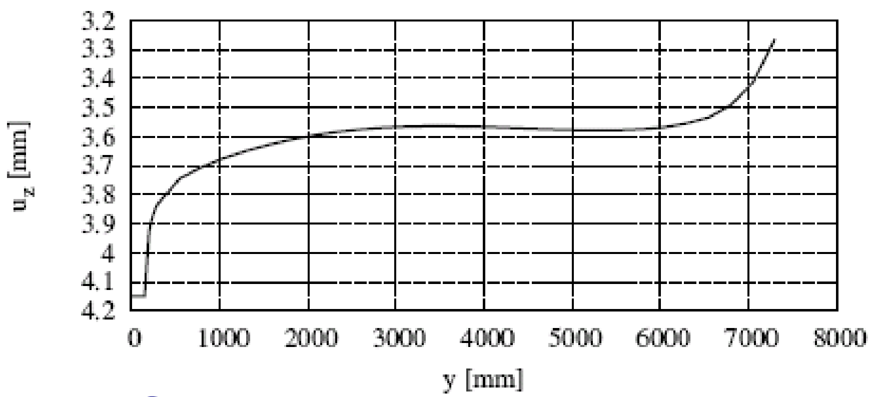
Typ: Obundet linjärt



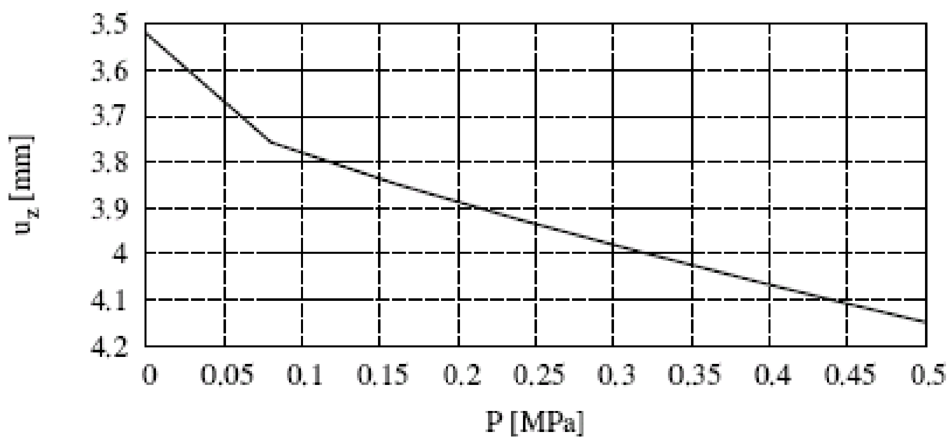
VagFEM – Plate Loading – Resilient modulus



Geometry for plate loading test

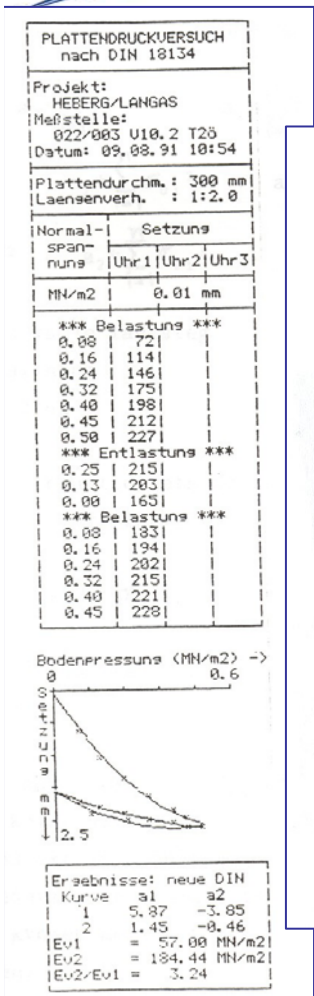


Deflection beside the plate at full load (compare FWD)



Deflection under the plate at various load steps

Test: Plate loading


PLATTENDRUCKVERSUCH
nach DIN 18134

Projekt:
HEBERG/LANGAS
Meßstelle:
022/003 V10.2 T2ö
Datum: 09.08.91 10:54

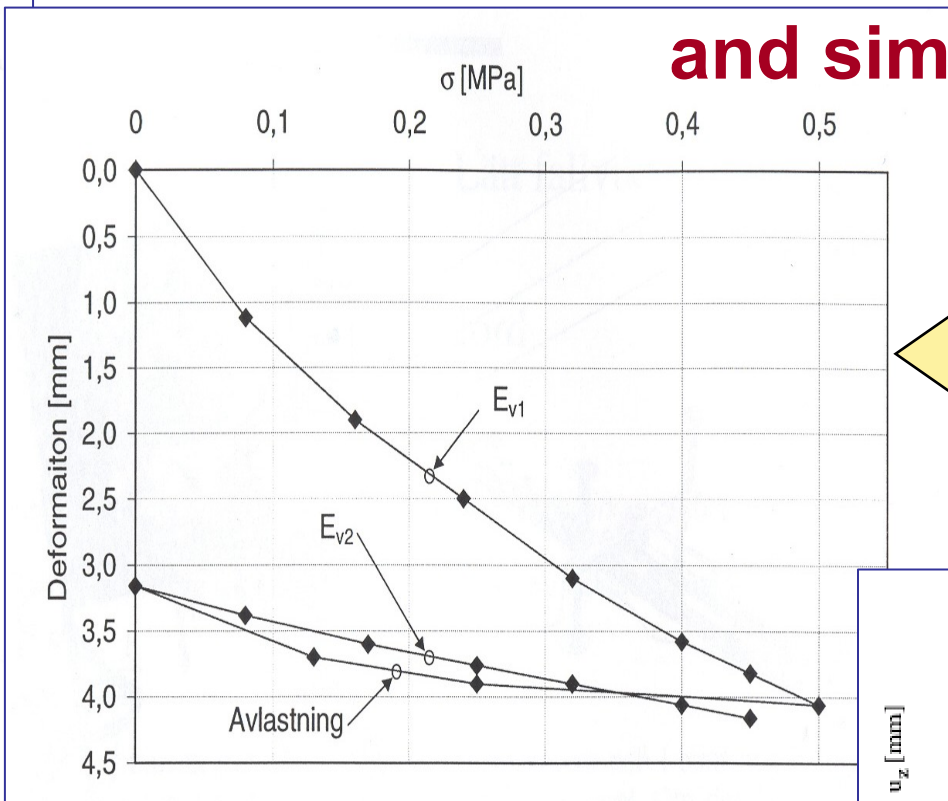
Plattendurchm.: 300 mm
Laengenverh. : 1:2.0

Normal-spannung	Setzung Uhr1	Uhr2	Uhr3
MN/m2	0.01 mm		
*** Belastung ***			
0.08	72		
0.16	114		
0.24	146		
0.32	175		
0.40	198		
0.45	212		
0.50	227		
*** Entlastung ***			
0.25	215		
0.13	203		
0.00	165		
*** Belastung ***			
0.08	183		
0.16	194		
0.24	202		
0.32	215		
0.40	221		
0.45	228		

Ergebnisse: neue DIN

Kurve	a1	a2
1	5.87	-3.85
2	1.45	-0.46

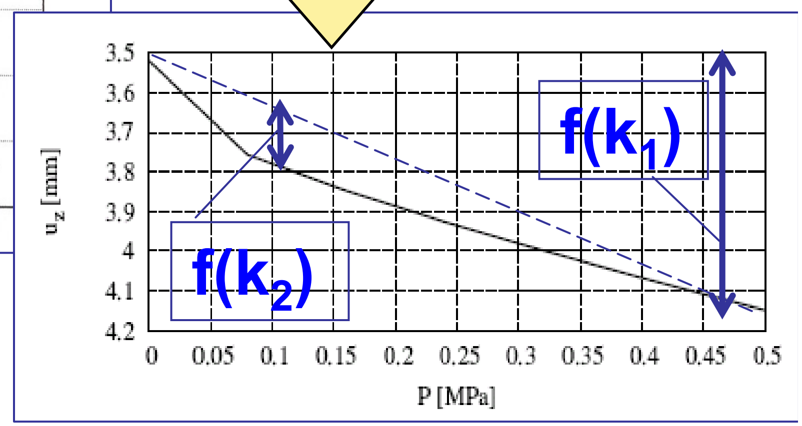
Ev1 = 57.00 MN/m2
Ev2 = 184.44 MN/m2
Ev2/Ev1 = 3.24



Result from Plate loading and simulation in VagFEM

Resilient Module

$$Mr = k_1 \Theta^{k2}$$



Measured Mr_1 in subgrade is used as input data in calculation of Mr_2 in subbase

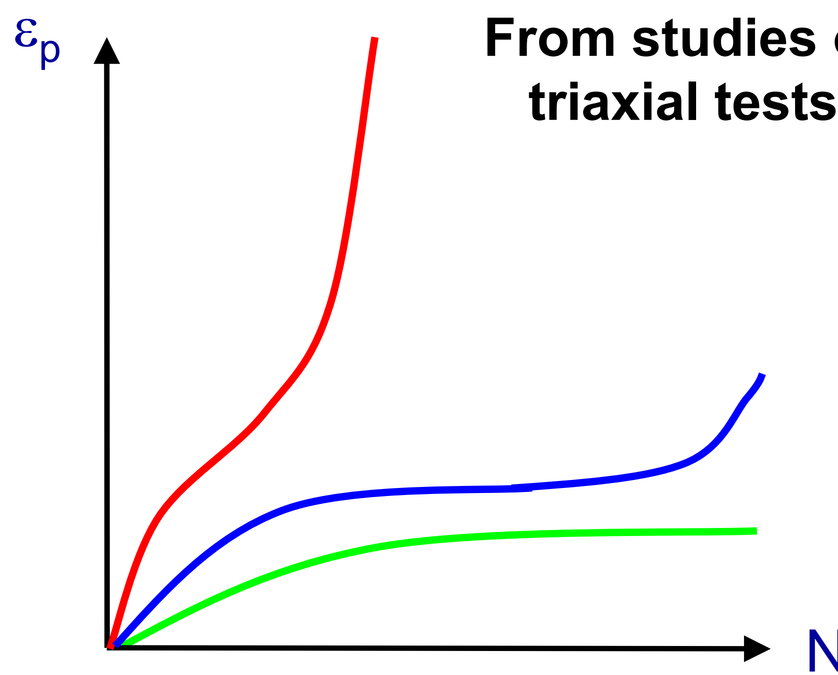
MATERIAL MODELS
Rutting in unbound materials

**Shake Down load
(Dresden)**

Decision of critical stress conditions in unbound layers

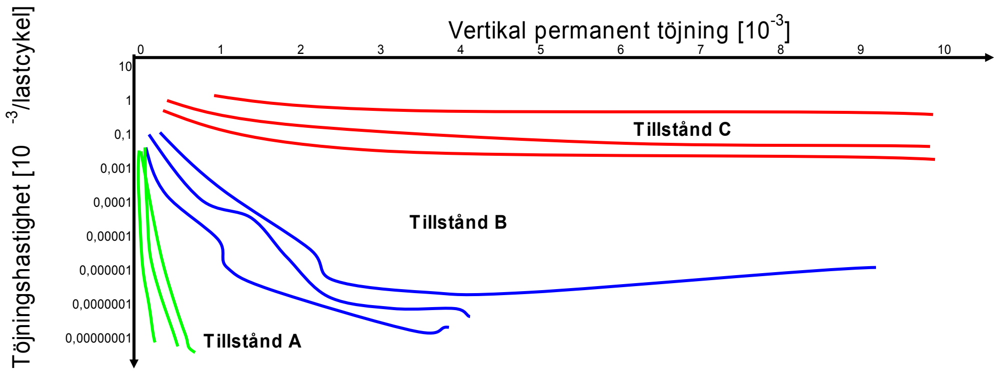
- Shakedownkoncept
  - Stable state (little rutting)
  - Unstable state (severe rutting)

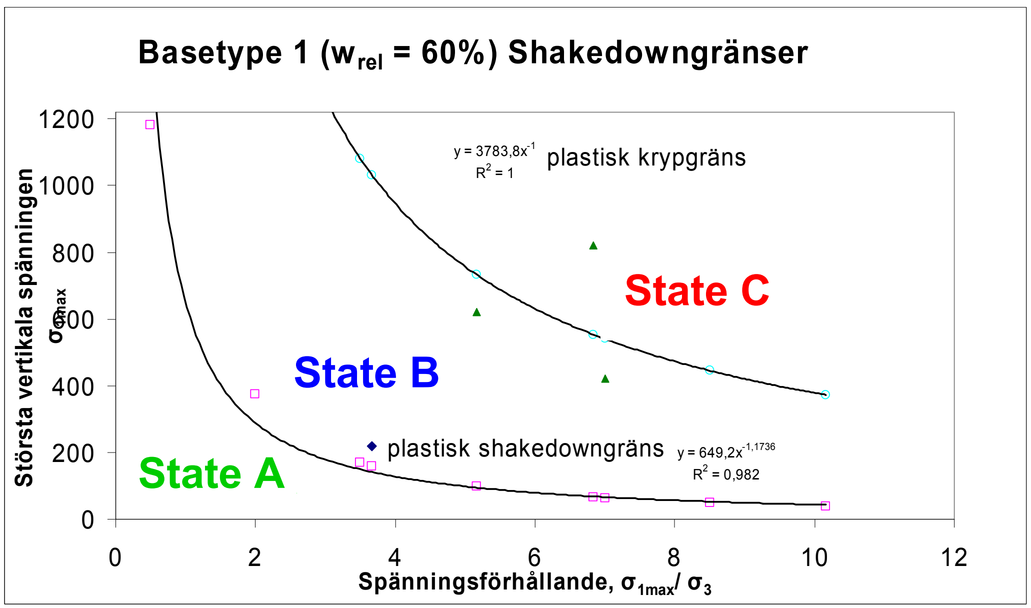
- State A (stable behaviour)
- State B (unstable behaviour)
- State C (collapse)

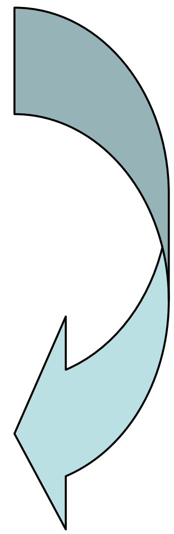


From studies of triaxial tests

The Shake Down concept







$$\sigma_{1,\max} = \alpha \cdot \left(\frac{\sigma_{1,\max}}{\sigma_c} \right)^{\beta}$$

Permanent deformations, depending on shear stress

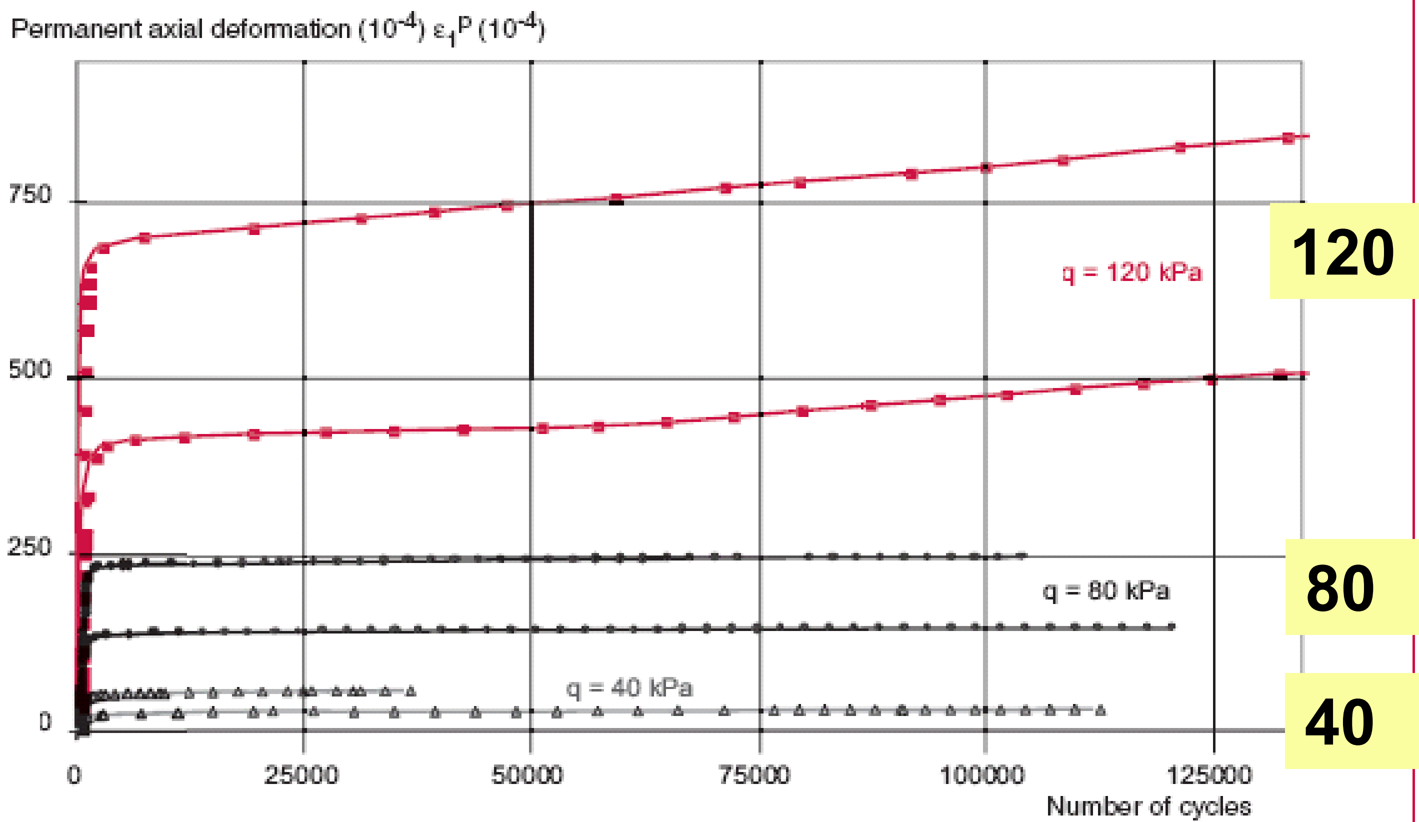


Fig. 3 - Influence of the number of loading cycles (after Martinez [14]).

MATERIAL MODELS
Rutting in unbound materials

SAMARIS

Increase in permanent deformations per load cycle

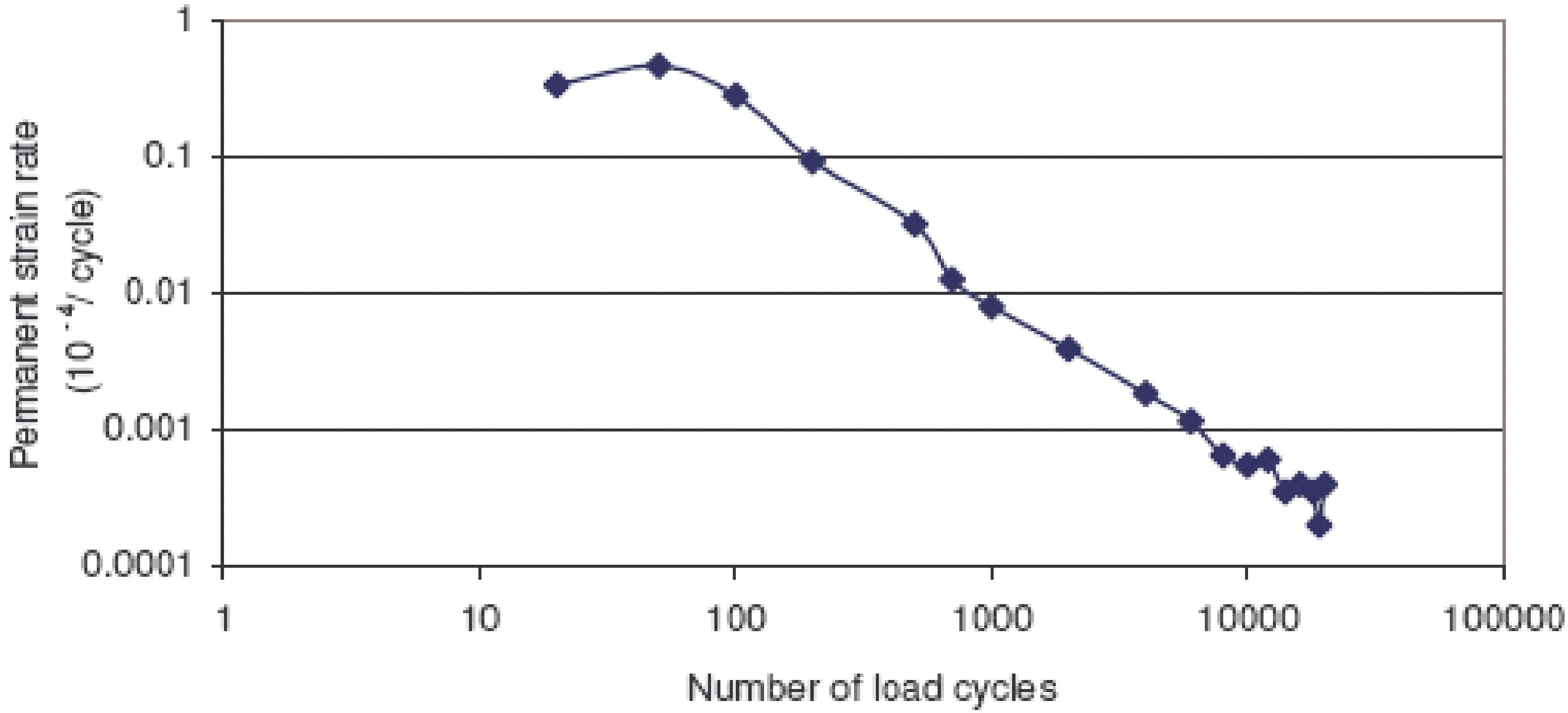
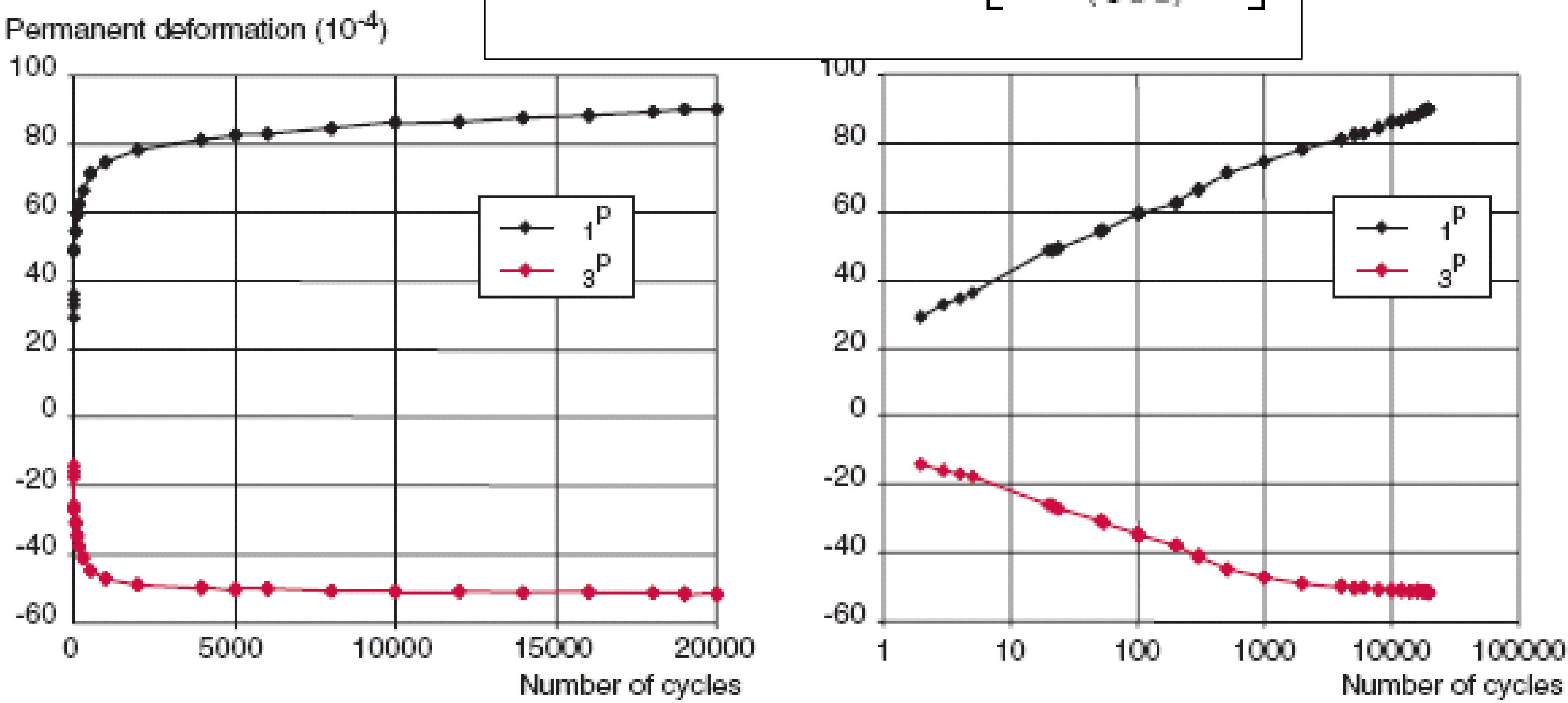


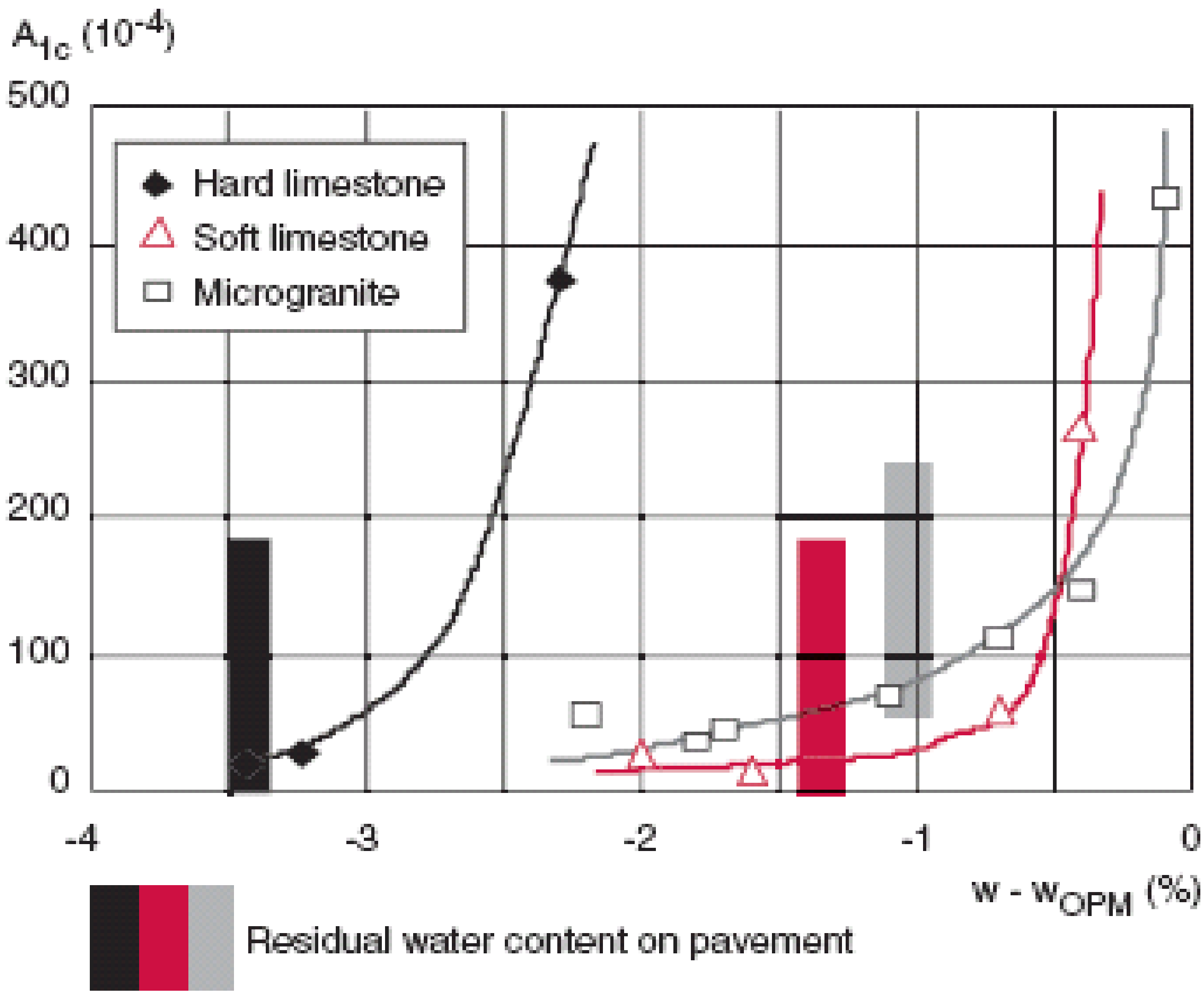
Figure 3. Evolution of the permanent axial strain increment per load cycle.

Connection between load cycles – permanent deformations

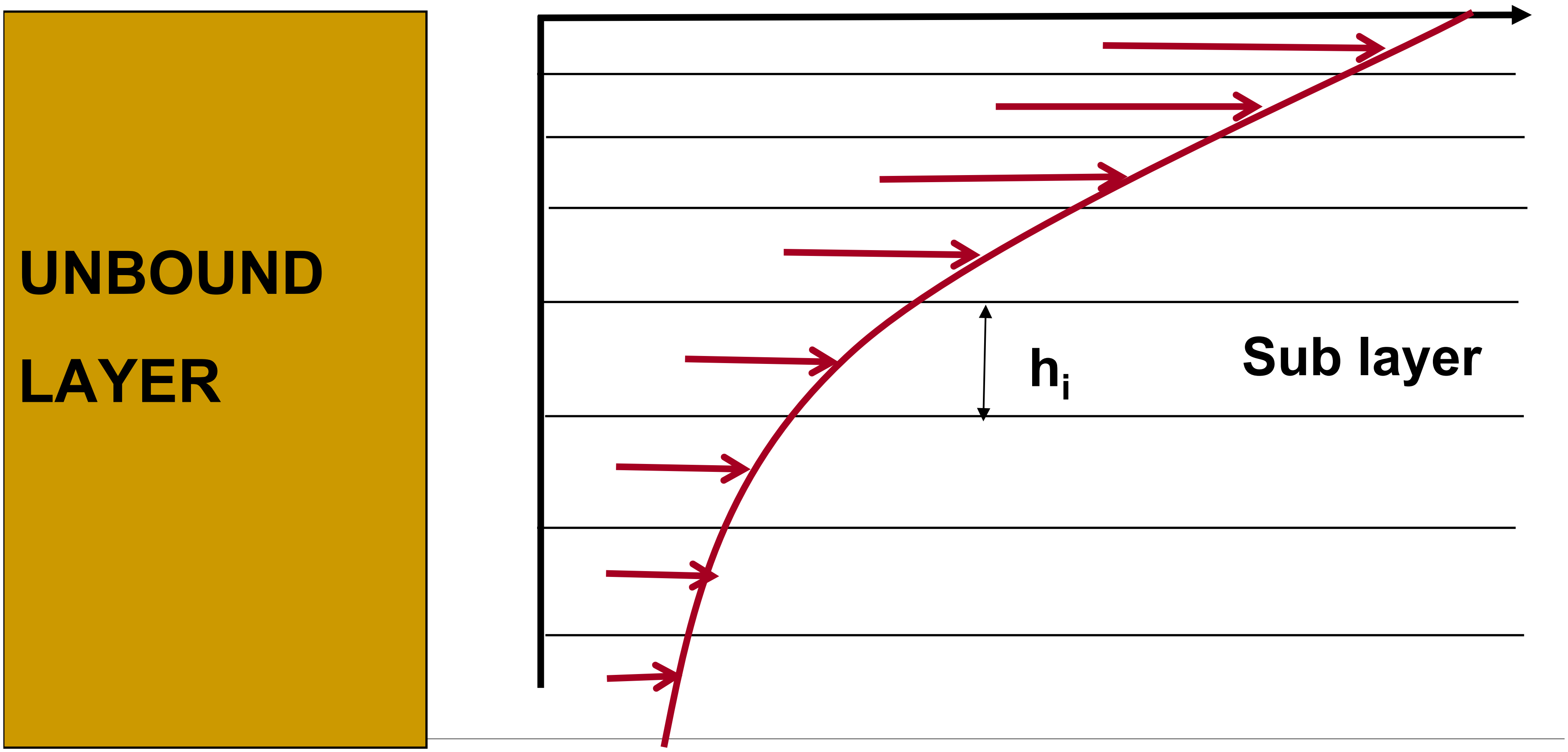
$$\varepsilon_1^P(N) = \varepsilon_1^P(100) + A_1\left[1 - \left(\frac{N}{100}\right)^{-B}\right]$$



Permanent deformations depending on moisture content



Calculation of stress (σ), deviatoric stress (q), strain (ε) and resilient modulus (Mr) with VagFEM



Evaluation of triaxial test

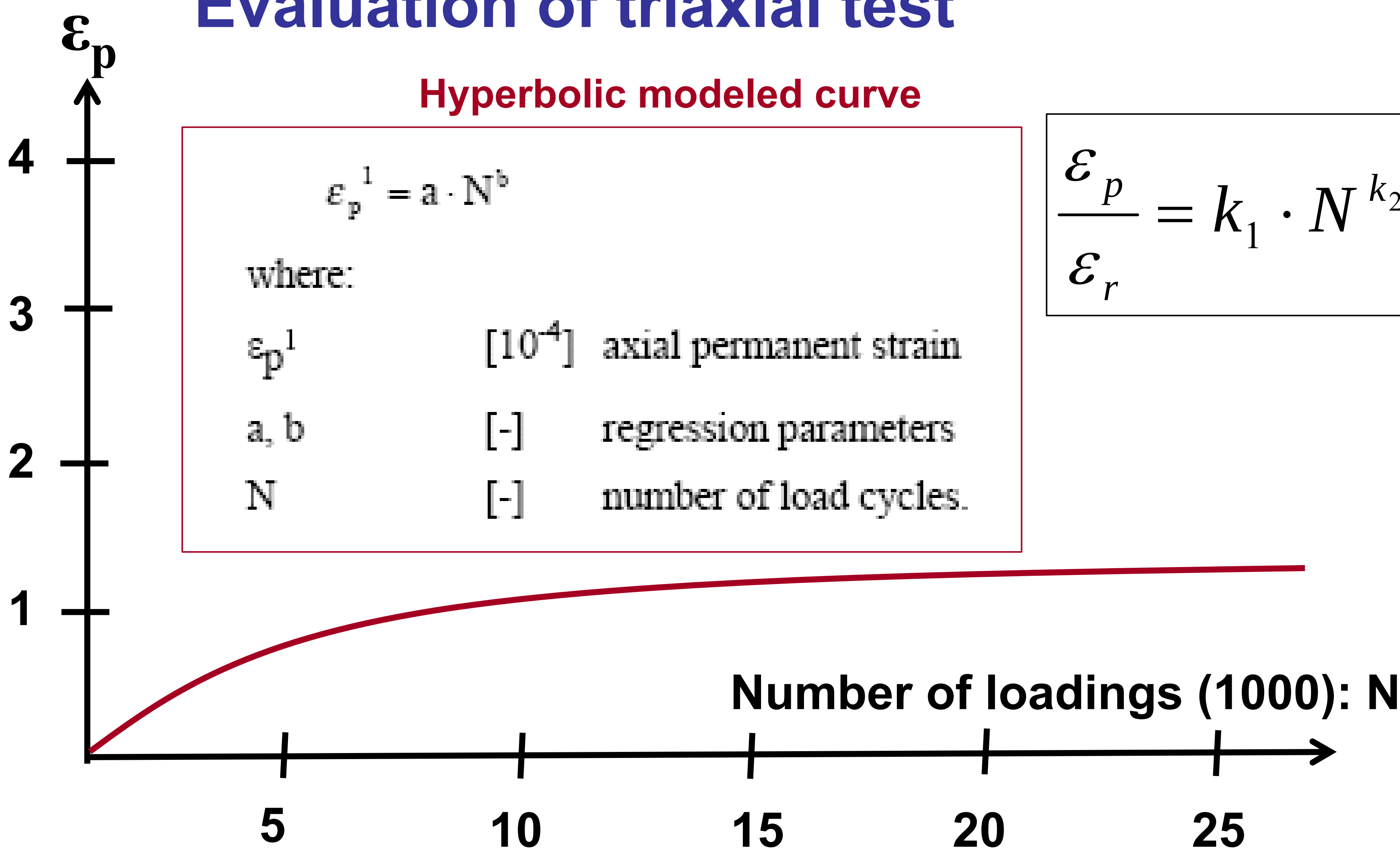
Hyperbolic modeled curve

$$\varepsilon_p^{\,1} = a \cdot N^b$$

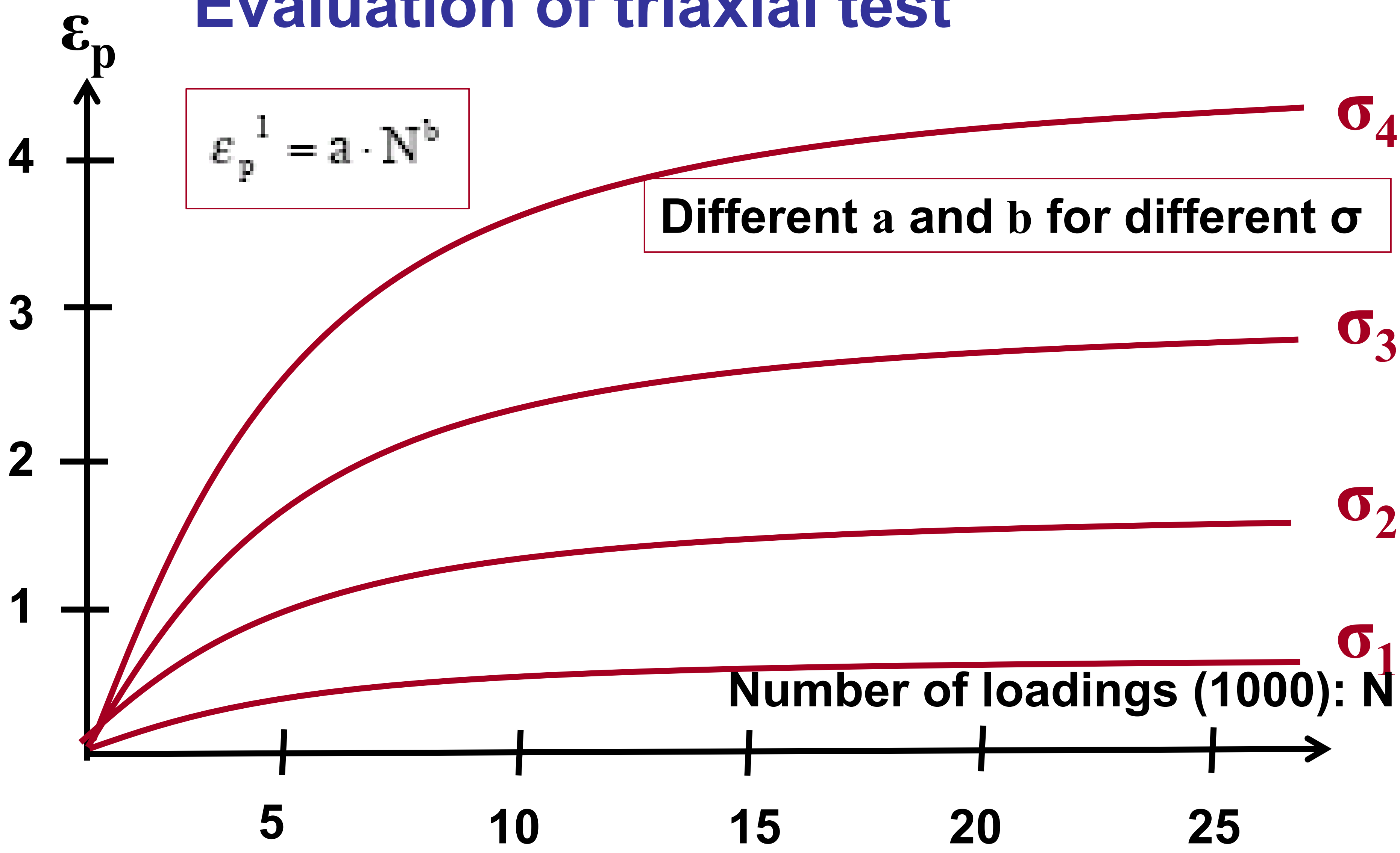
where:

$\varepsilon_p^{\,1}$	$[10^{-4}]$	axial permanent strain
a, b	[-]	regression parameters
N	[-]	number of load cycles.

$$\frac{\varepsilon_p}{\varepsilon_r} = k_1 \cdot N^{k_2}$$



Evaluation of triaxial test



Calculation of permanent deformations – LCPC

$$\varepsilon_1^p(N) = \varepsilon_{10}^p \cdot \left[1 - \left(\frac{N}{N_0}\right)^{-B}\right] \cdot \left[\frac{L_{max}}{p_a}\right]^n \cdot \frac{1}{(m + \frac{s}{p_{max}} - \frac{q_{max}}{p_{max}})}$$

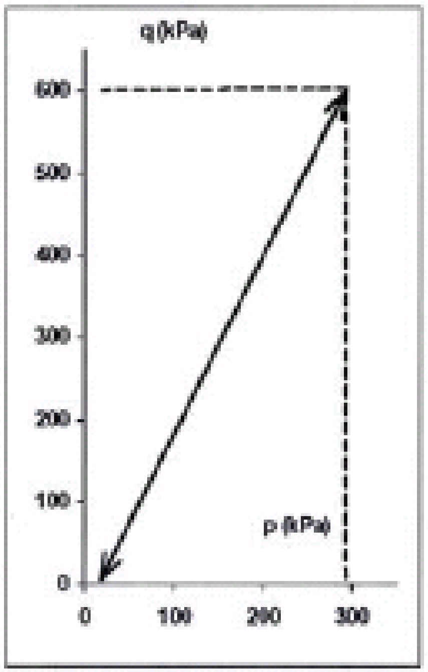
ε_1^p : permanent axial strain; N : number of load cycles;
p_{max}, q_{max} : maximum values of the mean normal stress p and deviatoric stress q;

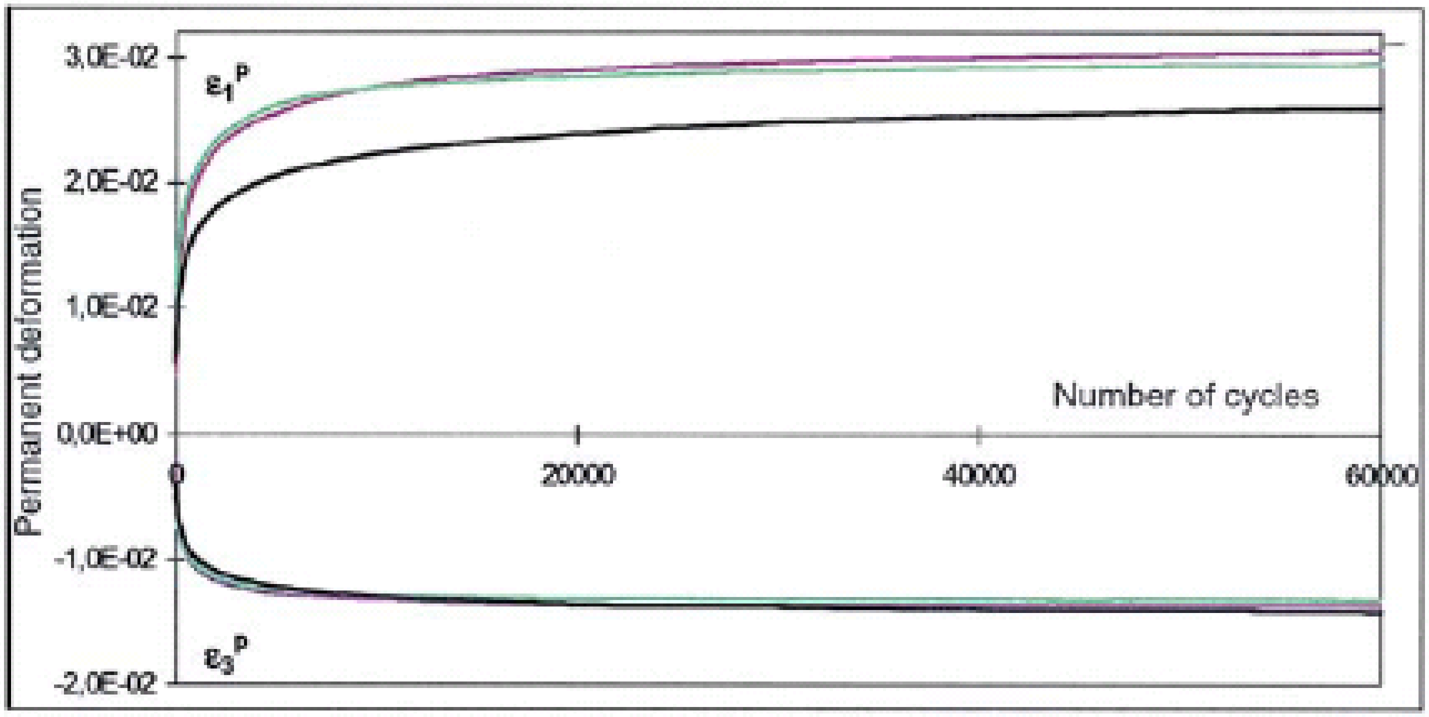
$$L_{max} = \sqrt{p_{max}^2 + q_{max}^2}$$

Samaris

P_a : reference pressure equal to 100 kPa;
ε_1^{p0}, B, n model parameters;
m,s parameters of the failure line of the material, of equation q = m.p+s;
(from experience, m=2.5 to 2.6 and s=20 kPa)

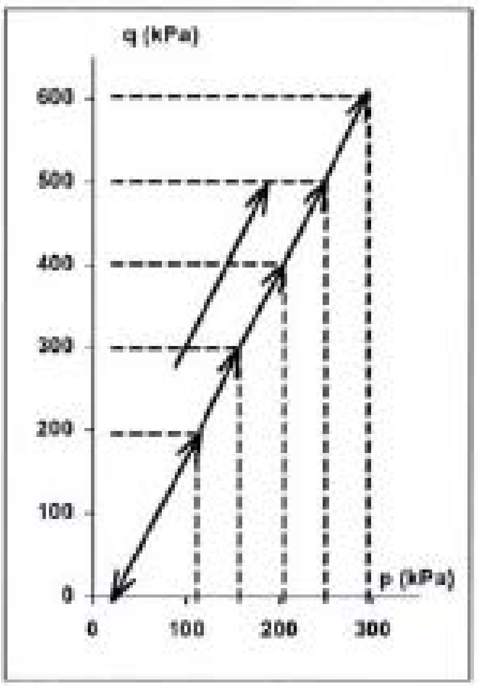
Loading to maximum load in one step

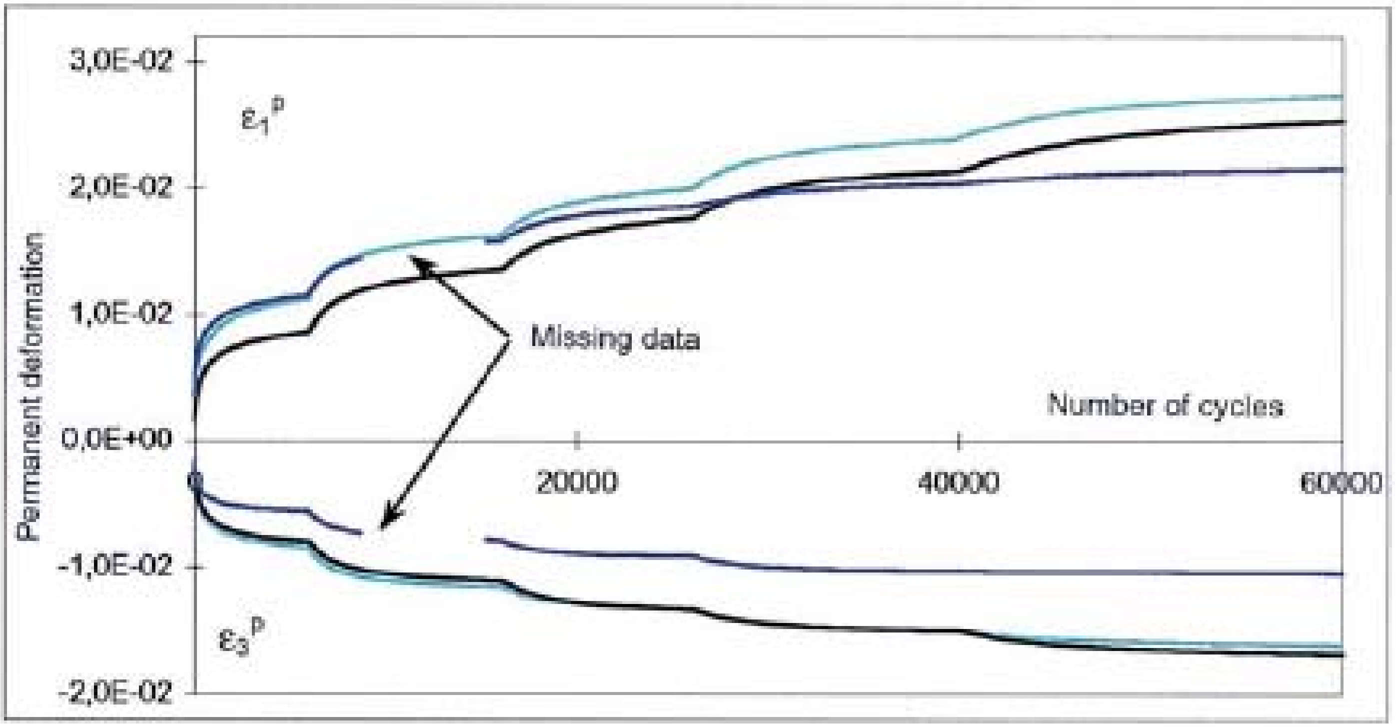




a. First loading mode (a single level of stress).

Loading to maximum load in several steps





b. Second loading mode (five increasing levels of stress).

Same final permanent deformations as for one load step

Permanent deformations proportional to shear stress, q (and also p)

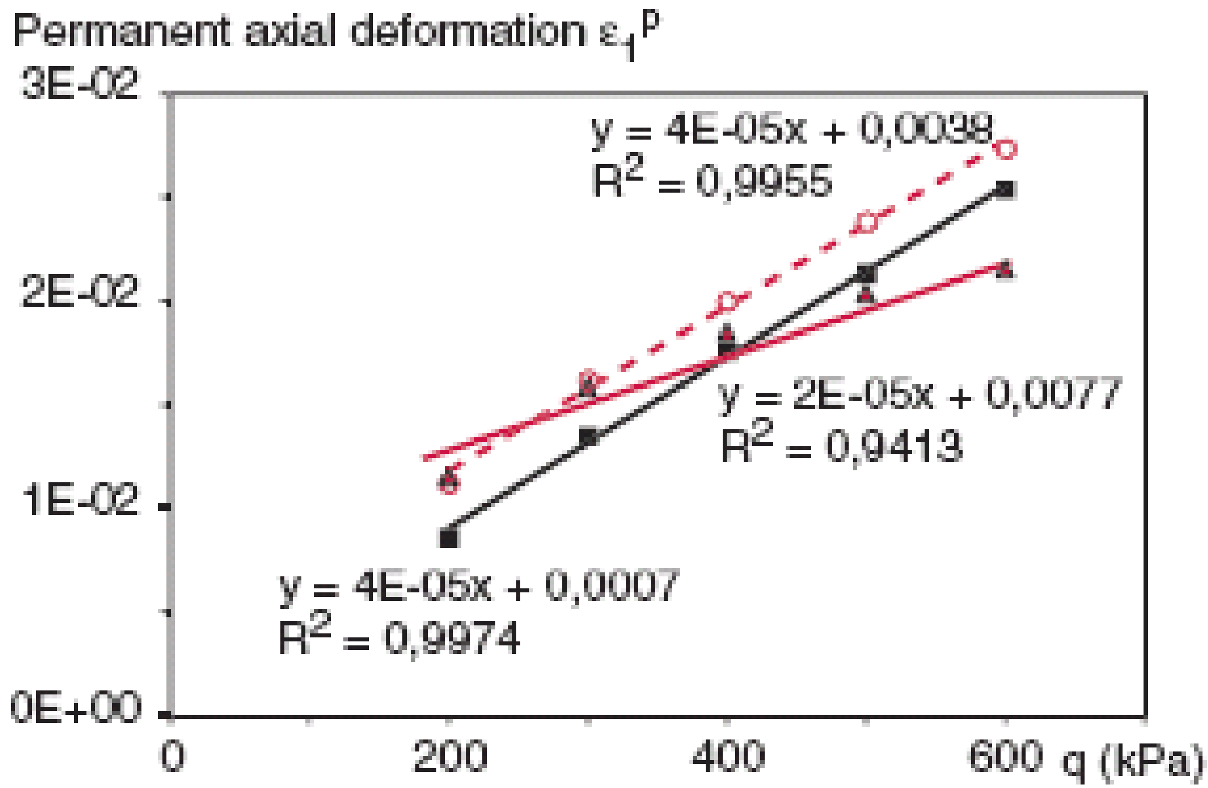


Fig. 8 - Second loading mode - Permanent axial deformation at the end of the loading stage against q.

Comparison between model and result in triaxial test

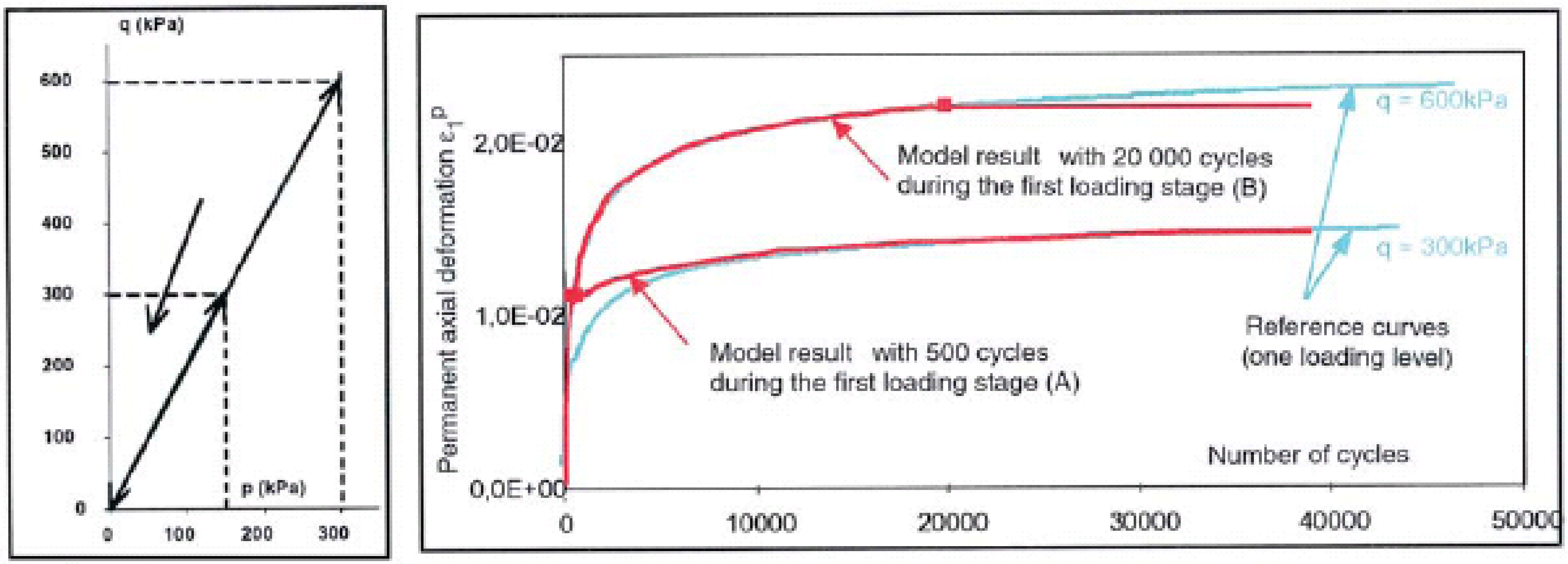
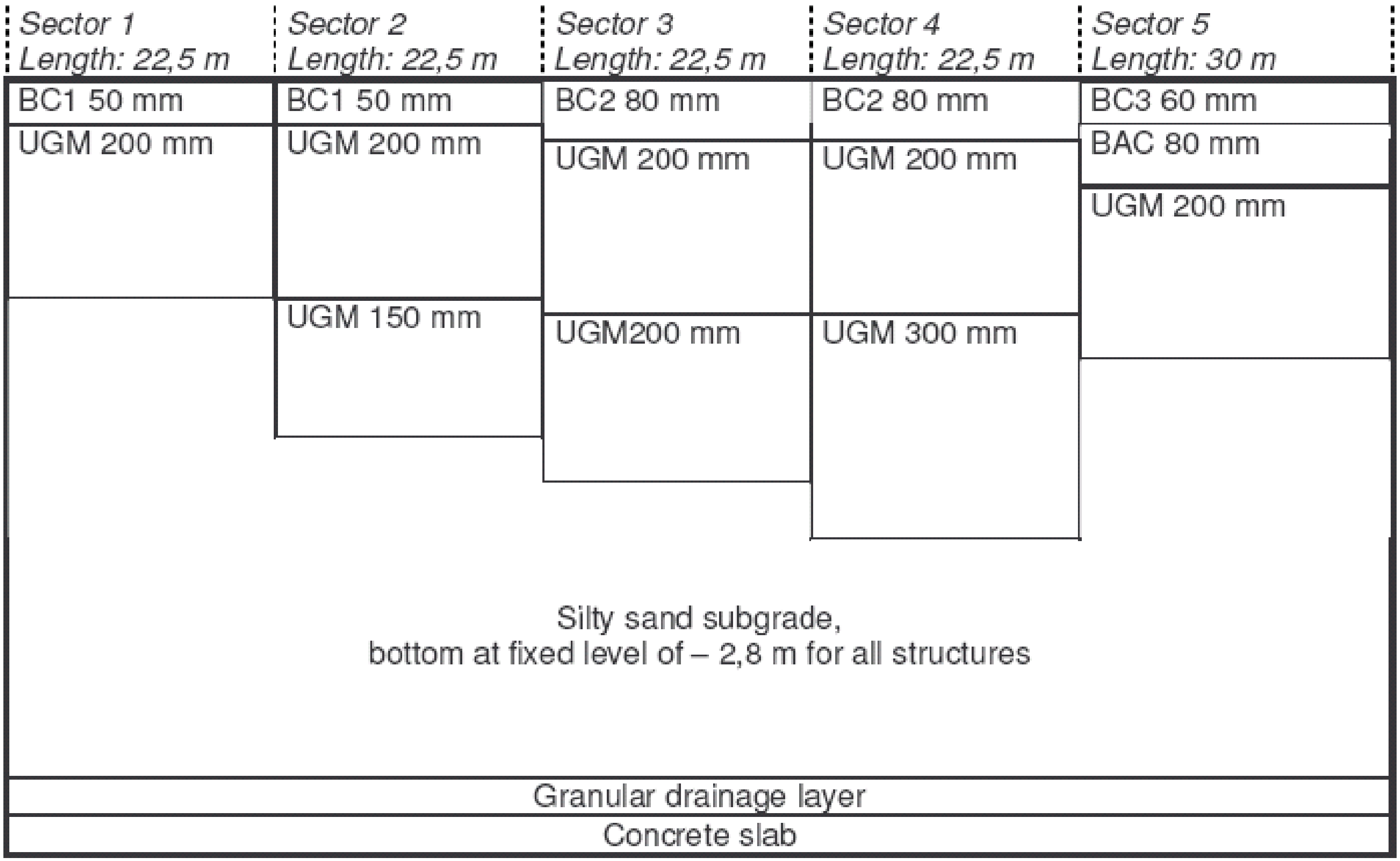
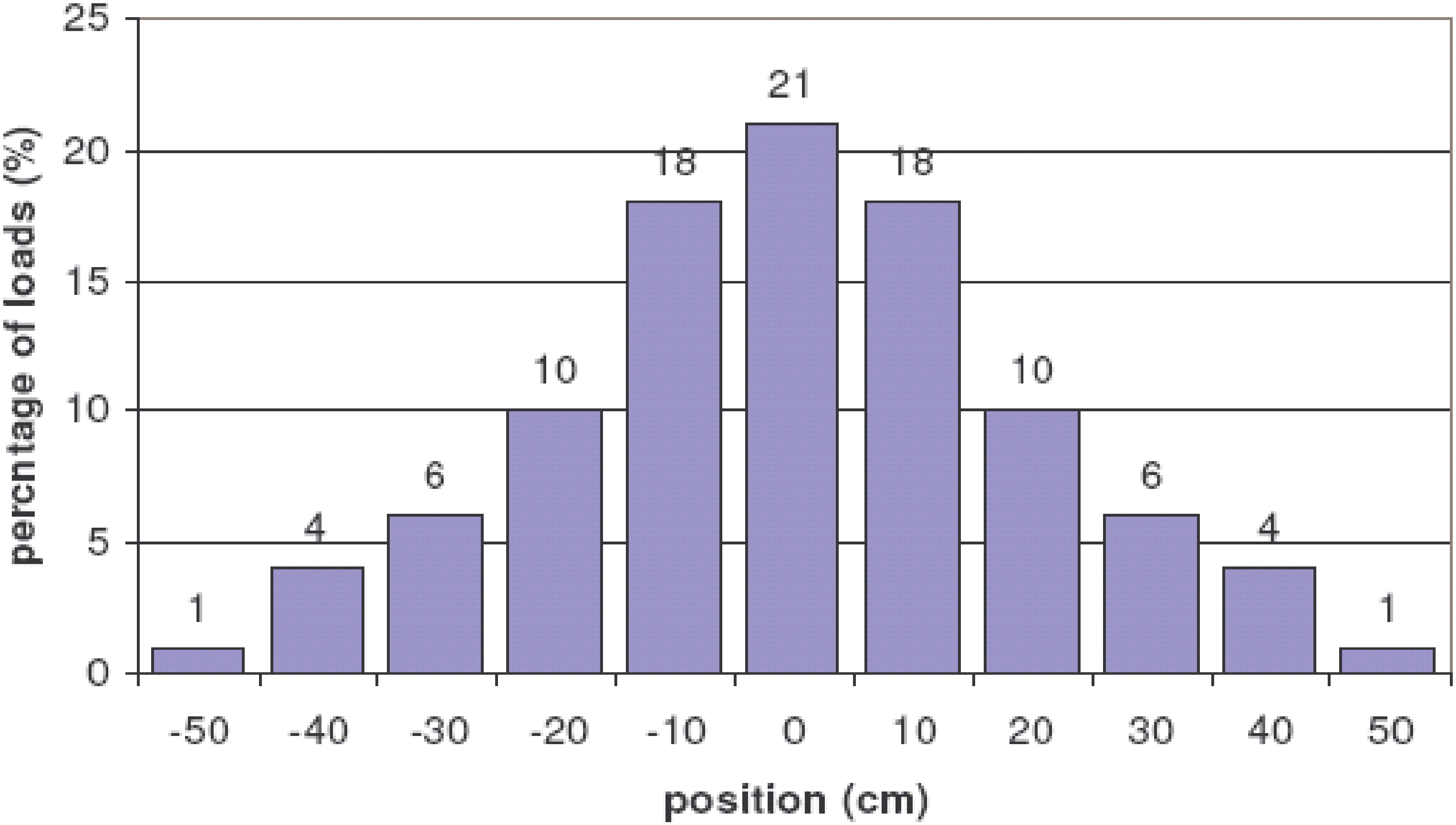


Fig. 10 - Test under decreasing levels of stress: loading modes and deformation predicted by the model's.

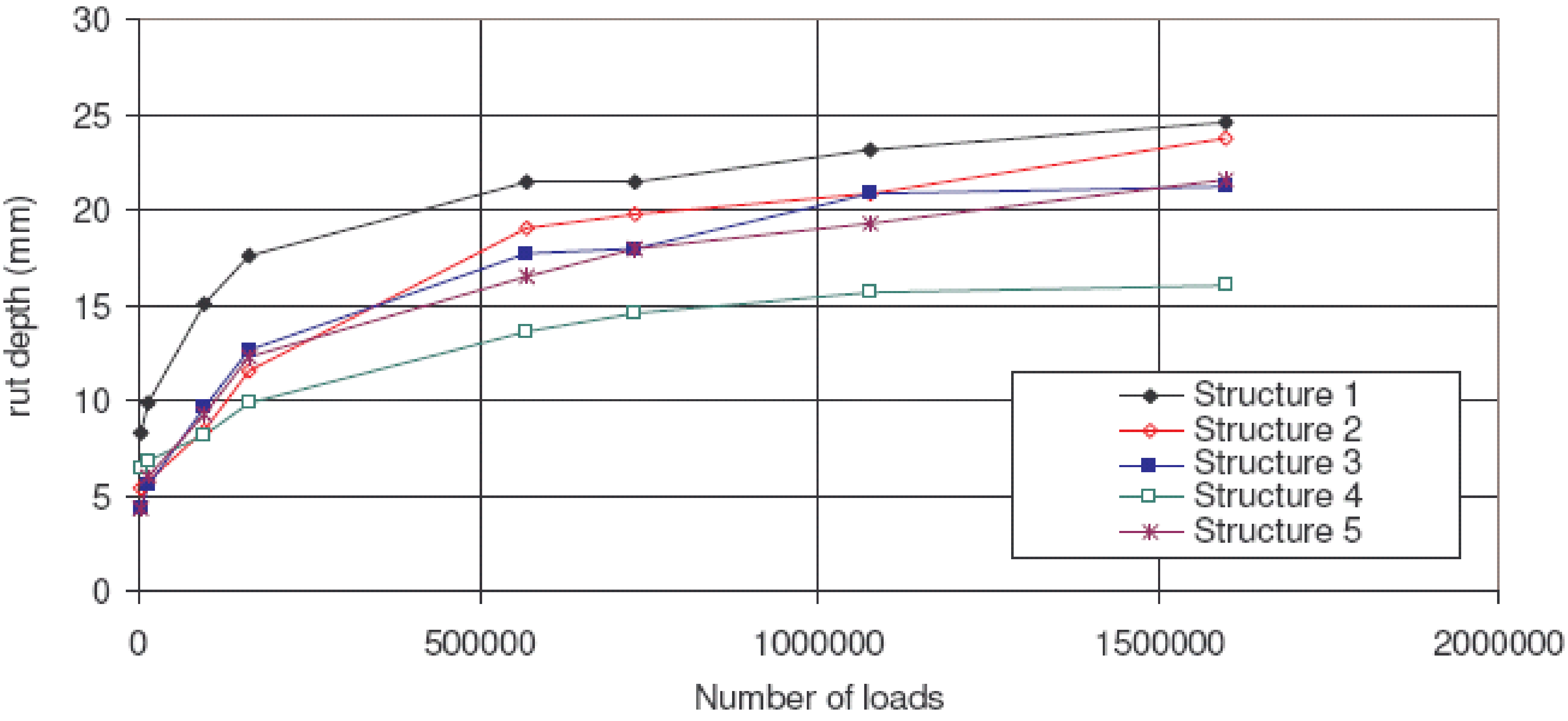
Tested sections



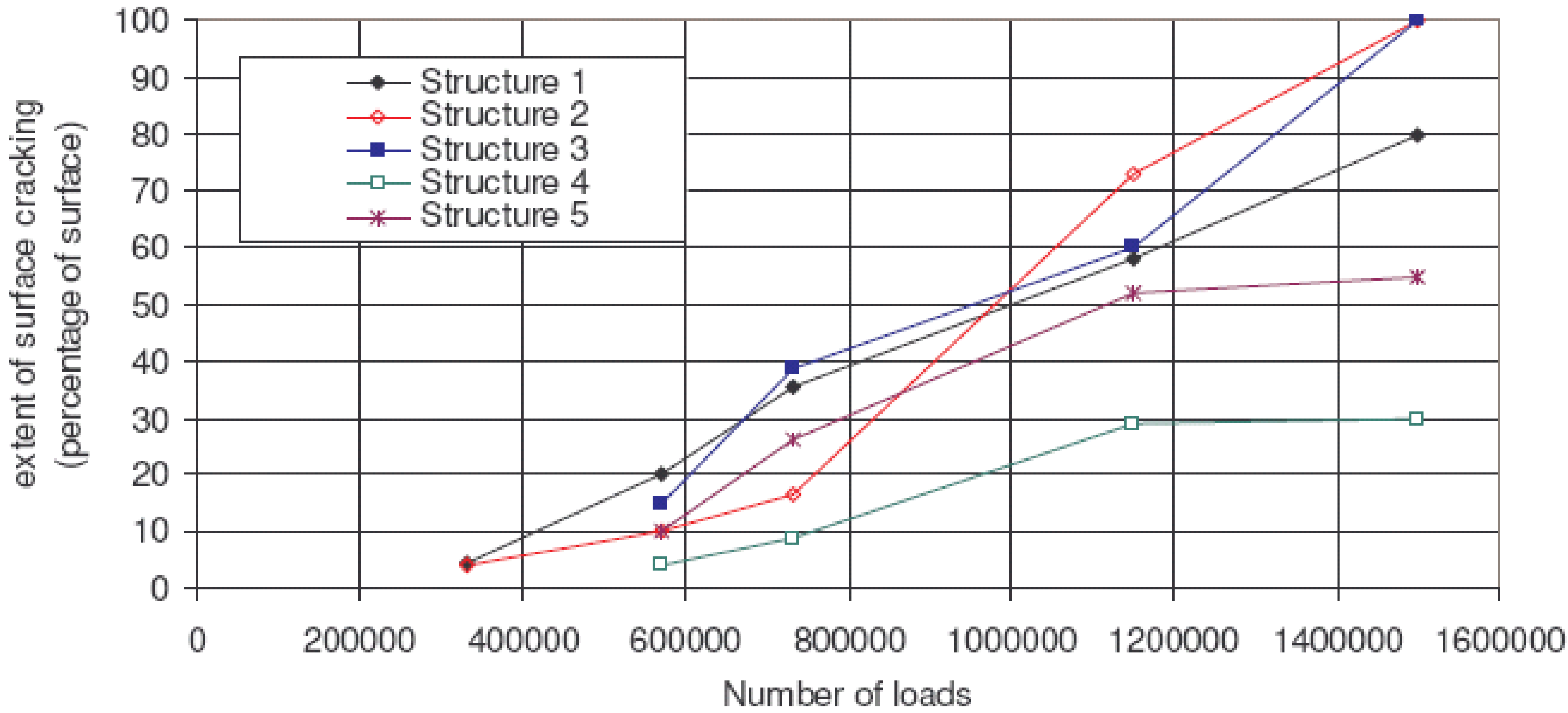
Lateral wander of wheel load



Result: Rutting



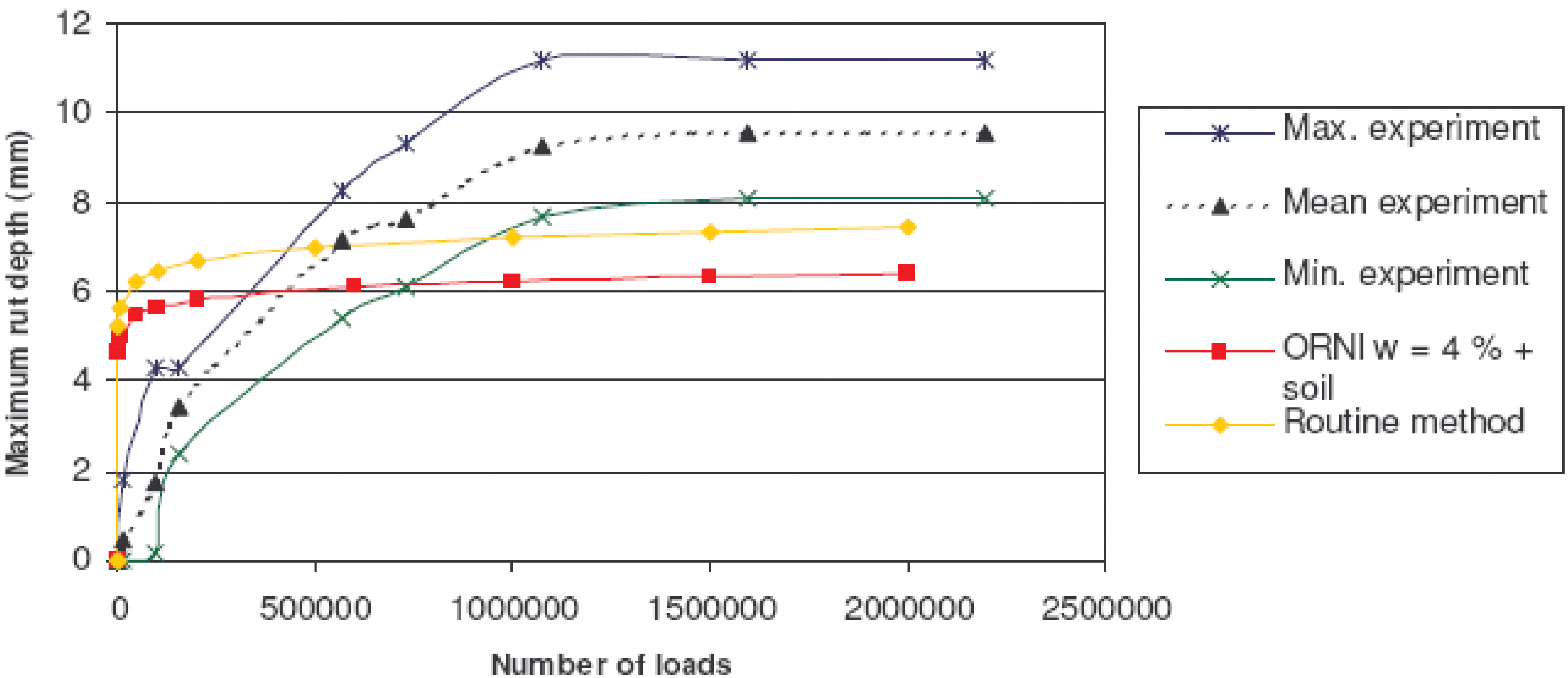
Result: Cracking



Ruts and cracks

Structure 5

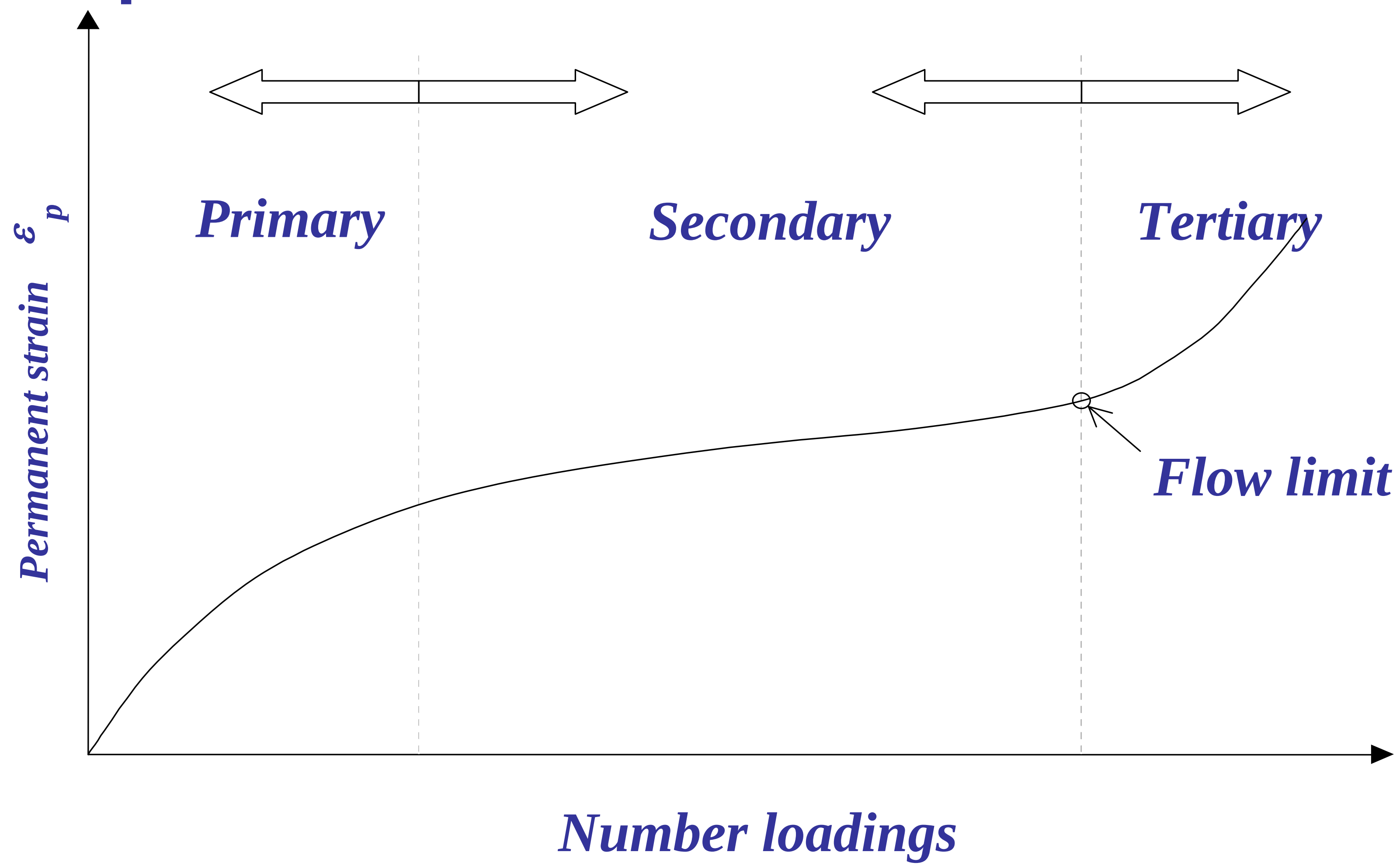
Result: Prediction of permanent deformation, rutting



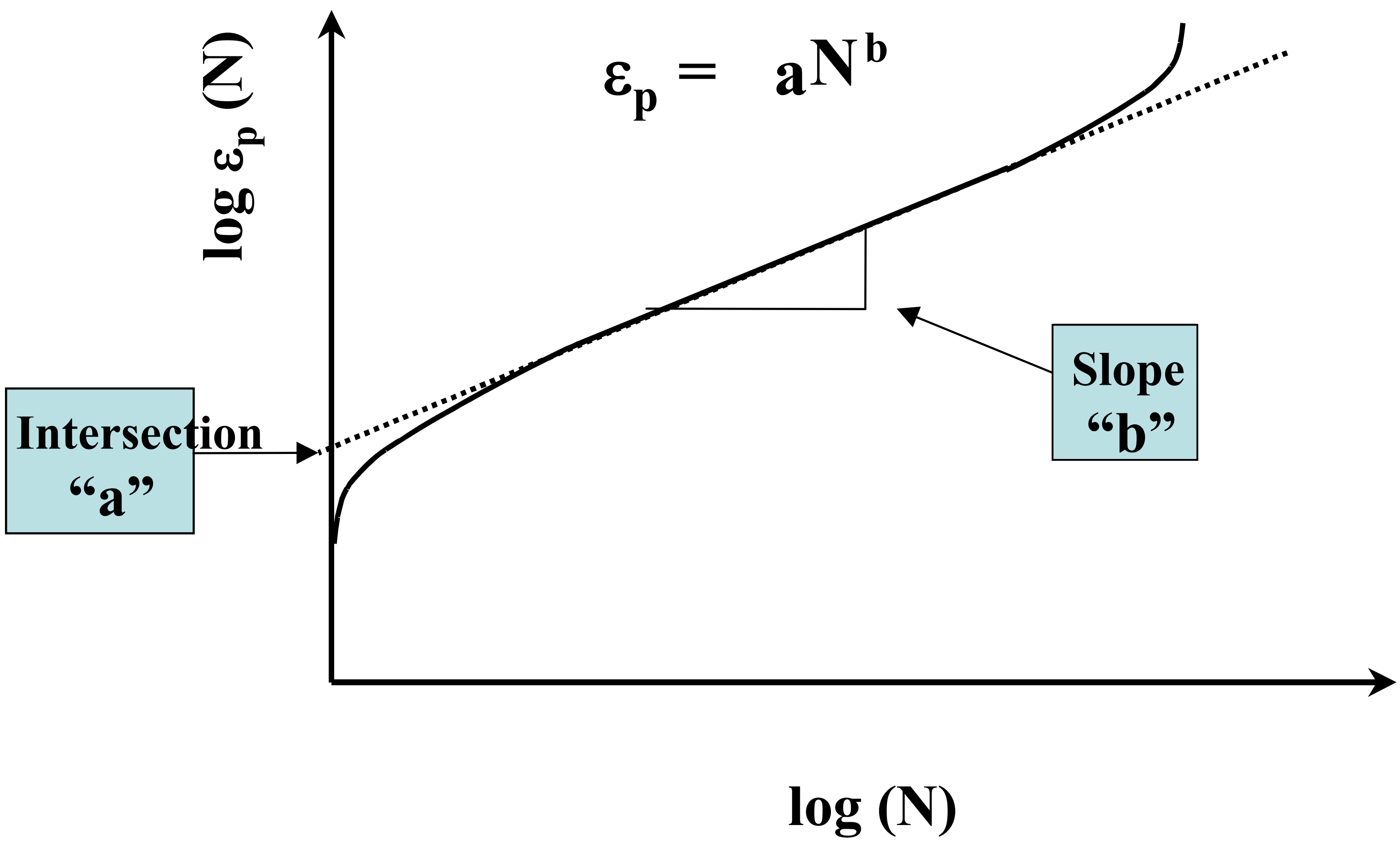
MATERIAL MODELS
Rutting in bituminous bound materials

Design Guide

Development of permanent deformations at typical periodic load



Permanent deformation test; Parameters



Calculation of Permanent Deformations; The form of the Model

$$\varepsilon_p = \varepsilon_r \cdot f(T, N)$$

where:

ε_p = total plastic strain
ε_r = resilient (elastic) strain
T = temperature
N = total number of loading cycles

Effect from real stress level

Ground equation for rutting

$$\log\left(\frac{\varepsilon_p}{\varepsilon_r}\right) = a_o + a_1 \log(N) + a_2 \log(T)$$

Function from material characteristics, but these are less important than N and T

R^2 = 0.73

S_e = 0.309

S_e/S_y = 0.522

N_{tests} = 3476 (>300 mixes)

Similar equations for permanent deformations in unbound material

Model for calculation of permanent deformations

$$\log\left(\frac{\varepsilon_p}{\varepsilon_r}\right) = -3.74938 + 0.4262\ \log(N) + 2.02755\log(T)$$

$R^2 = 0.73$

$S_e = 0.309$

$S_e/S_y = 0.522$

$N_{tests} = 3476$

Modelling permanent deformation

Asphalt layer – Design Guide

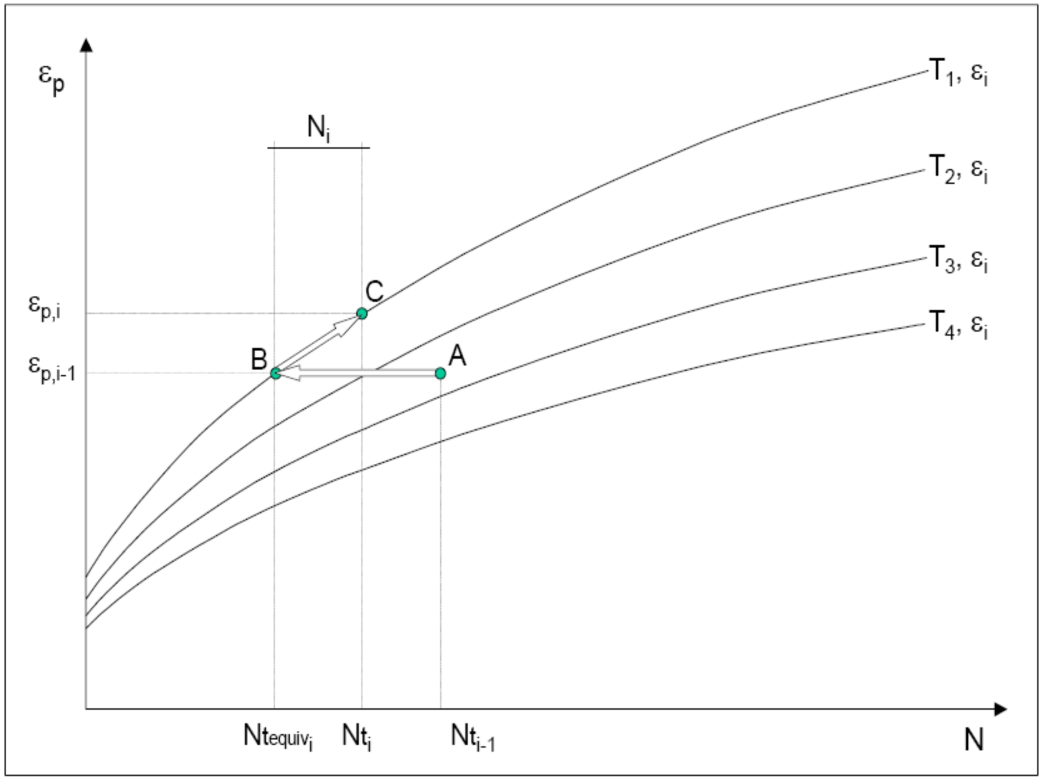
$$\frac{\varepsilon_p}{\varepsilon_r} = a_1 \cdot N^{a_2} \cdot T^{a_3}$$

ε_p – Accumulated plastic strain at N repetitions of load
ε_r – Resilient strain of the asphalt material
N – Number of load repetitions
T – Temperature (10°C)
a_i – Non-linear regression coefficients (from NCHRP 1-37A)

MEPDG – Summation of deformations

$$\frac{\varepsilon_p}{\varepsilon_r} = k_1 \beta_{r1} 10^{-3.15552} T^{1.734\beta_{r2}} N^{0.39937\beta_{r3}}$$

$$PD = \sum_{i=1}^{nsublayers} \varepsilon_p^i h^i$$

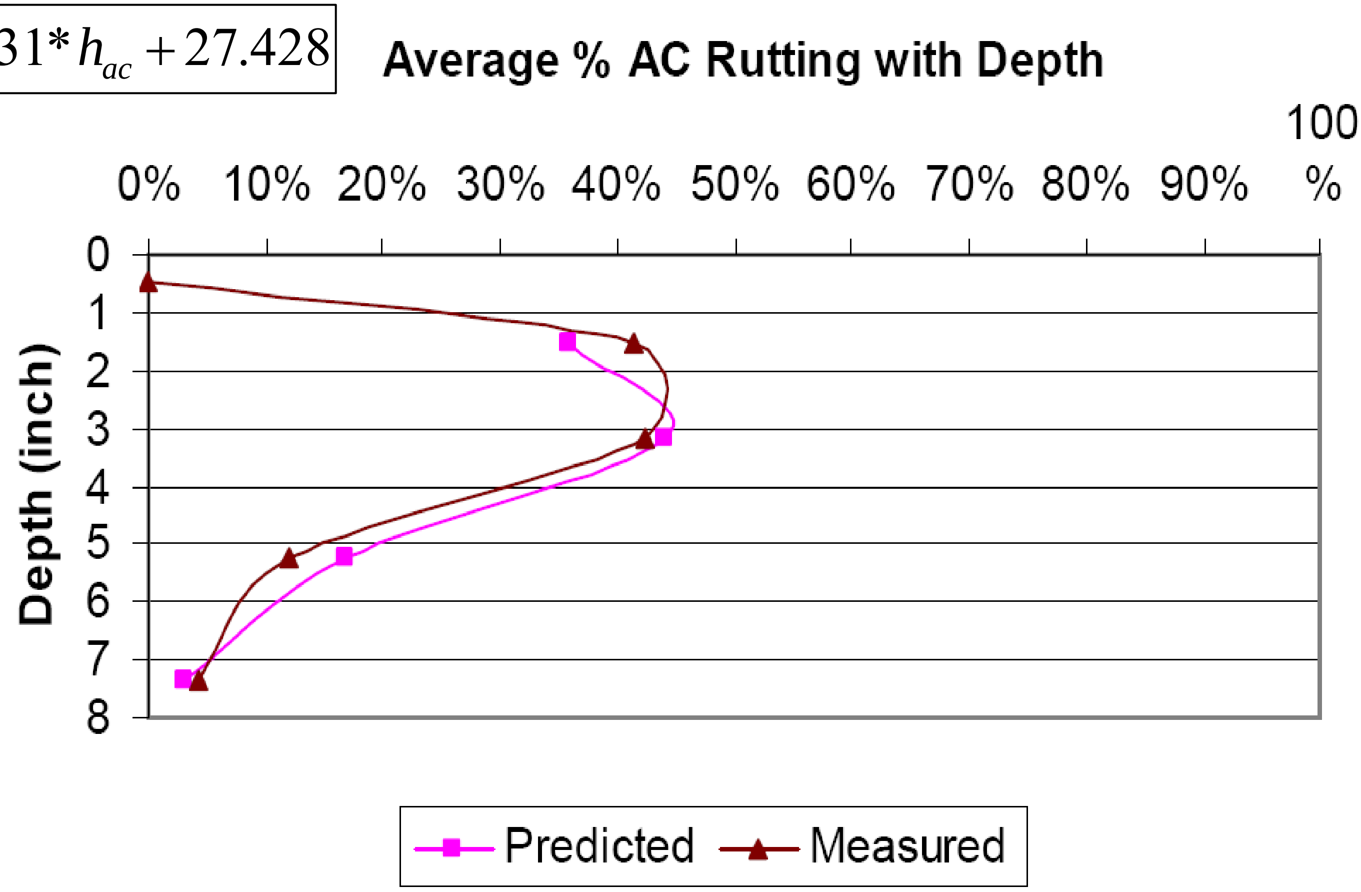


MEPDG – Calibration to Mnroad

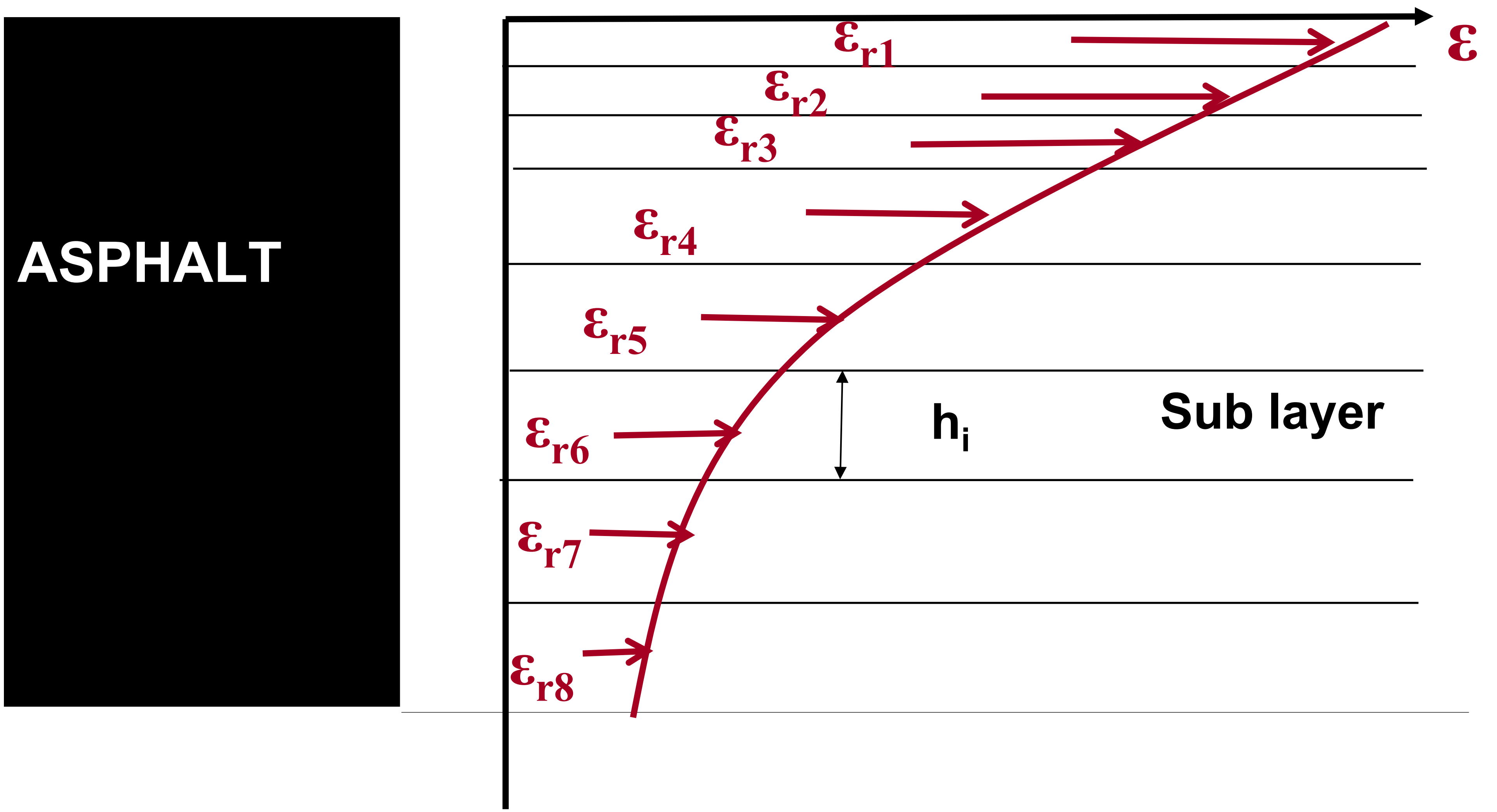
$$C_1 = -0.1039 * h_{ac}^2 + 2.4868 * h_{ac} - 17.342$$

$$C_2 = 0.0172 * h_{ac}^2 - 1.7331 * h_{ac} + 27.428$$

$$k_1 = (C_1 + C_2 * depth) * 0.328196^{depth}$$



Calculation of stress (σ) and strain (ε) with VagFEM



One important problem to solve!

All parameters is strongly dependant of the moisture content!

How is it possible to measure moisture content in the road structure?

Test metods!

- It is important that the test methods is syncronized to the design models.
- It must be possible to use results from the test methods as input data in the design models.