66th IBPC
Champaign, Il
Dec. 9-10, 2025

TOWARDS ZERO EMISSION ROAD CONSTRUCTION – THE USE OF RECYCLED MATERIALS IN PAVEMENT STRUCTURES

Sigurdur Erlingsson (sigurdur.erlingsson@vti.se)

VTI - Swedish National Road and Transport Research Institute, Linköping, Sweden

KTH Royal Institute of Technology, Stockholm, Sweden

University of Iceland, Reykjavik, Iceland

Background

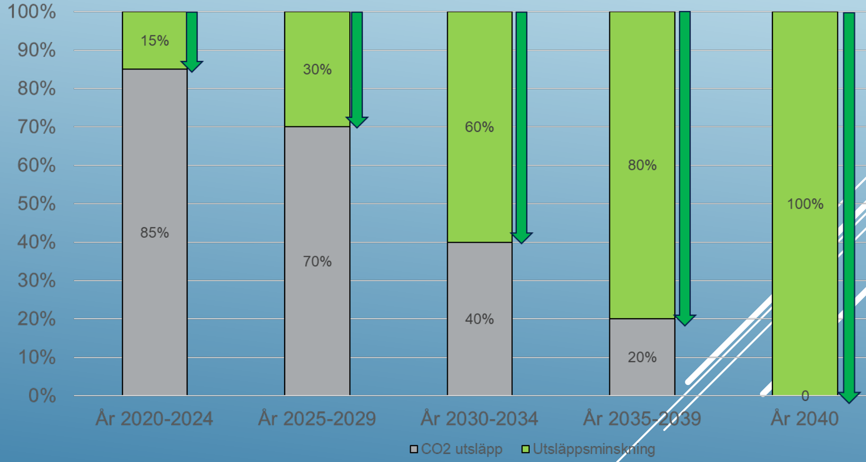
The Swedish Transport Administration (Trafikverket (TRV)) has set the goal of achieving climate neutral infrastructure by 2040.

To reach this goal, increased usage of residual and recycled materials in road constructions is indispensable.

Construction and industrial waste (CIW) materials from various industries are mostly piled up and dumped as landfill.

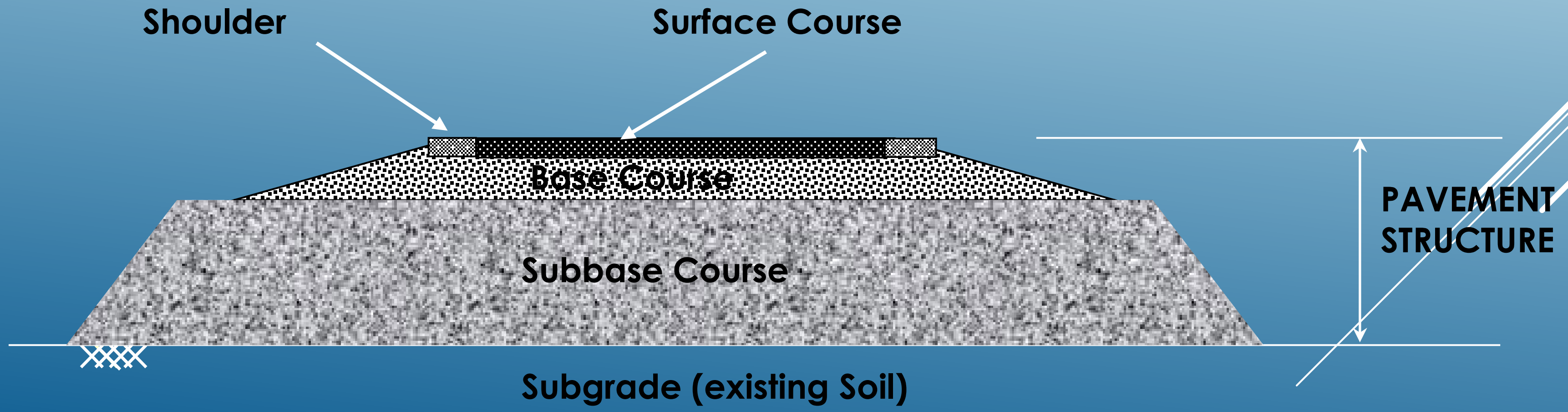
Replacing the fresh aggregates with recycled or residual materials has the potential of significant positive impact towards circular economy and climate neutrality.

CO_2 reduction



Objective

To investigate several recycled and residual (CIW) materials for their potential usage in pavement structures and to create the necessary design basis for this, particularly by updating the ME design tool ERAPave PP.

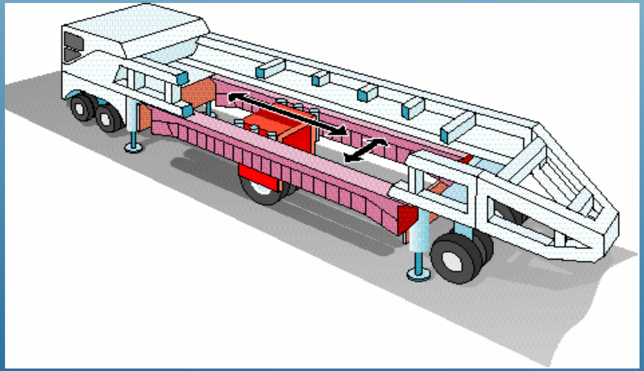


The approach - Divided into three main steps:

1. Small-scale Multi-Stage (MS) Repeated Load Triaxial (RLT) laboratory testing.
2. Full-scale Accelerated Pavement Test (APT) using a Heavy Vehicle Simulator (HVS).
3. In-service pavement monitoring.

Small-scale MS RLT testing

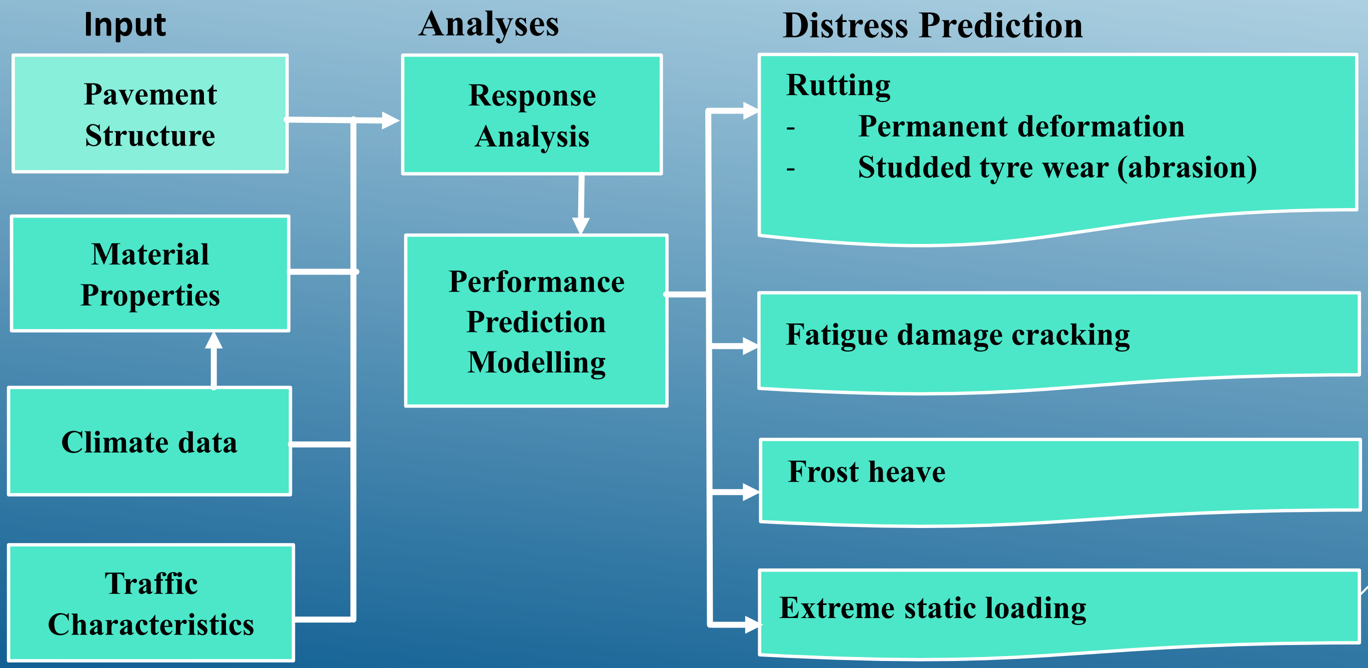
Full-scale APT using HVS



In-service road

ERAPave PP (Elastic Response Analysis of Pavements – Performance Predictions)

A new M-E pavement design method has been developed in Sweden.



Four CIW materials were tested in this project:

Incinerated Bottom Ashes - IBA
- Umeå 0/15
- Sysav 0/45

Crushed concrete 0/64

Milled asphalt 0/16

IBA Sysav 0/45

IBA Umeå 0/15

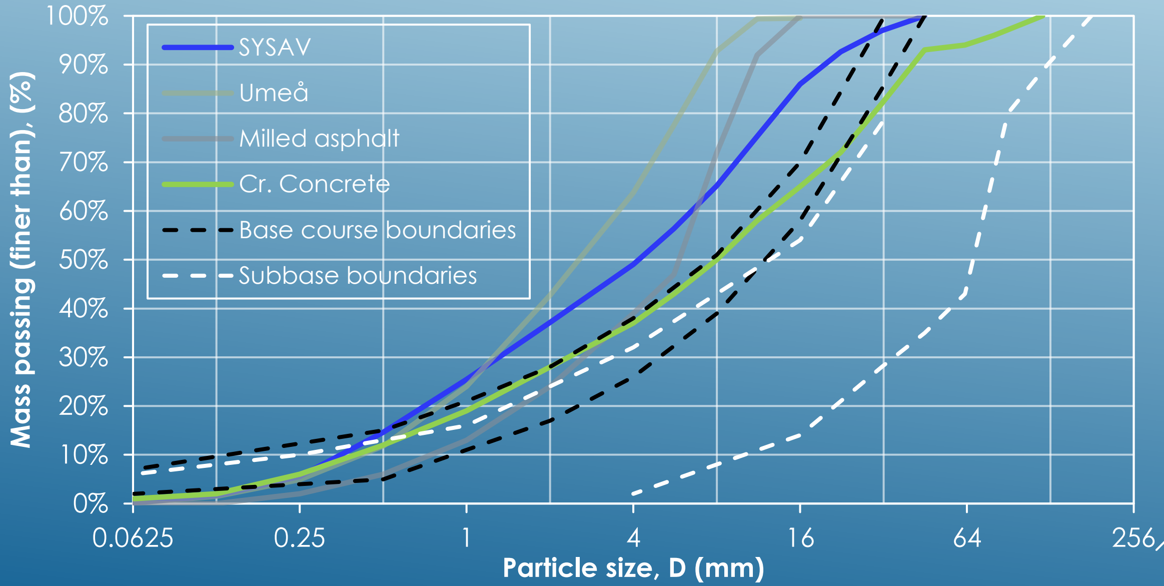
Crushed concrete 0/64

Milled asphalt 0/16

The four materials

Grain size distribution curves

The grain size distribution curve does not fulfil boundaries of base course or subbase materials.



The laboratory testing

Multi-Stage Repeated Load Triaxial (**MS RLT**) testing was done to investigate the performance properties of the waste materials.

- Cylindrical specimens (d = 150 mm, H = 300 mm).
- Vibrocompaction, free drainage conditions.
- Constant confining pressure (air) with cyclic axial loading (10 Hz) with no rest period (Haversine pulses).

Resilient properties - M_R

Permanent deformation properties - *PD*

30 stress paths, 10,000 load repetitions.

Stress paths (low stress levels)

Resilient (M_r) & Permanent Deformation (PD) properties

30 stress paths, 10,000 load repetitions.

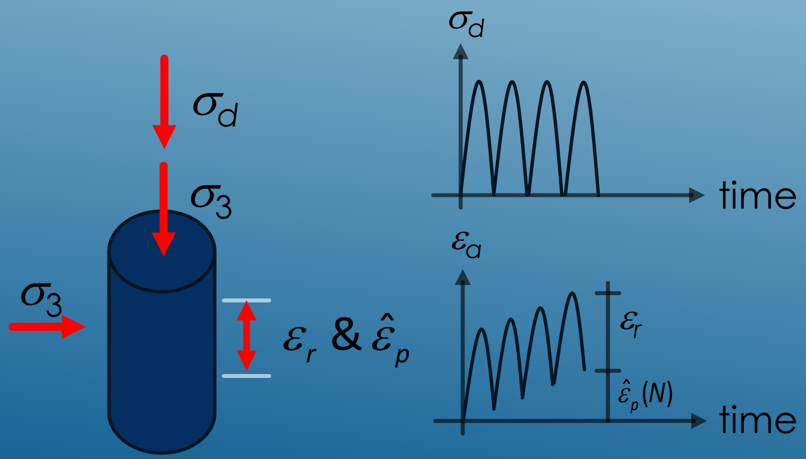
	Low stress level														
	Sequence 1			Sequence 2			Sequence 3			Sequence 4			Sequence 5		
	Confining stress, σ_3 kPa	Deviator stress, σ_d kPa		Confining stress, σ_3 kPa	Deviator stress, σ_d kPa		Confining stress, σ_3 kPa	Deviator stress, σ_d kPa		Confining stress, σ_3 kPa	Deviator stress, σ_d kPa		Confining stress, σ_3 kPa	Deviator stress, σ_d kPa	
	constant	min	max	constant	min	max	constant	min	max	constant	min	max	constant	min	max
1.	20	0	20	45	0	60	70	0	80	100	0	100	150	0	100
2.	20	0	40	45	0	90	70	0	120	100	0	150	150	0	200
3.	20	0	60	45	0	120	70	0	160	100	0	200	150	0	300
4.	20	0	80	45	0	150	70	0	200	100	0	250	150	0	400
5.	20	0	100	45	0	180	70	0	240	100	0	300	150	0	500
6.	20	0	120	45	0	210	70	0	280	100	0	350	150	0	600

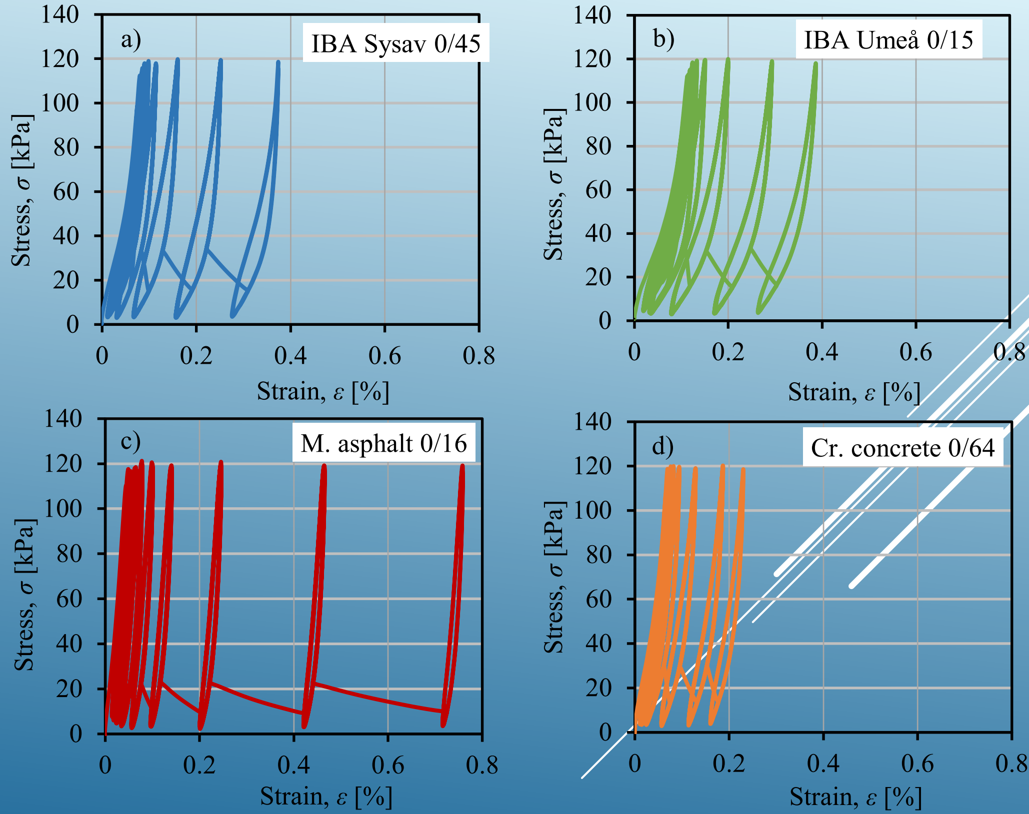
Test results from MS RLT testing

The last stress path in sequence 1 is where σ_3 = 20 kPa and σ_d = 120 kPa.

The loops correspond to load cycles:

10, 45, 95, 195, 395, 995, 2495 and 4995.





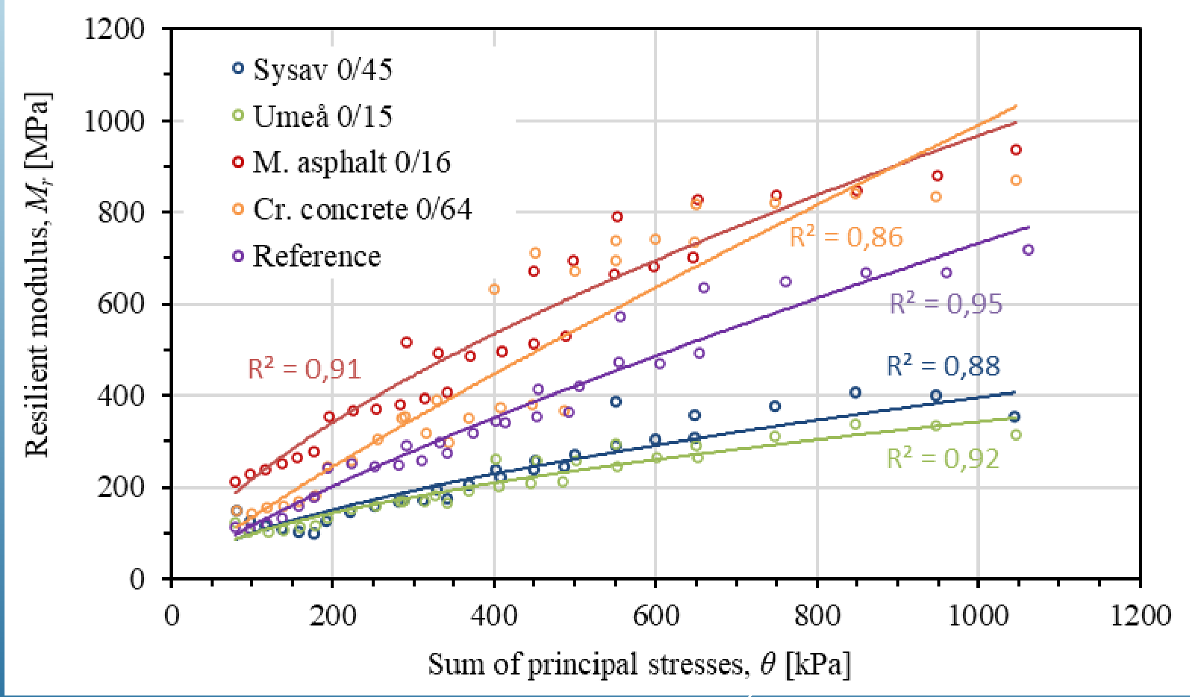
Resilient properties M_r

At 75% of w_{opt}.

$$M_r = \frac{\sigma_d}{\varepsilon_r}$$

$$M_r = k_1 \left(\frac{\theta}{p_a} \right)^{k_2}$$

k_1, k_2	Material properties
θ	Sum of principal stresses
p_a	Reference stress



Permanent deformation properties *PD*

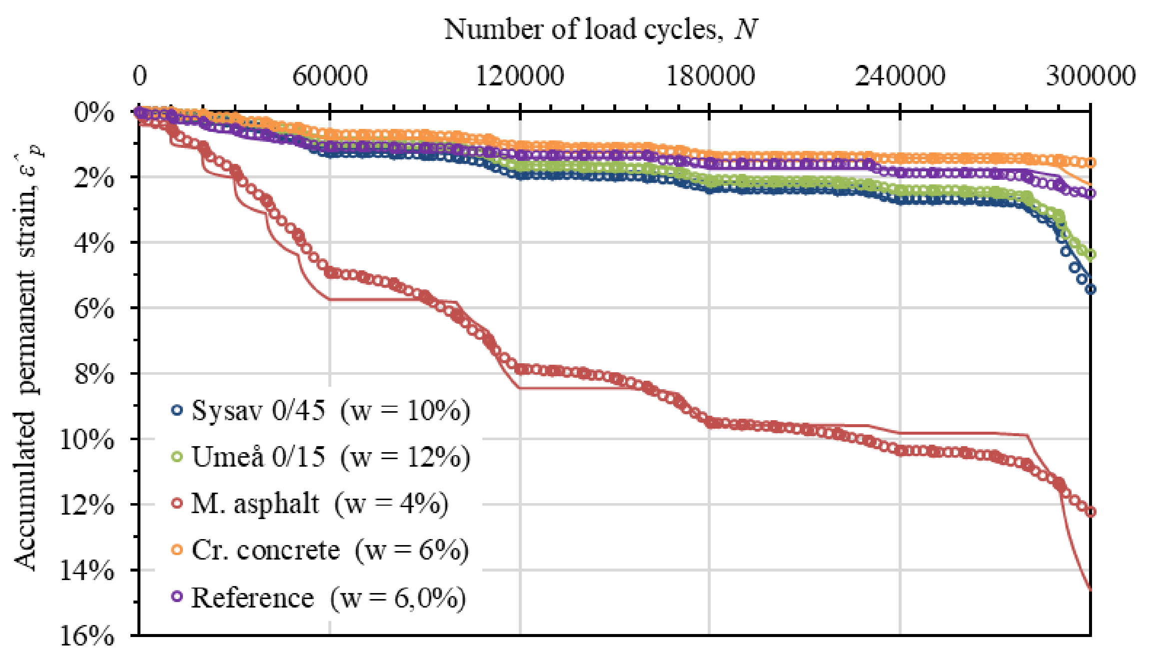
At 75% of w_{opt}.

Dots – Test results

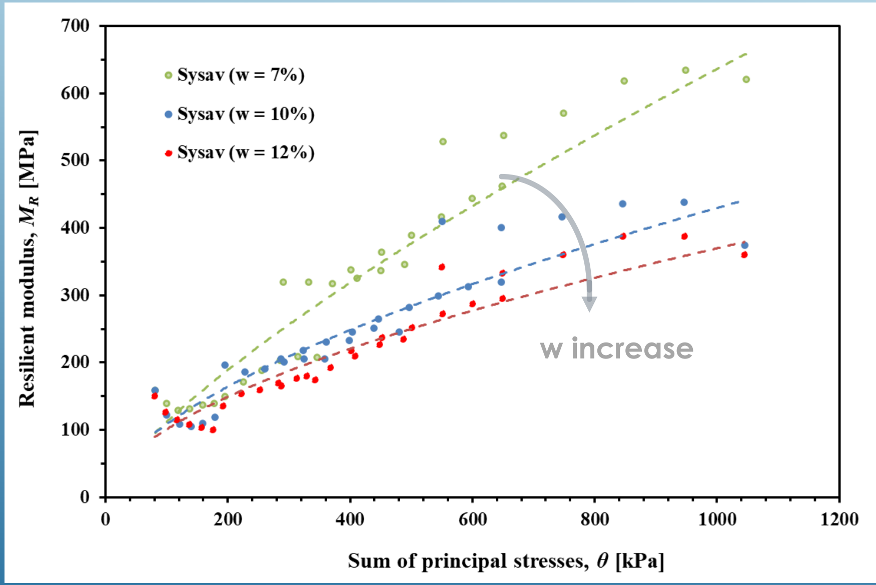
Lines – Modelled results

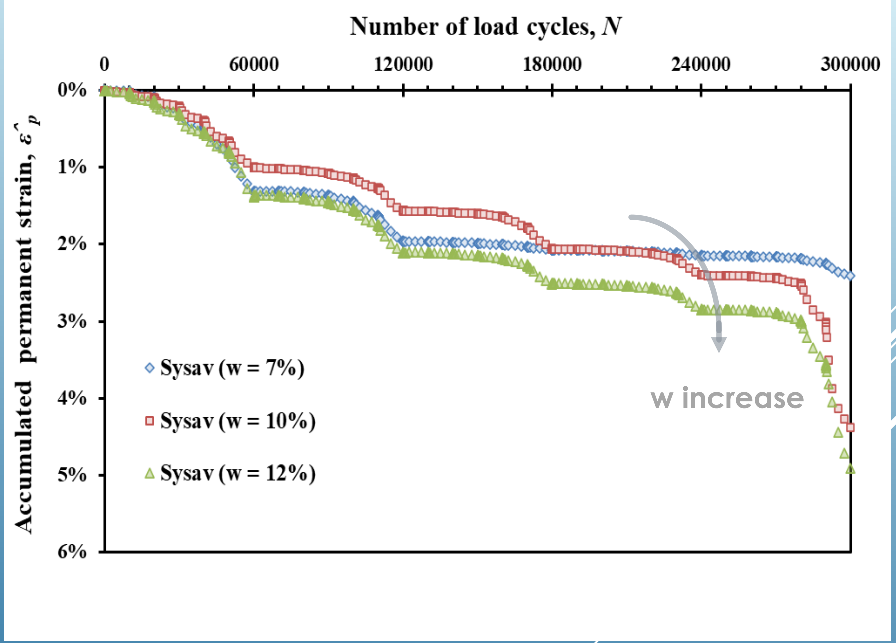
$$\hat{\varepsilon}_p(N) = aN^{b(\varepsilon_r)^c}\varepsilon_r$$

a, b, c	Material properties
N	Number of load repetitions
ε_r	Resilient strain
w	Moisture content



M_R and *PD* are moisture dependent

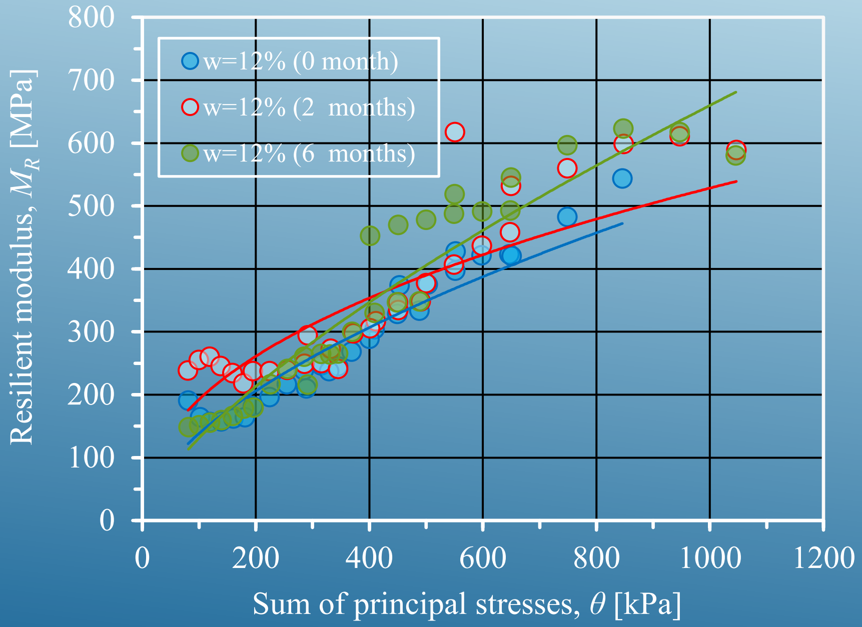




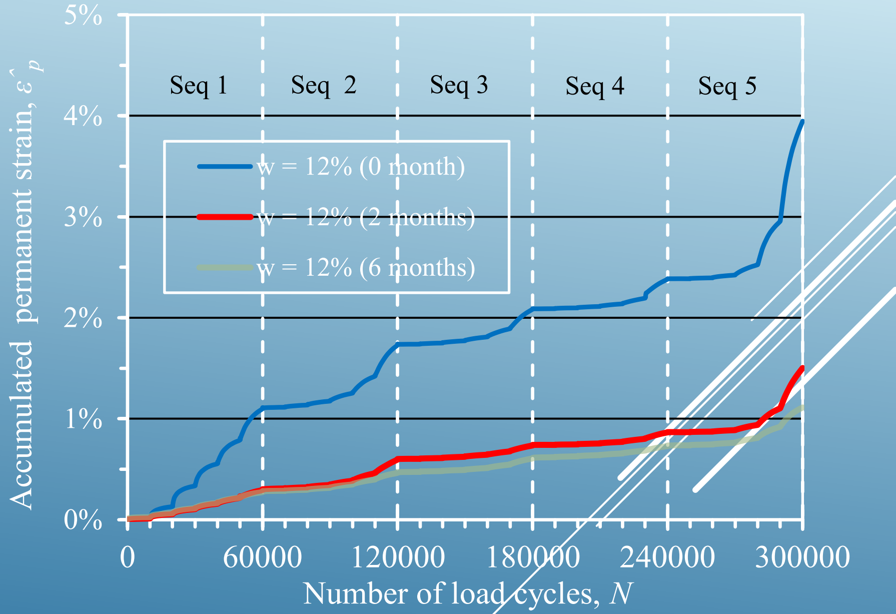
$$M_r = k_1 \left(\frac{\theta}{p_a} \right)^{k_2} \qquad k_1 = k_1(w)$$

$$\hat{\varepsilon}_p(N) = a N^{b(\varepsilon_r)^c} \varepsilon_r \qquad a = a(w)$$

M_R & *PD* properties are time dependent *IBA*

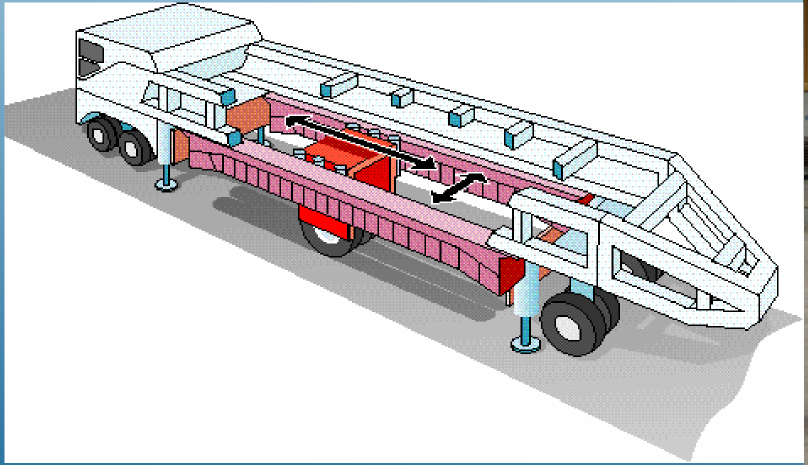


$$M_r = k_1 \left(\frac{\theta}{p_a} \right)^{k_2} \qquad k_1 = k_1(t)$$



$$\hat{\varepsilon}_p(N) = aN^{b(\varepsilon_r)^c}\varepsilon_r \qquad a = a(t)$$

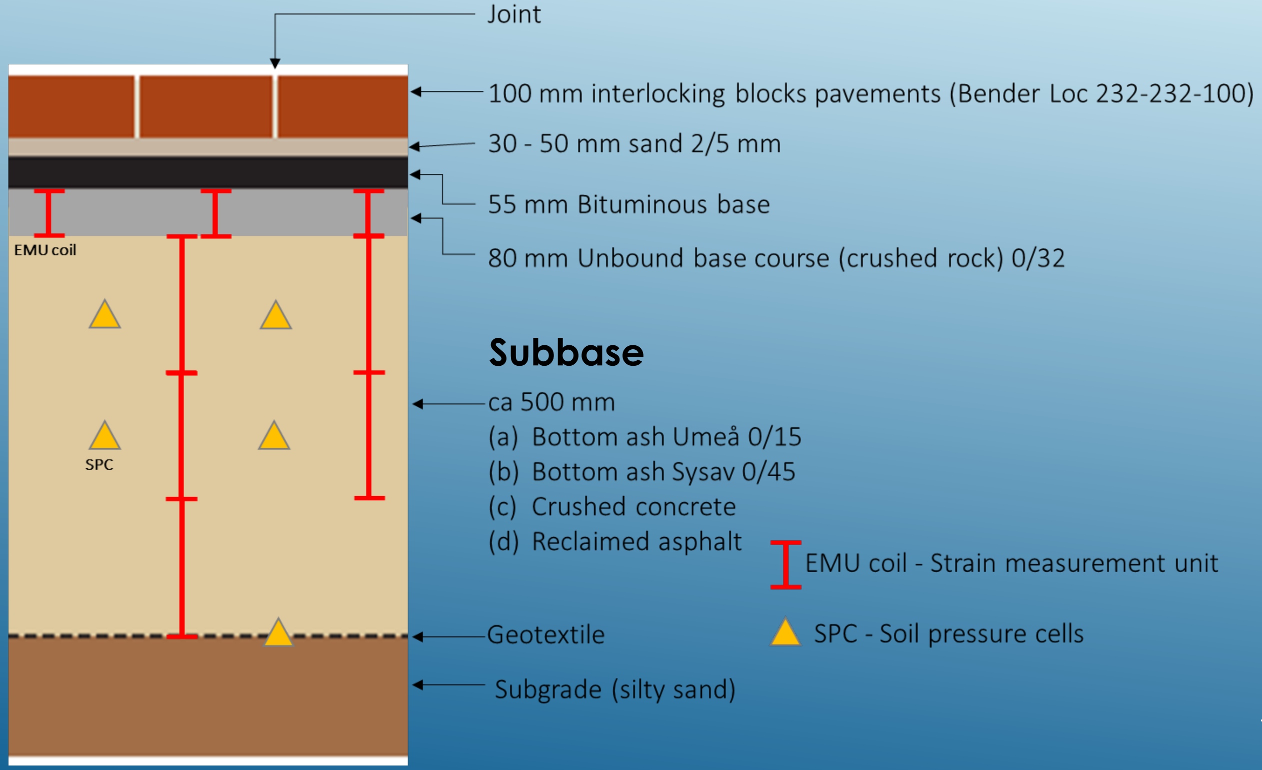
Full scale APT using an HVS machine



APT = Accelerated Pavement Test

HVS = Heavy Vehicle Simulator

Four structures were tested.



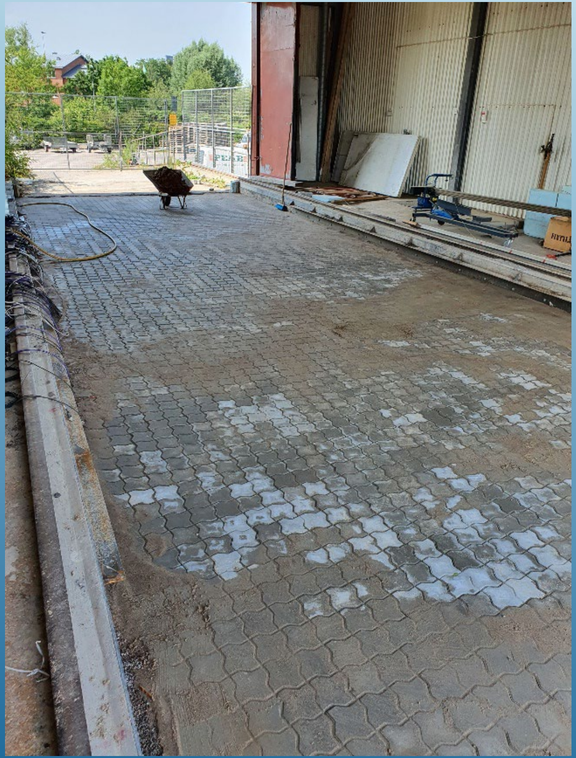
Construction of test objects #1

Construction of test objects #2

Construction of test objects #3 IBA

Construction of test objects #4

Construction of test objects #5



Rut development

HVS was used to measure the rutting development.

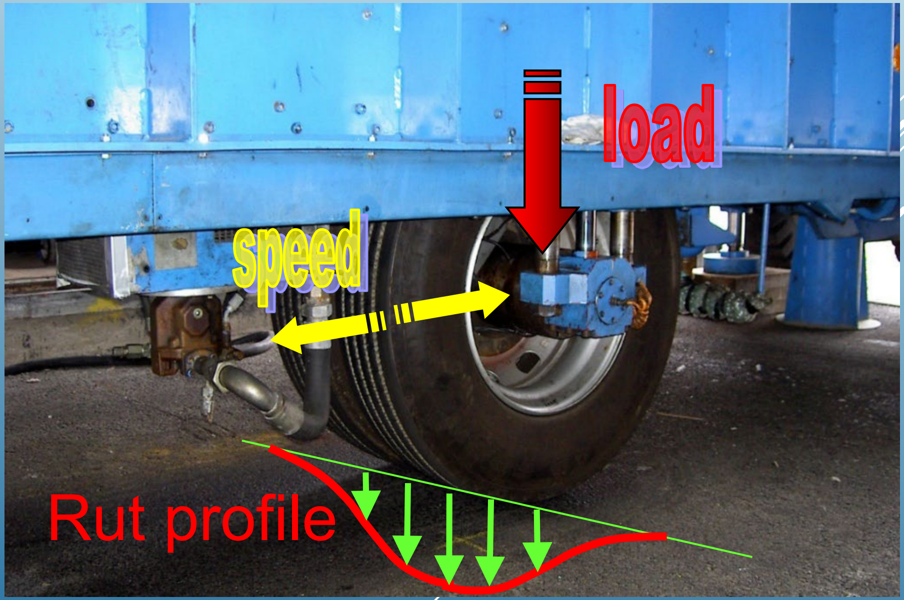
Four testing phases, T = 10°C, speed = 12 km/h.

1st Preloading phase, W = 30 kN, SW, p = 700 kPa

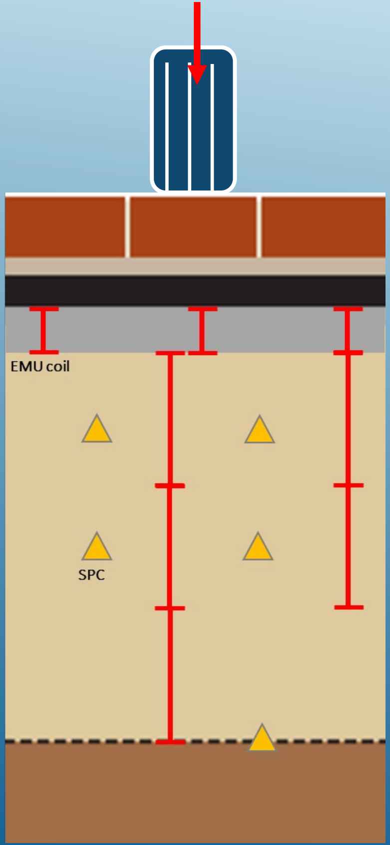
2nd T. Ph. M1 W = 40 kN, DW, p = 800 kPa

3rd T. Ph. M2 W = 60 kN, DW, p = 800 kPa

4th T. Ph. M3 W = 60 kN, DW, p = 800 kPa, raised gwt.

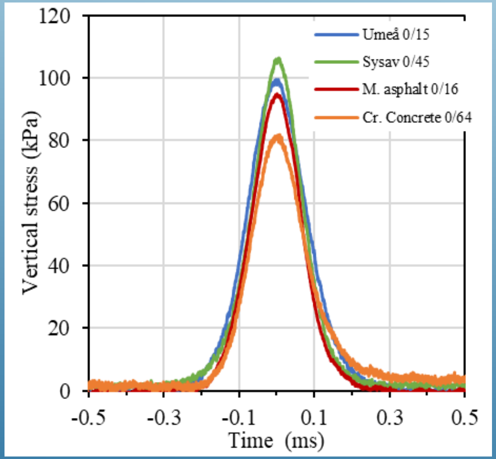


The HVS testing

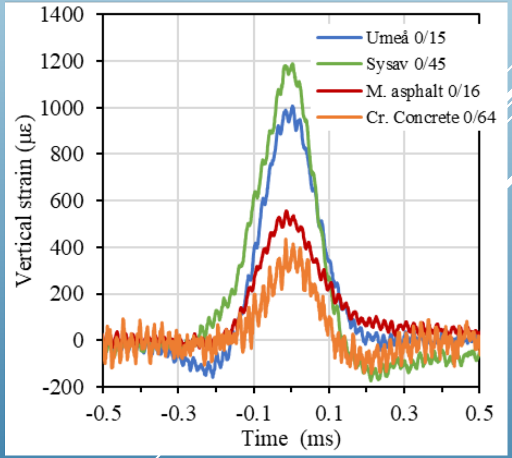


Response from embedded sensors.

Vertical stress



Vertical strain



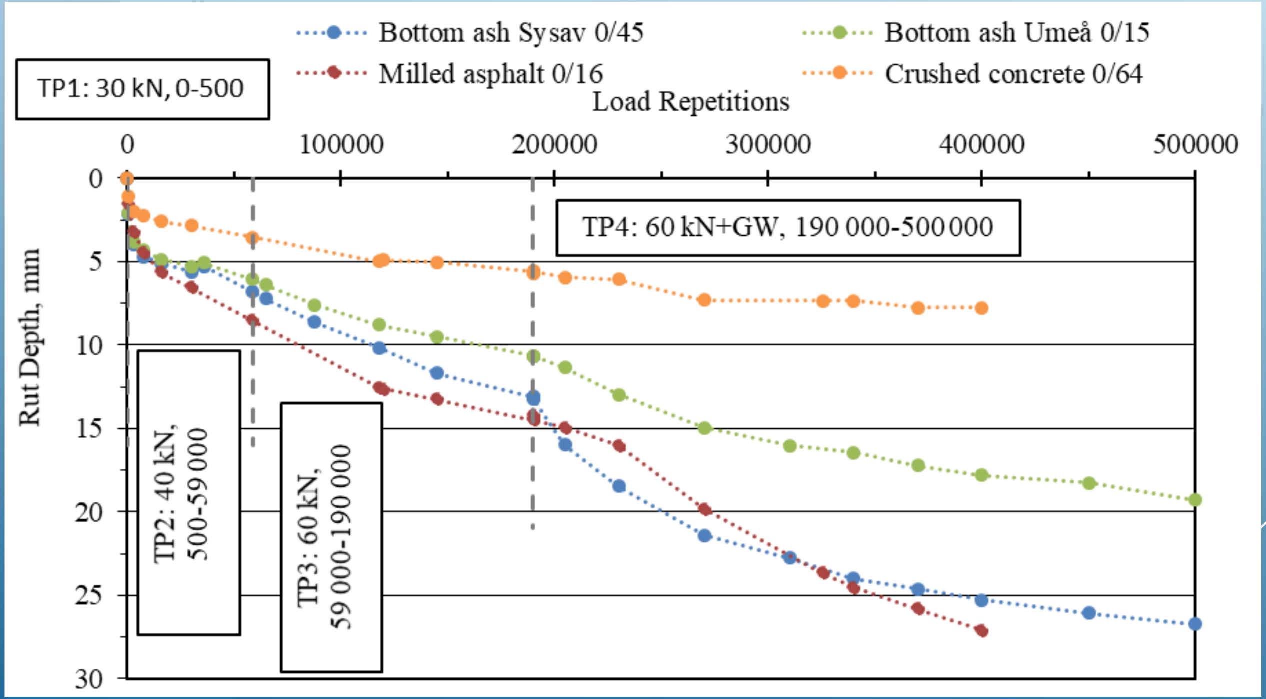
Rut as a function of load repetitions

Surface rut after 400 000 load repetitions
Two incineration bottom ash (IBA) materials as subbase materials.

Sysav 0/45 closest and Umeå 0/15 further away

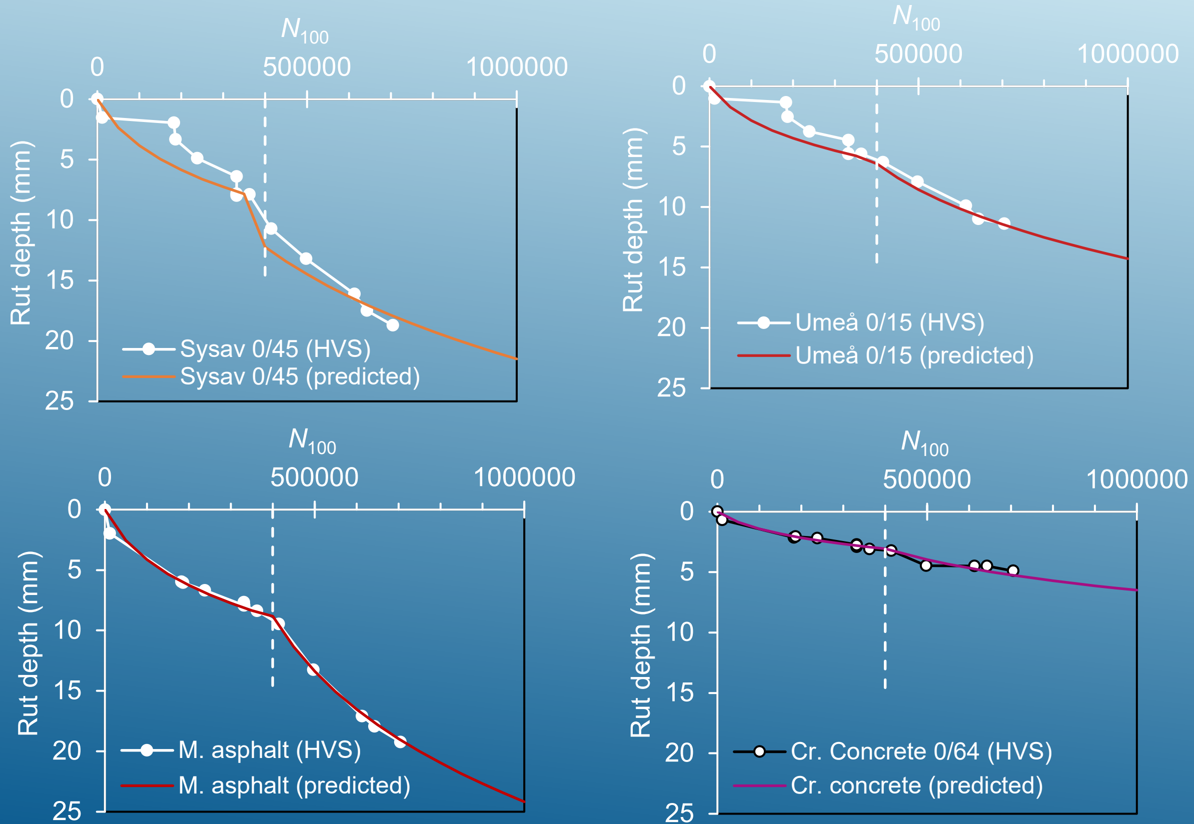
Close-up of the developed rut

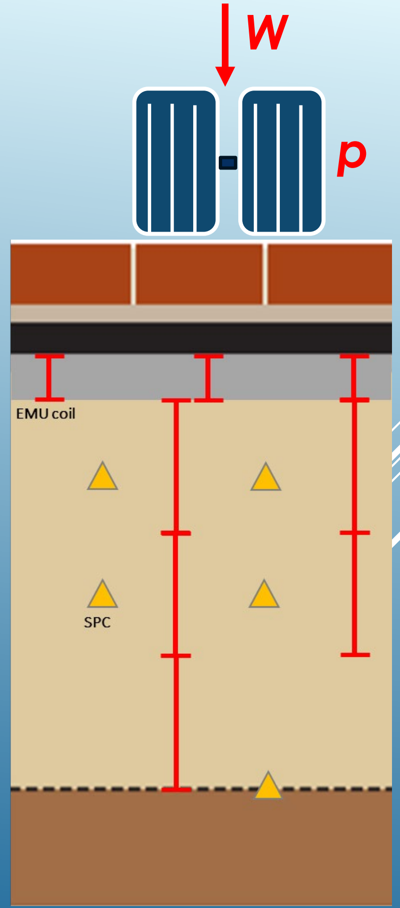
Rut as a function of load repetitions



Modelling of rutting

$$\hat{\varepsilon}_p(N) = \beta_1 a N^{\beta_2 b(\varepsilon_r)^{\beta_3 c}} \varepsilon_r$$





In-service test road

Regular FWD measurement & rut monitoring

Conclusions

Construction and Industrial Waste (CIW) materials have been tested to get information about their suitability to be used as unbound subbase materials in pavement structures.

A three step ME approach is used.

- **(1) Realistic small-scale MS RLT Lab testing, (2) Full-scale HVS loading (APT) & (3) In-service road monitoring.**

- **All the CIW materials showed moisture dependent mechanical behaviour (M_r and *PD*).**
- **They further showed time (age) dependent mechanical behaviour (Increased stiffness and stability with time).**
- **It was difficult to compact the materials in the full-scale APT. Generally, the achieved degree of compaction was higher in the small-scale RLT lab tests.**
- **Some calibration of M_r and accumulation of *PD* is necessary between small-scale lab testing and full-scale APT (HVS) testing.**
- **This discrepancy needs to be eliminated, and some well-established protocol should be developed to deal with it.**

Thank you - questions?

Sigurdur Erlingsson, sigurdur.erlingsson@vti.se