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Accelerated load testing of pavements

HVS-Nordic tests at VTI Sweden 2003–2004

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Title:
Accelerated load testing of pavements – HVS-Nordic tests at VTI Sweden 2003–2004

Abstract (background, aim, method, result) max 200 words:

During 2003 and 2004 two accelerated load tests were performed at the VTI test facility in Sweden (SE05 and SE06).

The objective of SE05 was to investigate the deformation behaviour of two different unbound base materials. Half of the test area was constructed with a base layer of natural granular material and the other half with a base layer of crushed rock aggregate. This means that the two structures were tested simultaneously.

The objective of SE06 was to be the third test in a series of structural design tests with stepwise higher bearing capacity. The previous two tests in this series are SE01 and SE02.

In the unbound base material test, SE05, the surface rut depth propagation during the accelerated load testing was greater on the crushed rock aggregate structure especially in wet condition. This was not expected and more than half of the difference in surface rut depth was found in the difference in the base layer deformations. One main reason for this unexpected behaviour is believed to be unsatisfactory compaction of the crushed rock aggregate.

The performance of the pavement structures SE01, SE02 and SE06 during the accelerated load testing will be analysed in more detail in the future. One preliminary conclusion is that there seems to be a fairly strong correlation between the rut depth propagation in dry condition and surface deflections from falling weight deflectometer (FWD) measurement on these three structures with gradually increasing bearing capacity.

Keywords:
Accelerated load testing, bearing capacity, pavement design, instrumentation, pavement response, pavement performance, rut depth

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Titel:
Accelererad provning av vägkonstruktioner – HVS-Nordic tester i VTI:s provhallar 2003–2004

Referat (bakgrund, syfte, metod, resultat) max 200 ord:

Under åren 2003 och 2004 genomfördes två tester med accelererad provning i VTI:s provhallar i Linköping, (SE05 och SE06).

Syftet med testet SE05 var att jämföra deformationsegenskaperna hos två olika bärlagermaterial. Två vägkonstruktioner byggdes parallellt i en av VTI:s provhallar. Den ena med bärlager av naturmaterial (Olivehult) och den andra med krossat berg (Skärlunda). Båda konstruktionerna kunde på detta sätt provas samtidigt.

Syftet med testet SE06 var att utgöra det tredje testet i en serie med tre vägkonstruktioner med successivt ökad bärighet. De två tidigare testerna är SE01 och SE02.

I testet med olika bärlagermaterial, SE05, blev spårbildningen/spårtillväxten på ytan större på konstruktionen med krossat berg i bärlagret, speciellt i fuktigt tillstånd med grundvattenyta i undergrunden. Detta resultat var oväntat och mer än hälften av skillnaden i spårbildning kunde hänföras till skillnad i deformation av bärlagren. En huvudorsak till det oväntade resultatet anses vara otillräcklig packning av det krossade bergbärlagret trots att det uppfyllde normenliga krav.

Resultaten från testerna SE01, SE02 och SE06 kommer att studeras mer i detalj vid kommande analyser. En preliminär slutsats är dock att det tycks råda ett relativt starkt samband mellan spårutvecklingen på respektive konstruktion och resultatet från provbelastning med fallvikt (ytdeflektioner).

Nyckelord:

Accelererad provning, bärighet, dimensionering, tung trafik, instrumentering, bärlager, spårbildning, deformation

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Preface

Finland and Sweden jointly invested in the Heavy Vehicle Simulator (HVS-Nordic) in 1997. The HVS-Nordic machine has since then been used in Finland and Sweden on an almost two-year basis. The first period in Finland is reported by Huhtala and Pihlajamäki, 2000, and the first period in Sweden by Wiman, 2001.

From 2000 to 2002 it was located in Finland, and at the beginning of 2002 Sweden received an inquiry from Poland about HVS testing at the construction site of the A2 motorway in Poland. The ongoing test in Finland was interrupted and the machine was taken by ship and trailer to the test site, close to Poznan. The tests were carried out during 2002 and Sweden and Finland jointly operated the machine, and made response measurements and carried out data acquisition.

After the tests in Poland, the machine was returned to Finland to conclude the Finnish test programme, after which it was taken to Sweden.

The Swedish tests, which are presented in this report, are SE05 (Unbound base material test) and SE06 (Structural design test). The report covers documentation of characteristics and properties of the test structures during and after construction, instrumentation, test procedure, and some results and conclusions focusing on pavement performance (rutting and deformation). Results from the comprehensive response measurement programs will be analysed and reported later in future projects.

The work carried out in the Swedish HVS-Nordic accelerated loading tests has been funded by the Swedish Road Administration, which is gratefully acknowledged.

Many people have been involved in the tests and the author expresses his sincere thanks to them all. Special thanks go to Håkan Arvidsson, Håkan Carlsson, Thomas Halldin, Leif Lantto, Peter Ståhl, and Andreas Waldemarson at VTI, and to our friends in Finland, Pekka Halonen and Janne Sikiö.

Linköping April 2006

Leif G Wiman

Coverpictures: VTI and Photos.com

Quality review/Kvalitetsgranskning

Review seminar was held on 2006-03-24 with Niclas Odermatt, Swedish Road Administration, as the reader. Leif G Wiman has made alterations to the final manuscript of the report. The research director of the project manager Safwat Said examined and approved the report for publication on 2006-05-02.

Granskningsseminarium genomfört 2006-03-24, där Niclas Odermatt, Vägverket, var lektör. Leif G Wiman har genomfört justeringar av slutligt rapportmanus 2006-04-28. Projektledarens närmaste chef, Safwat Said, har därefter granskat och godkänt rapporten för publicering 2006-05-02.

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Accelerated load testing of pavements – HVS-Nordic tests at VTI Sweden 2003–2004

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Summary

During 2003 and 2004, two accelerated load tests were performed at the VTI test facility in Sweden (SE05 and SE06).

The objective of SE05 was to investigate the deformation behaviour of two different unbound base materials. Half of the test area was constructed with a base layer of natural granular material and the other half with a base layer of crushed rock aggregate. This means that the two structures were tested simultaneousy.

The objective of SE06 was to be the third test in a series of structural design tests with stepwise higher bearing capacity. The previous two tests in this series are SE01 and SE02.

Before the accelerated loading test, a pre-loading and a comprehensive response measurement programme were performed.

The pre-loading was done in order to relieve possible residual stresses and cause some post-compaction. This was done by 20,000 passes during one day with a lower wheel load (30 kN single wheel load) with an even lateral distribution. The size of the single wheel was 425/65R22.5.

The response measurement programme embraced considerable measurement of stresses, strains, and deflections at different positions in the test structures and at different test-loads, lateral positions, speeds, and temperatures, and with different test-wheels and tyre pressures.

After the response measurement programme, the accelerated loading test was begun. Normal running was day and night, five days a week, with interruptions only for daily service of the machine, which means about 22,000 loadings per day, both directions included. The following standard set of test parameters was used in the main tests:

- Dual wheel load 60 kN
- Tyre pressure 800 kPa
- Wheel size 295/80R22.5
- Wheel speed 12 km/h
- Bidirectional loading
- Pavement temperature +10°C
- Lateral distribution.

Pavement performance has been studied by visual inspection and measurement of cross profiles at fixed longitudinal positions on the test structures for rut depth calculations.

All collected data will be stored in a common Finnish-Swedish database with information on test sites, pavement structures, sensors, materials, and response and performance measurement results.

Findings from the unbound base material test (SE05) was that the surface rut depth propagation during the accelerated load testing was greater on the structure with crushed rock aggregate in the base compared to the structure with natural gravel in the base, especially in wet condition. This was not expected and the difference in the base layer deformations accounted for more than half of the difference in surface rut depth.

One main reason for this unexpected behaviour is believed to be unsatisfactory compaction of the crushed rock aggregate base.

In these tests, the degrees of compaction were correlated to modified Proctor tests. The degree of compaction was the same (close to 100%) for both base layers. However, there are indications that this is not enough to obtain a sufficient degree of compaction for crushed materials. Greater compaction might probably be necessary to reduce the pore volume and obtain the density needed for good performance. For the crushed material, an increase in compaction energy will also increase the density. For the natural gravel, an increase in compaction energy will probably not result in as great an increase in density. This means that also in laboratory tests, the density of crushed rock is probably more sensitive to compaction energy than the density of the natural gravel.

To obtain sufficient compaction with the crushed material, two approaches could be used. One is to require a higher degree of compaction for crushed materials in the specifications; perhaps more than 100% of modified Proctor test. The other is to use higher compacting energy in the laboratory than the modified Proctor to determine the degree of compaction.

The objective of this structural design test (SE06) was the third test in a series of three tests with gradually increasing bearing capacity.

The performance of these pavement structures during the accelerated load testing will be analysed in more detail in future projects. One preliminary conclusion is that there seems to be a fairly strong relationship between the rut depth propagation in dry condition and surface deflections from falling weight deflectometer (FWD) measurement.

The rut depth propagation during the first phase, in dry condition, for these three tests showed a good fit with exponential regression lines.

In an attempt to find a relation between pavement structure and pavement performance, the relationship between surface deflections from FWD and the exponents in the rut depth propagation regression lines was used. The exponents were related to the surface curvature index SCI 300 from FWD (deflection at the centre of the loading plate minus deflection 300 mm from the loading plate) measured before the tests, and a good linear relationship was found.

These results and findings will be added to and studied further in other, future tests. A similar relationship was also found with data from the Swedish LTPP (Long Term Pavement Performance) sections, which indicates a possible link between ALT (Accelerated Load Testing) and RLT (Real-time Load Testing).

Accelererad provning av vägkonstruktioner – HVS-Nordic tester i VTI:s provhallar 2003–2004

av Leif G Wiman
VTI
581 95 Linköping

Sammanfattning

Under år 2003 och 2004 har två tester genomförts i VTI:s provhallar (SE05 och SE06).

Syftet med SE05 var att undersöka deformationsegenskaperna hos två olika grusbärlager. Halva testytan byggdes med bärlager av naturgrus och den andra halvan med bärlager av bergkrossmaterial. Båda konstruktionerna testades samtidigt.

Syftet med SE06 var att utgöra det tredje testet i en serie konstruktioner med successivt ökad bärighet. De föregående testerna i den här serien är SE01 och SE02.

Innan huvudtesterna startades genomfördes dels en förbelastning, dels ett responsmätprogram.

Förbelastningen gjordes för att frigöra eventuella inspänningar och för att få en viss efterpackning. Den omfattade 20 000 överfarter med ett singelhjul med låg last (30 kN) jämnt fördelad i sidled. Dimensionerna på singelhjulet var 425/65R22.5.

Responsmätprogrammen omfattade en mängd mätningar av spänningar, töjningar och deflektioner i olika positioner i vägkroppen och vid variation av hjullast, hjultyp, ringtryck, sidoläge, hastighet och temperatur.

Efter responsmätningarna startades huvudtestet som normalt pågick 24 timmar per dygn fem dagar i veckan med avbrott för daglig service av maskinen, vilket betyder ca 22 000 belastningar per dygn då belastningen påförs i båda riktningarna. Följande testparametrar gäller för huvudtesterna:

- Hjultyp: Parhjul
- Hjullast: 60 kN
- Ringtryck: 800 kPa
- Däckdimension: 295/80R22.5
- Hastighet: 12 km/tim
- Belastningsriktning: Dubbelriktad
- Beläggningstemperatur: +10°C
- Sidoläge: Normalfördelad.

Tillståndförändringen under huvudtesterna har följts genom okulära besiktningar och tvärprofilmätningar i förutbestämda positioner för beräkning av spårdjup och spårdjupstillväxt.

All datainsamling kommer att läggas in i en gemensam finsk/svensk databas med information om provplats, vägkonstruktion, material, instrumentering och resultaten från responsmätningar och tillstånduppföljning.

Testet med olika material i grusbärlager (SE05) resulterade i större spårdjupstillväxt på konstruktionen med bärlager av krossat berg jämfört med naturgrus speciellt i fuktigt tillstånd (grundvattenyta 30–40 cm under terrassytan). Detta var inte väntat och mer än hälften av skillnaden i spår på ytan kunde hänföras till deformation i grusbärlagren.

En huvudorsak till detta oväntade resultat antas vara otillräcklig packning av bärlagret med krossat material. Båda materialen uppvisade samma packningsgrad dvs. samma förhållande mellan torr densitet i fält och torr densitet från modifierad Proctorinstampning i laboratorium. Det finns dock indikationer på att modifierad Proctorinstampning inte är tillräckligt för att krossat material ska få eftersträvade egenskaper. En ökad packningsinsats skulle förmodligen leda till en större ökning av densiteten för det krossade materialet jämfört med naturmaterialet.

För att erhålla tillräcklig packning för krossat material kan man antingen höja kraven på packningsgraden till mer än 100 % av modifierad Proctor eller öka packningsinsatsen i laboratoriet till mer än vad metoden modifierad Proctor föreskriver.

Dimensioneringstestet (SE06) var det tredje i en serie tester med successivt ökad bärighet.

Resultaten från detta test och de två tidigare genomförda testerna (SE01 och SE02) kommer att analyseras mer i detalj senare. En preliminär slutsats är att det tycks finnas ett relativt starkt samband mellan spårdjupsutvecklingen i torrt tillstånd och ytdeflektioner från provbelastning med fallvikt (FWD).

Spårdjupsutvecklingen under den första delen, (torrt tillstånd), av huvudtestet visade god överensstämmelse med exponentiella regressionsekvationer.

I ett försök att finna samband mellan vägkonstruktion och spårdjupsutveckling jämfördes ytdeflektioner uppmätta med fallvikt och exponenterna i regressionsekvationerna. Ett linjärt samband kunde konstateras mellan SCI 300, (deflektion D_0 minus D_{300}), uppmätt före test och exponenterna.

Dessa resultat kommer att kompletteras och studeras vidare i andra och kommande tester. Ett liknade samband har konstaterats från mätningarna på befintliga vägar inom projektet ”Tillståndsuppföljning av observationssträckor” som indikerar att detta kan vara en koppling mellan accelererad provning och verklig trafikbelastning.

1 Introduction

Finland and Sweden jointly invested in the Heavy Vehicle Simulator (HVS-Nordic) in 1997. The HVS-Nordic machine has since then been used in Finland and Sweden for periods of up to almost two years in each case. The first period in Finland is reported by Huhtala and Pihlajamäki, 2000 and the first period in Sweden by Wiman, 2001.

From 2000 to 2002 it was located in Finland, and at the beginning of 2002 Sweden received an inquiry from Poland about HVS testing at the construction site of the A2 motorway in Poland. The ongoing test in Finland was interrupted and the machine was taken by ship and trailer to the test site, close to Poznan. The tests were carried out during July and August 2002 and Sweden and Finland jointly operated the machine, made response measurements and carried out data acquisition. Experts from different universities in Poland and Austria analysed the test data and the results can be found in Blab et al. 2002 and Blab et al. 2004.

After the tests in Poland, the machine was returned to Finland to conclude the Finnish test programme (Korkiala-Tanttu and Jovanoski, 2003), after which it was taken to Sweden.

The Swedish tests, which are presented in this report, are SE05 (Unbound base material test) and SE06 (Structural design test). The SE05 test was carried out during January–April 2003 and the SE06 test over two periods, April–May 2003 and March–June 2004.

In the period between the two SE06 periods, tests were performed on two different construction sites in the west and south of Sweden. Close to the motorway E6 at Uddevalla, in the western region, 8 structures were tested. Four structures with variable mica content in the unbound base material and four structures of different lightweight fill design. These tests are reported elsewhere, Provväg E6, Vägverket 2004:84 (in Swedish) and Lenngren, 2004.

In the southern part of Sweden, at the construction site of motorway E4 at Markaryd, tests were performed both for the Swedish Road Administration, Construction and Maintenance, and the Danish Road Administration (Vejdirektoratet). The objectives of the Swedish tests were to study the effect of aggregate size in coarse crushed rock sub-base and will be reported elsewhere. The objectives of the Danish tests were to study design parameters for semi rigid pavements. These tests are reported by Thøgersen et al., 2004.

An overview of all tests performed in Finland and Sweden since the start in 1997 can be found in Appendix A.

2 Objective

During 2003 and 2004, two tests were performed at the VTI test facility in Sweden (SE05 and SE06).

The objective of SE05 was to investigate the deformation behaviour of two different unbound base materials. Half of the test area was constructed with a base layer of natural granular material (named “Olivehult”) and the other half with a base layer of crushed rock aggregate (named “Skärlunda”). This means that the two structures were tested simultaneously.

The objective of SE06 was to be the third test in a series of structural design tests with stepwise higher bearing capacity. The previous two tests in this series are SE01 and SE02.

3 Test set-up

Details about layer thickness, instrumentation of the test sections and material properties and characteristics are given below.

3.1 Test structure SE05

3.1.1 Layer thickness

The thickness of the subgrade was 2.5 m on a rigid bottom (cement concrete).

The pavement layer thicknesses in the test structures are given below.

Table 1 Pavement layer mean thickness in SE05 centre line.

Layer	Planned thickness	Actual thickness	
		Natural granular material (Olivehult)	Crushed rock aggregate (Skärlunda)
Asphalt concrete	40 mm	50 mm	55 mm
Unbound base	450 mm	462 mm	451 mm
Total thickness	490 mm	512 mm	506 mm

The total thickness of the unbound bases (450 mm) was chosen because it was believed to give a clearer and more distinct difference between the two materials used compared to thinner base layers on a sub-base layer.

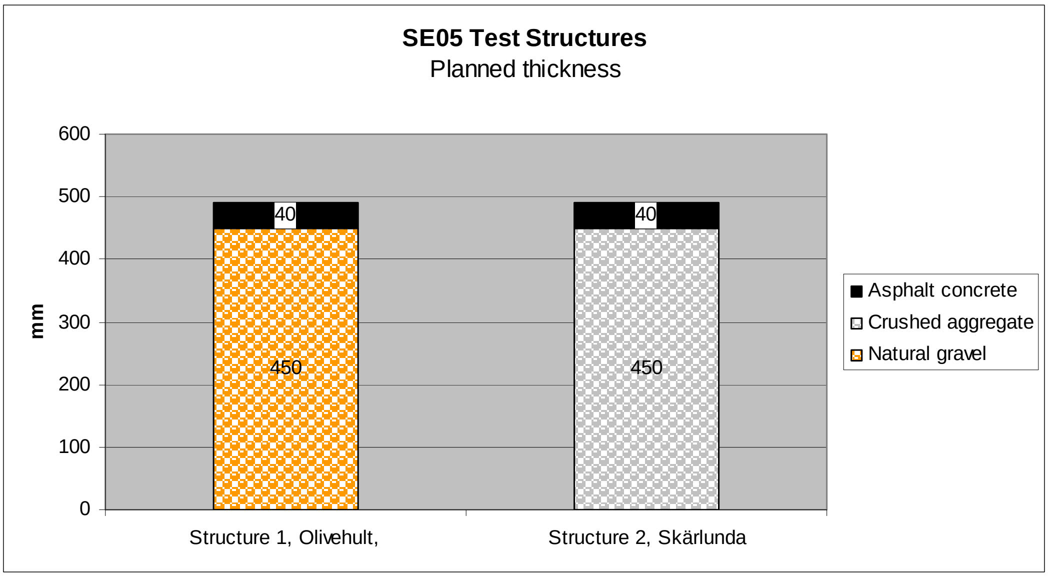


Figure 1 Planned thicknesses of test structures in SE05.

3.1.2 Instrumentation

Sensors were installed in the structures during construction to be used in the response measurement programme.

Most of the sensors were located in the centre line of the loaded area (6x1 m). The following sensors were used in test SE05:

- H-shaped asphalt strain gauges from Dynatest (ASG)
- Soil pressure cells from the University of Nottingham (SPC)
- LVDTs for vertical deflection and deformation
- Inductive coils (εMU) for vertical deformation and strain (static and dynamic)
- Water content reflectometers (WCR)
- Temperature gauges.

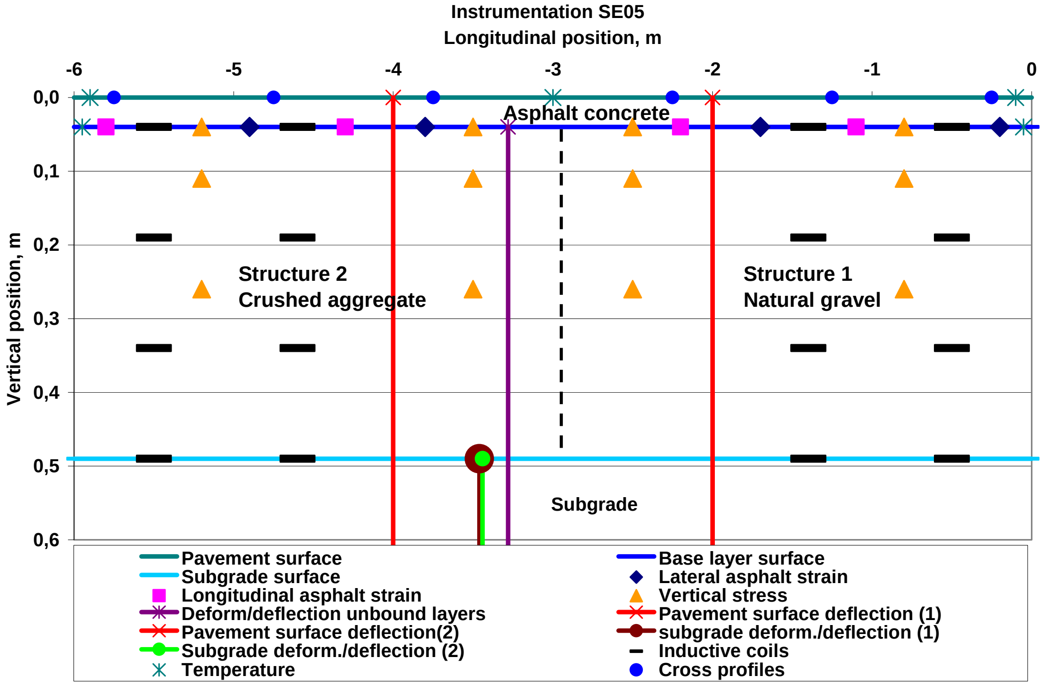


Figure 2 Longitudinal cross section of SE05 instrumentation.

Sensors for measurement of volumetric water content were installed at different depths. The sensors in the centre line were installed outside the test area but in the area where the loading wheel changes direction.

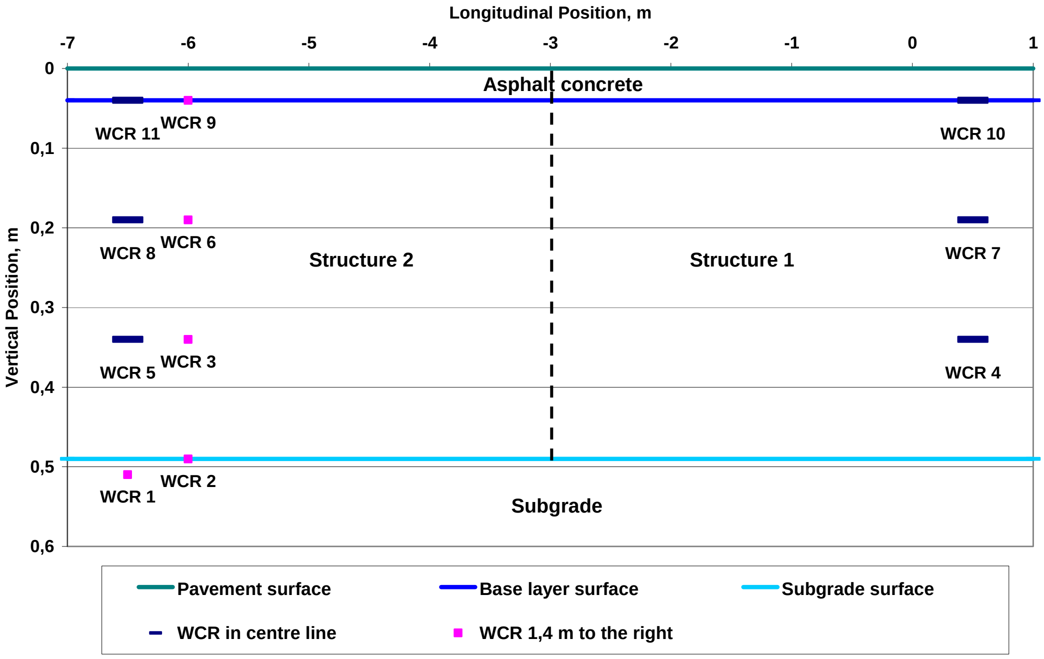


Figure 3 Positions of volumetric water content measurement sensors.

3.1.3 Characteristics and properties of the fine sand subgrade

Both test structures in SE05 and SE06 were constructed on the same fine sand subgrade as the previous tests at the VTI test facility.

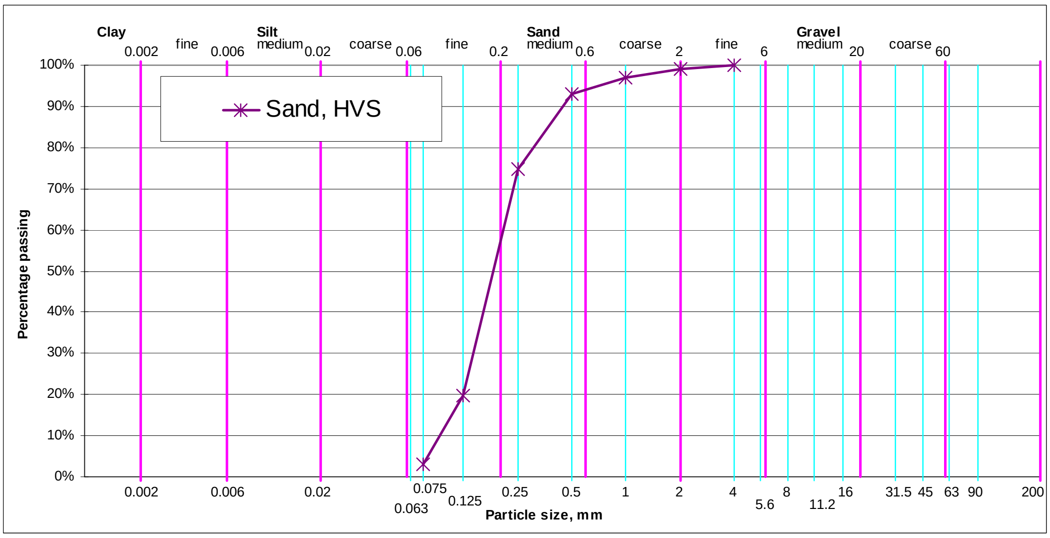
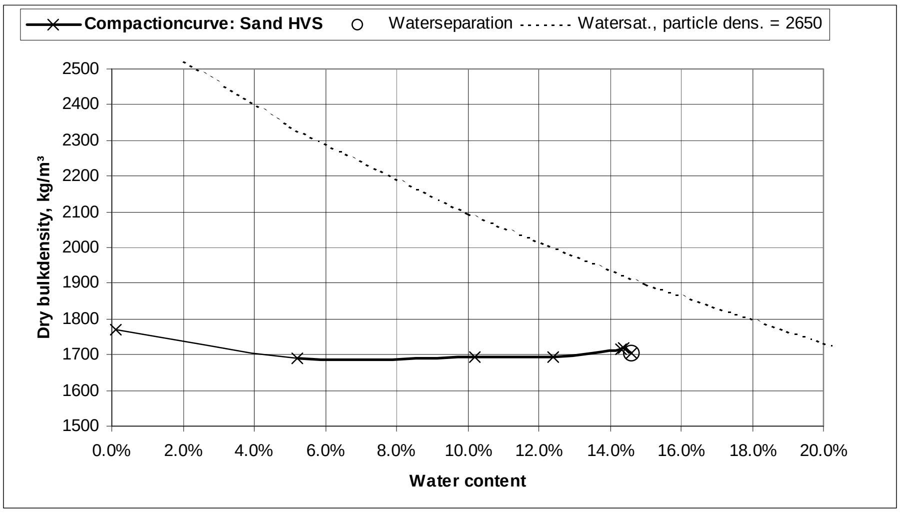


Figure 4 Fine sand subgrade particle size distribution.



Maximum dry density Method: Mod. Proctor VVMB 36:1977	1718 kg/m³
Optimum water content Method: Mod. Proctor VVMB 36:1977	14,4 %

Figure 5 Fine sand subgrade modified Proctor compaction curve.

Table 2 Properties of fine sand subgrade SE05.

Property	Natural granular material (Olivehult)	Crushed rock aggregate (Skärlunda)
Maximum dry density Method: Modified Proctor	1.718 kg/dm^3	1.718 kg/dm^3
Optimum water content	14.4 %	14.4 %
Isotopic measure: Wet density (average)	1.813 kg/dm^3	1.812 kg/dm^3
Oven dry water content (average)	6.2 %	5.3 %
Dry density	1.706 kg/dm^3	1.720 kg/dm^3
Degree of compaction	99.3 %	100.1 %
Static plate loading test. E_{v1} Method: DIN18134.	35.9 MPa	35.0 MPa
Static plate loading test. E_{v2} Method: DIN18134.	98.6 MPa	97.0 MPa
Static plate loading test. E_{v2}/E_{v1} Method: DIN18134.	2.75	2.80

3.1.4 Characteristics and properties of the base layers

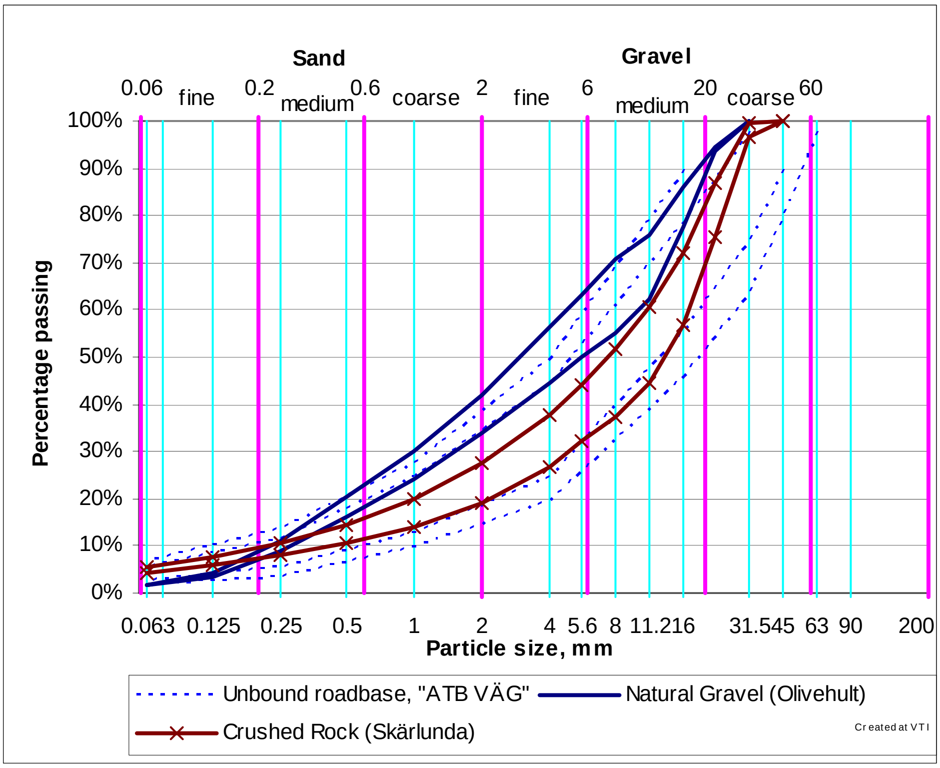


Figure 6 Base layer particle size distribution, maximum and minimum particle size distribution for each base layer material.

Table 3 Properties of the SE05 unbound base layers.

Property	Natural gravel material (Olivehult)	Crushed rock aggregate (Skärlunda)
Maximum dry density Method: Modified Proctor	2.182 kg/dm^3	2.168 kg/dm^3
Optimum water content	3.7 %	4.7 %
Isotopic measure: Wet density (average)	2.229 kg/dm^3	2.183 kg/dm^3
Oven dry water content (average)	2.4 %	2.7 %
Dry density	2.176 kg/dm^3	2.165 kg/dm^3
Degree of compaction	99.7 %	99.8 %
Static plate loading test. E_{v1} Method: DIN18134.	65.4 MPa	60.5 MPa
Static plate loading test. E_{v2} Method: DIN18134.	190.3 MPa	185.4 MPa
Static plate loading test. E_{v2}/E_{v1} Method: DIN18134.	2.95	3.32

Falling weight deflectometer (FWD) measurements were carried out on the surface of the unbound base layers before test SE05 at reduced load (30 kN).

This was done at 6 positions on each structure: three positions 0.5 m to the left and three positions 0.5 m to the right of the HVS loading centre line.

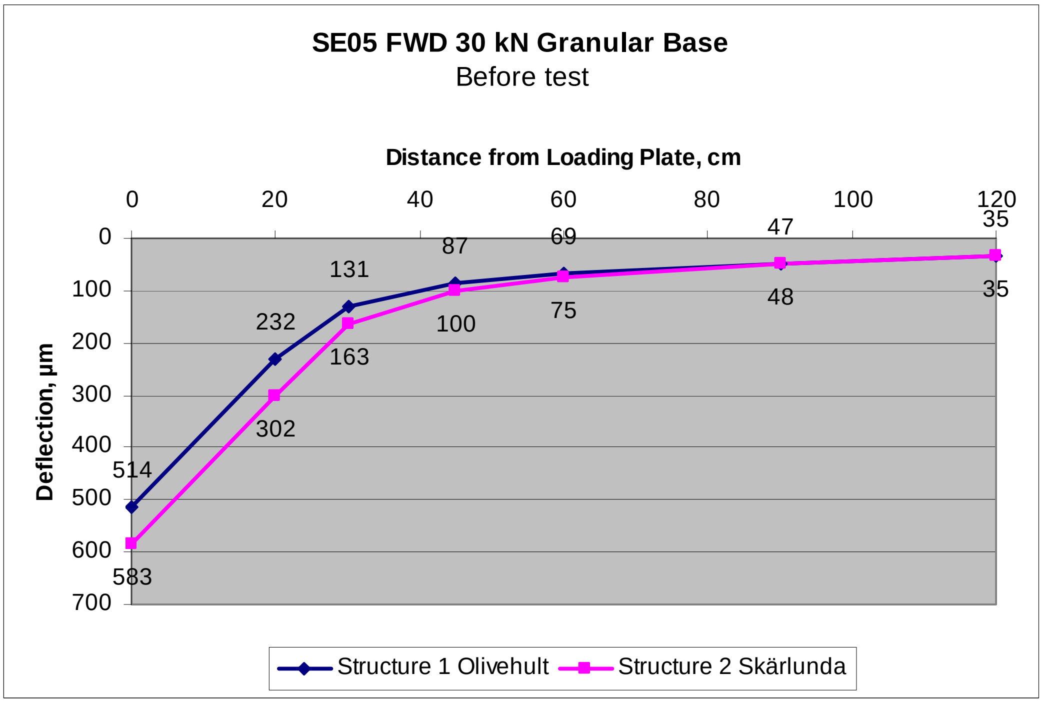


Figure 7 FWD deflections on the surface of the unbound base layers. The deflections shown are mean values from 6 loading positions.

3.1.5 Characteristics and properties of the surface layer

The surface layer was dense graded asphalt concrete, ABT16, according to the Swedish specifications.

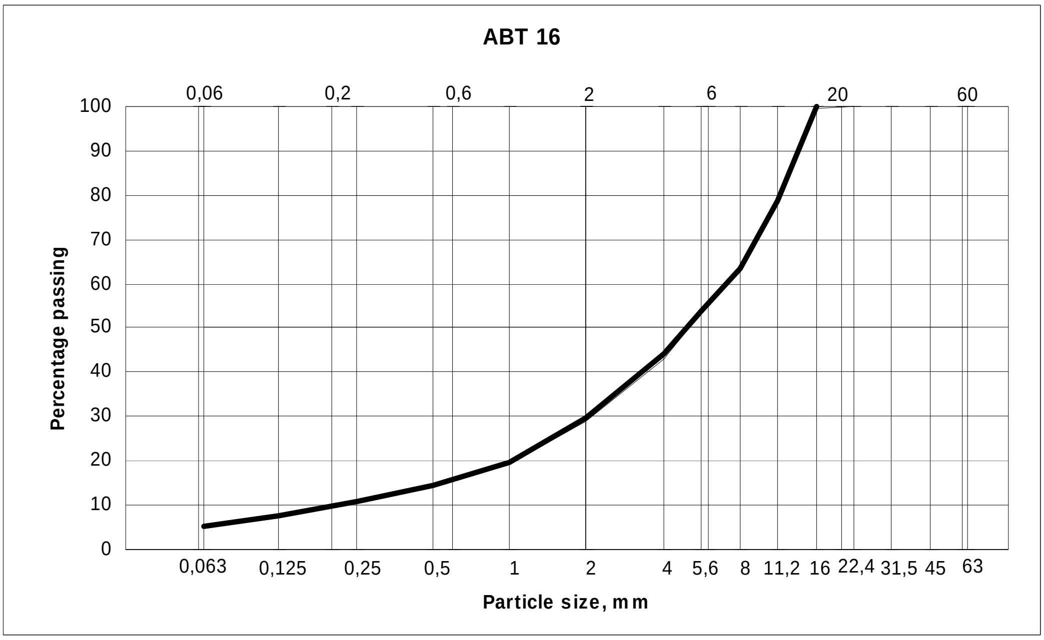


Figure 8 Particle size distribution of dense graded asphalt concrete. ABT16.

Core samples both from the loaded and unloaded area were analysed to determine the properties of the surface layer.

Table 4 Properties of the SE05 asphalt concrete surface layer from core samples after the test.

Property	SE05 asphalt concrete surface layer			
	Natural granular material (Olivehult)		Crushed rock aggregate (Skärlunda)	
	Test area	Outside test area	Test area	Outside test area
Binder content (percent weight of total)	5.8	5.9	6.1	6.0
Softening point: Ring & Ball Penetration. 25°C	50.3°C 62 (0.1mm)			
Void content, %	5.5	6.4	4.4	4.1
Bulk density, g/cm³	2.361	2.340	2.372	2.387
Density, g/cm³	2.497	2.499	2.480	2.488
E-modulus. MPa Indirect tensile test, +10°C	6,938	6,414	6,351	6,663

FWD test was carried out on pavement surface both before and after the HVS test.

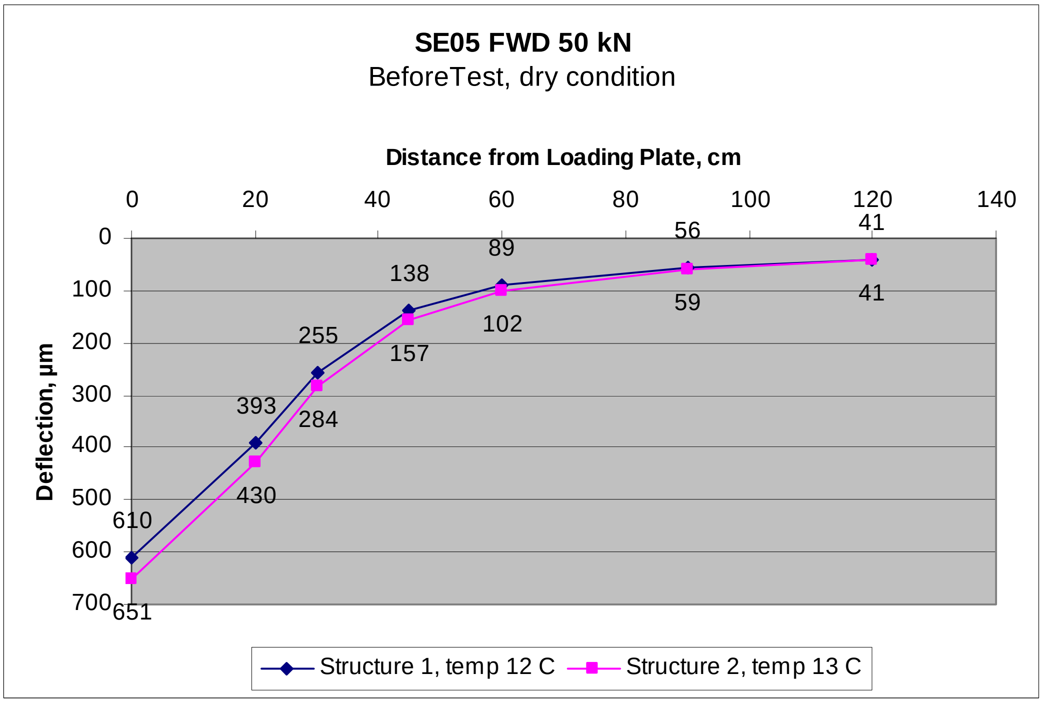


Figure 9 FWD deflections on the pavement surface before test in dry condition, i.e. no ground water table in the subgrade. The deflections shown are mean values from 3 loading positions in the HVS loading centre line.

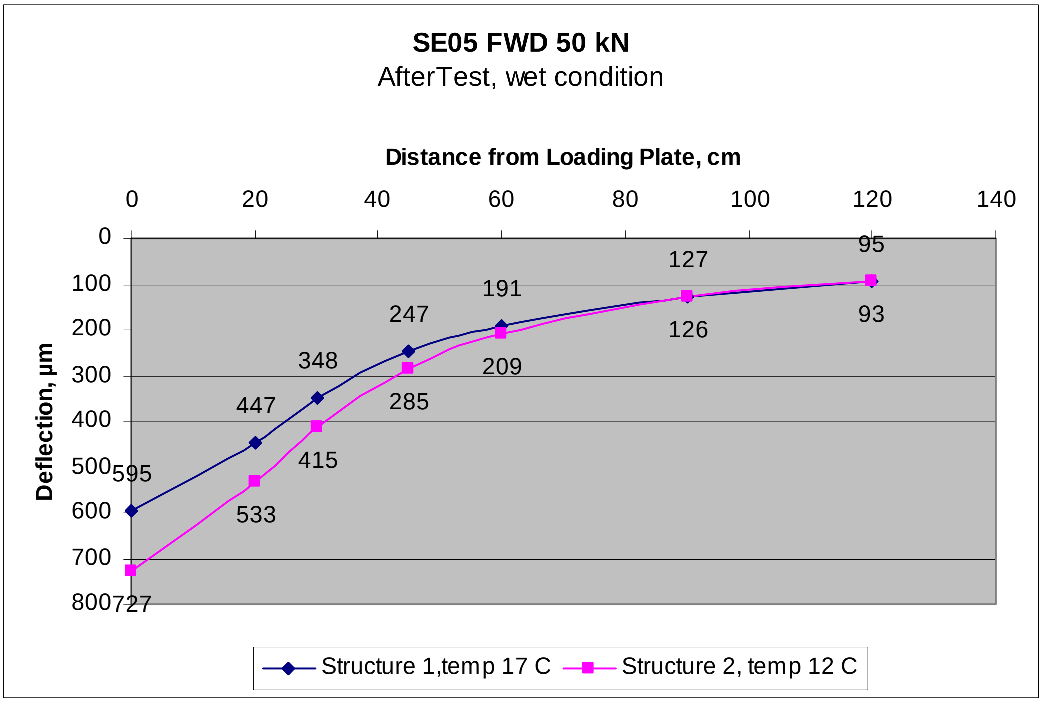


Figure 10 FWD deflections on the pavement surface after test in wet condition, i.e. a ground water table at 30–40 cm below the surface of the subgrade. The deflections shown are mean values from 3 loading positions in the HVS loading centre line.

3.2 Test structure SE06

3.2.1 Layer thickness

The thickness of the subgrade was 2.5 m on a rigid bottom (cement concrete).

The pavement layer thicknesses in the test structure are given below.

Table 5 Pavement layer mean thickness in SE06 centre line.

Layer	Planned thickness	Actual thickness
Asphalt concrete	40 mm	48 mm
Bituminous Base	60 mm	53 mm
Unbound Base	110 mm	108 mm
Unbound Sub-base	130 mm	142 mm
Total thickness	340 mm	351 mm

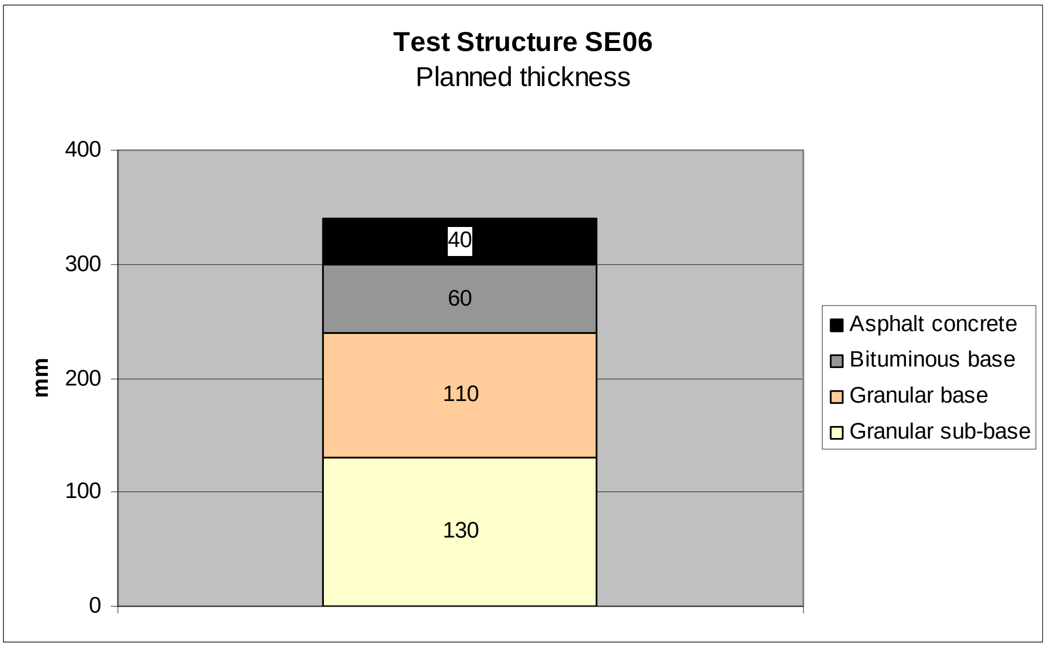


Figure 11 Planned thickness of test structure in SE06.

3.2.2 Instrumentation

Sensors were installed in the structure during construction to be used in the response measuring programme.

Most of the sensors were located in the centre line of the loaded area (6x1 m). The following sensors were used in the test SE06:

- H-shaped asphalt strain gauges from Dynatest (ASG)
- Soil pressure cells from the University of Nottingham (SPC)
- LVDTs for vertical deflection and deformation
- Inductive coils (εMU) for vertical deformation and strain (static and dynamic)
- Temperature gauges.

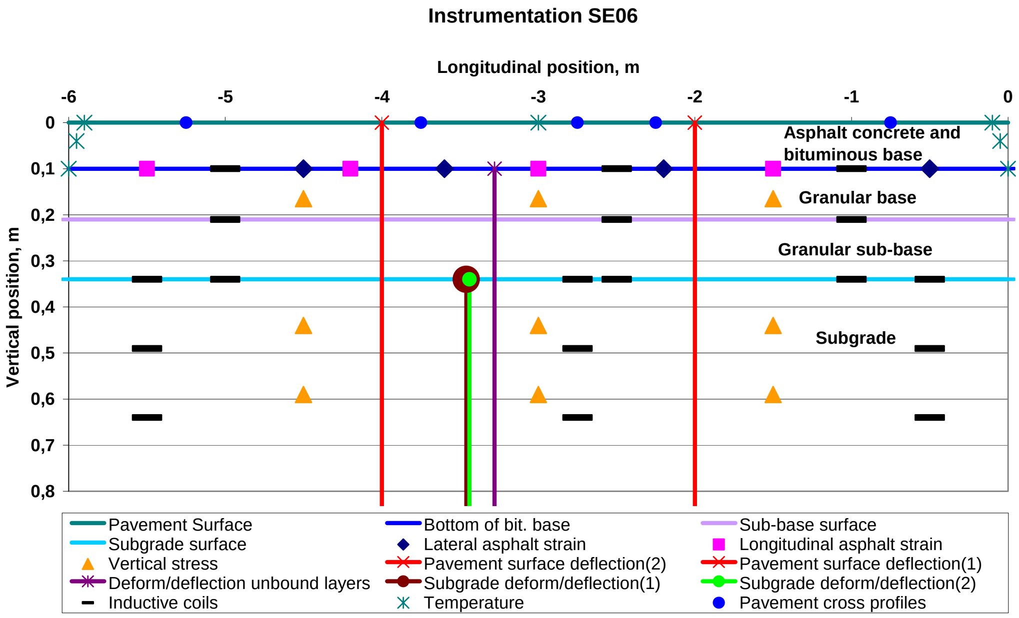


Figure 12 Longitudinal cross section of SE06 instrumentation.

3.2.3 Characteristics and properties of the fine sand subgrade

Both test structure SE05 and SE06 were constructed on the same fine sand subgrade as the previous tests at the VTI test facility.

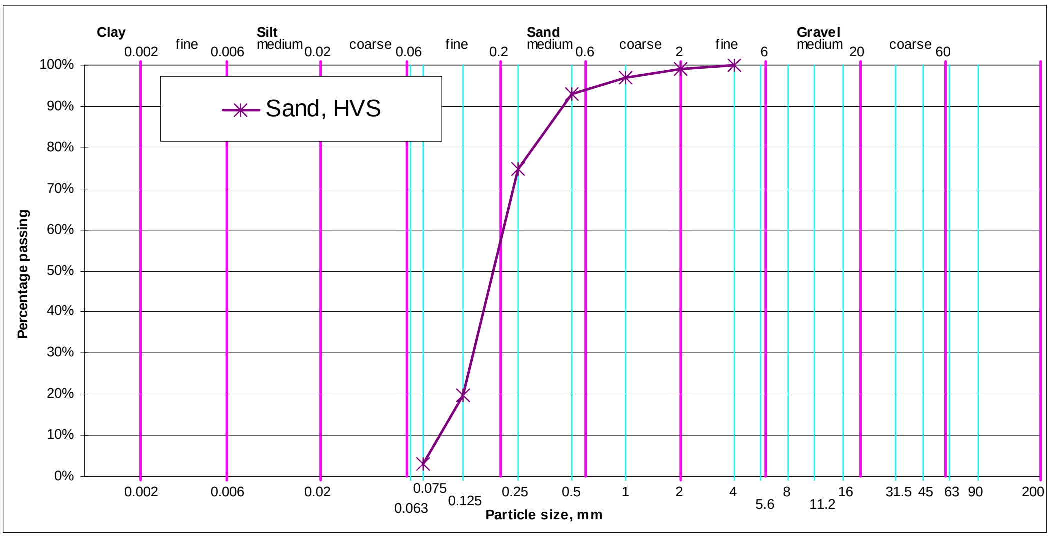
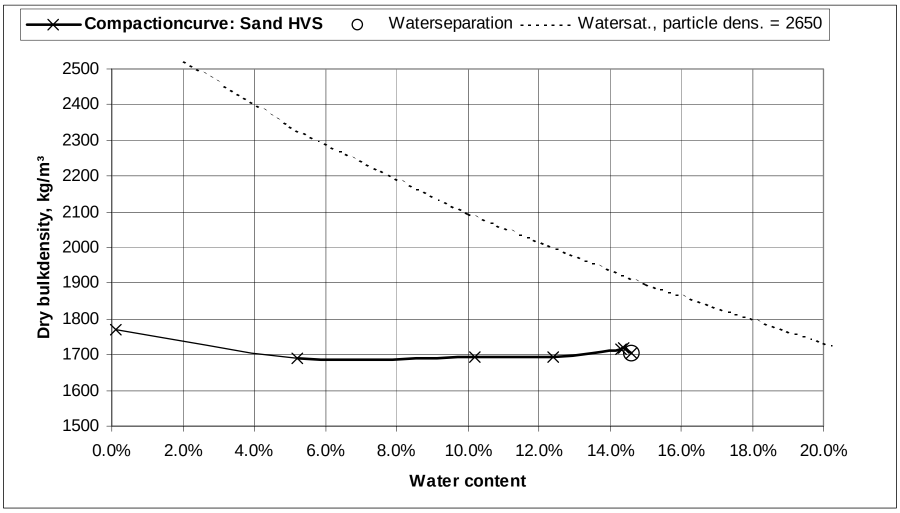


Figure 13 Fine sand subgrade particle size distribution.



Maximum dry density Method: Mod. Proctor VVMB 36:1977	1718 kg/m³
Optimum water content Method: Mod. Proctor VVMB 36:1977	14,4 %

Figure 14 Fine sand subgrade modified Proctor compaction curve.

Table 6 Properties of fine sand subgrade SE06.

Property	Fine sand subgrade
Maximum dry density Method: Modified Proctor	1.718 kg/dm^3
Optimum water content	14.4 %
Isotopic measure: Dry density (average)	1.742 kg/dm^3
Isotopic measure: Water content (average)	9.9 %
Degree of compaction	101.4 %
Static plate loading test. E_{v1} Method: DIN18134	36.1 MPa
Static plate loading test. E_{v2} Method: DIN18134	107.4 MPa
Static plate loading test. E_{v2}/E_{v1} Method: DIN18134	3.04

3.2.4 Characteristics and properties of the SE06 sub-base layer

The material in the sub-base layer was natural gravel and the same as in the previous test, SE02.

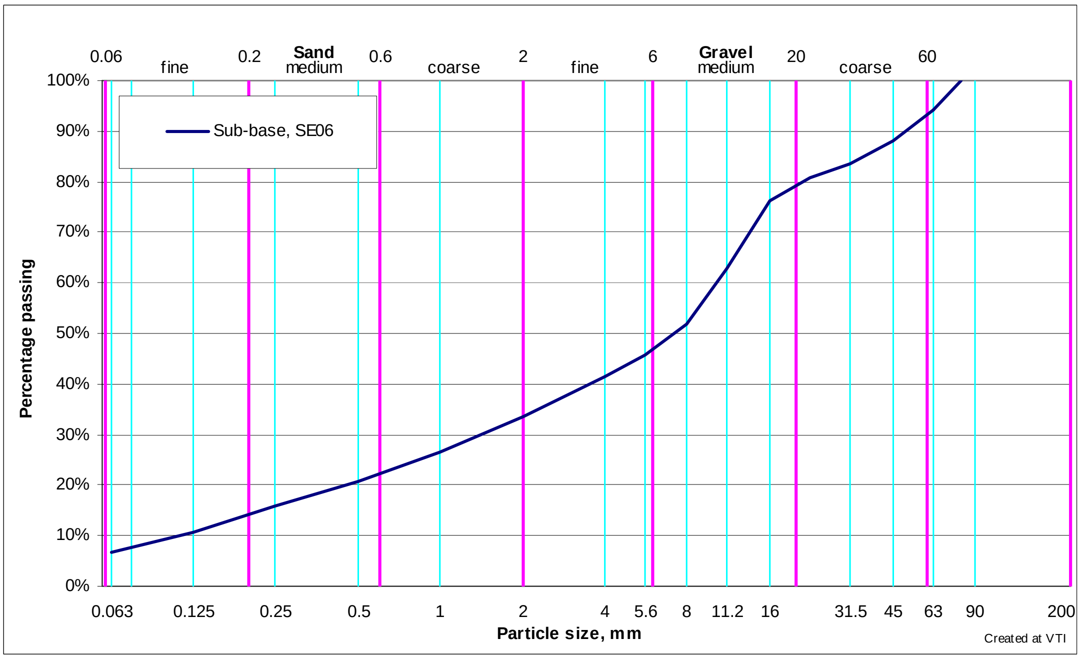


Figure 15 Particle size distribution for the SE06 granular sub-base material.

Table 7 Properties of the SE06 granular sub-base.

Maximum dry density Method: Vibrating table	2.380 kg/dm^3
Isotopic measure: Wet density (average)	2.441 kg/dm^3
Oven dry water content (average)	4.5 %
Dry density	2.335 kg/dm^3
Degree of compaction	98.1 %

3.2.5 Characteristics and properties of the SE06 base layer

The base layer material was a natural moraine mixed with crushed material and the same as in the previous tests, SE01 and SE02.

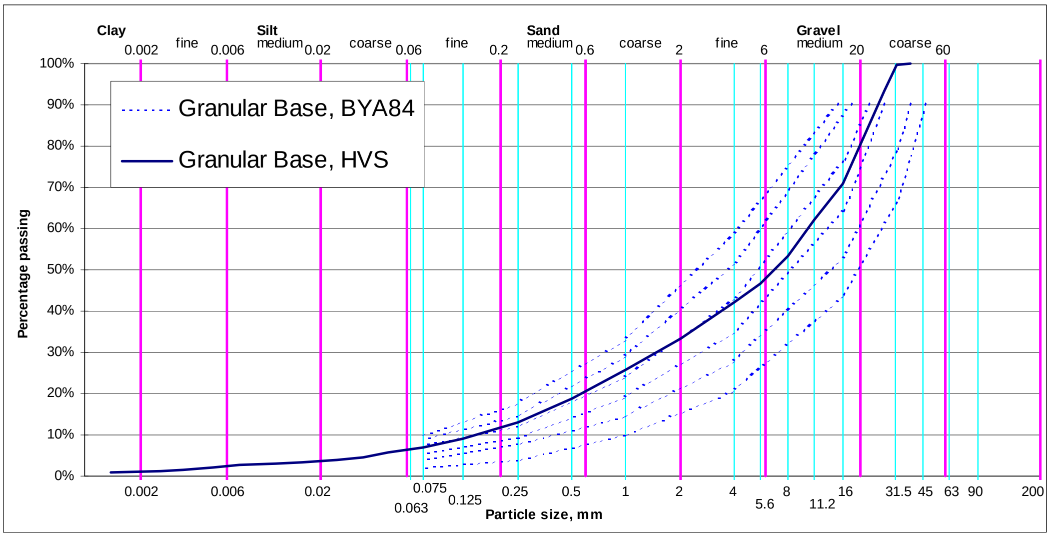


Figure 16 Particle size distribution for the SE06 granular base material.

Table 8 Properties of the SE06 granular base layer.

Maximum dry density Method: Modified Proctor	2.354 kg/dm^3
Optimum water content	4.5 %
Isotopic measure: Wet density (average)	2.305 kg/dm^3
Oven dry water content (average)	2.2 %
Dry density	2.255 kg/dm^3
Degree of compaction	95.8 %
Static plate loading test. E_{v1} Method: DIN18134	77.6 MPa
Static plate loading test. E_{v2} Method: DIN18134	190.5 MPa
Static plate loading test. E_{v2}/E_{v1} Method: DIN18134	2.51

Falling weight deflectometer (FWD) measurements was carried out on the surface of the unbound base layer before test SE06 at reduced load (30 kN).

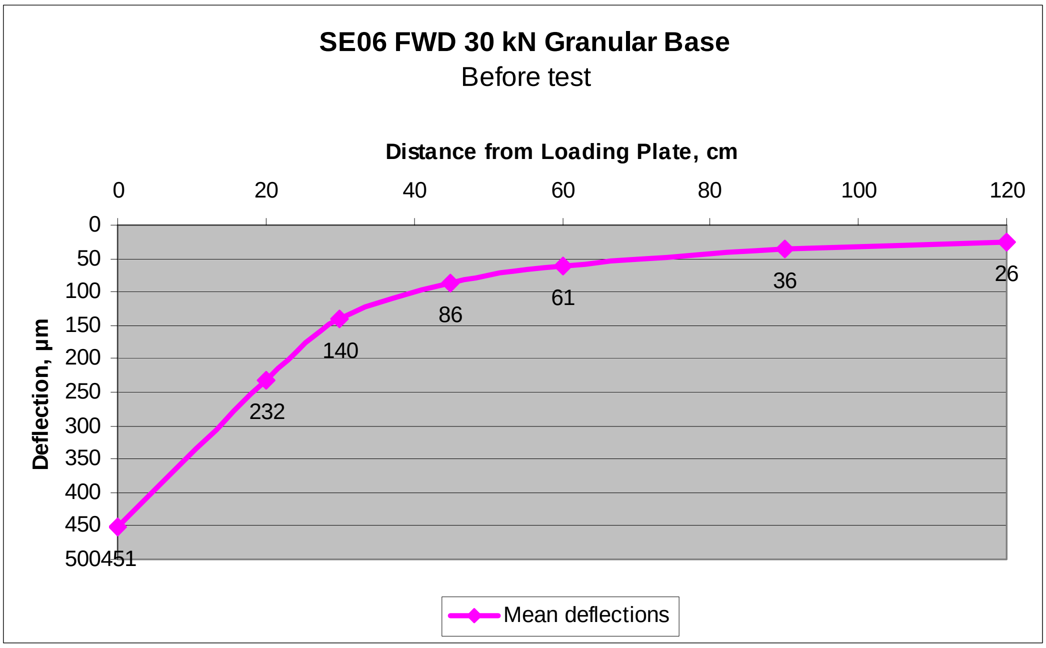


Figure 17 FWD test on surface of granular base layer before test SE06. The deflections shown are mean deflections from seven positions 0.5 m to the right and seven positions 0.5 m to the left of the HVS loading centre line.

3.2.6 Characteristics and properties of the bituminous bound base layer

The bound base layer was a bituminous bound crushed rock aggregate, AG22 according to Swedish specifications.

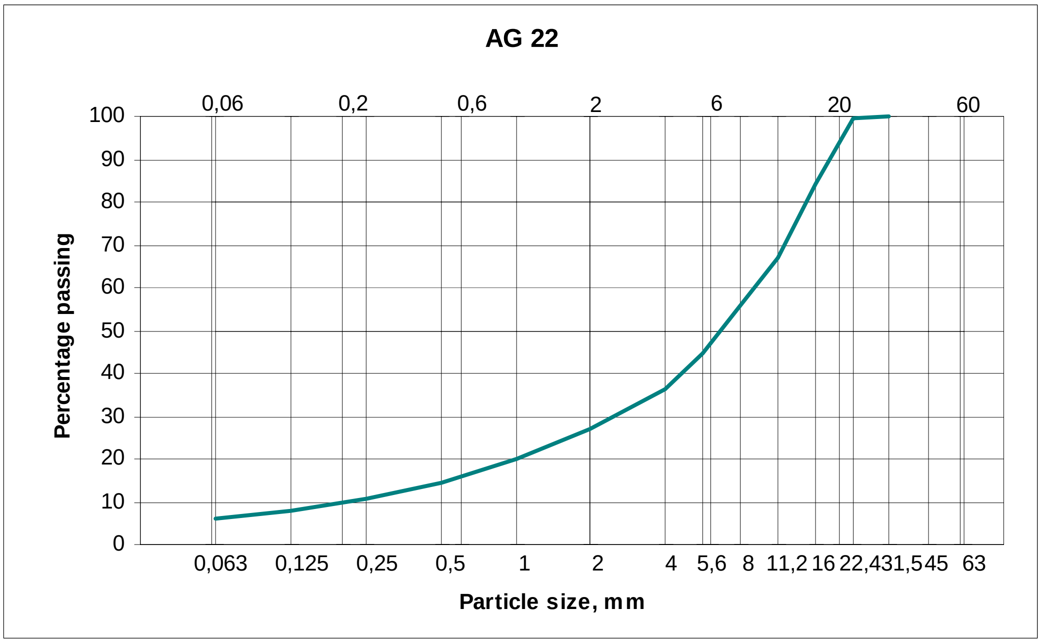


Figure 18 Particle size distribution of the bituminous bound base layer. AG22.

Core samples both from the test area and outside the test area were analysed to determine the properties of the asphalt layers.

Table 9 Properties of the SE06 bituminous base layer from core samples after the test.

Property	SE06 bituminous base layer	
	Test area	Outside test area
Binder content (percent weight of total)	4.10	
Softening point: Ring & Ball Penetration. 25°C	50.1 (°C) 67 (0.1 mm)	
Void content, %	7.5	7.8
Bulk Density, g/cm^3	2.362	2.358
Density, g/cm^3	2.552	2.557
E-modulus, MPa Indirect tensile test, +10°C	6,725	7,182

3.2.7 Characteristics and properties of the surface layer

The surface layer was dense graded asphalt concrete, ABT16 according to Swedish specifications.

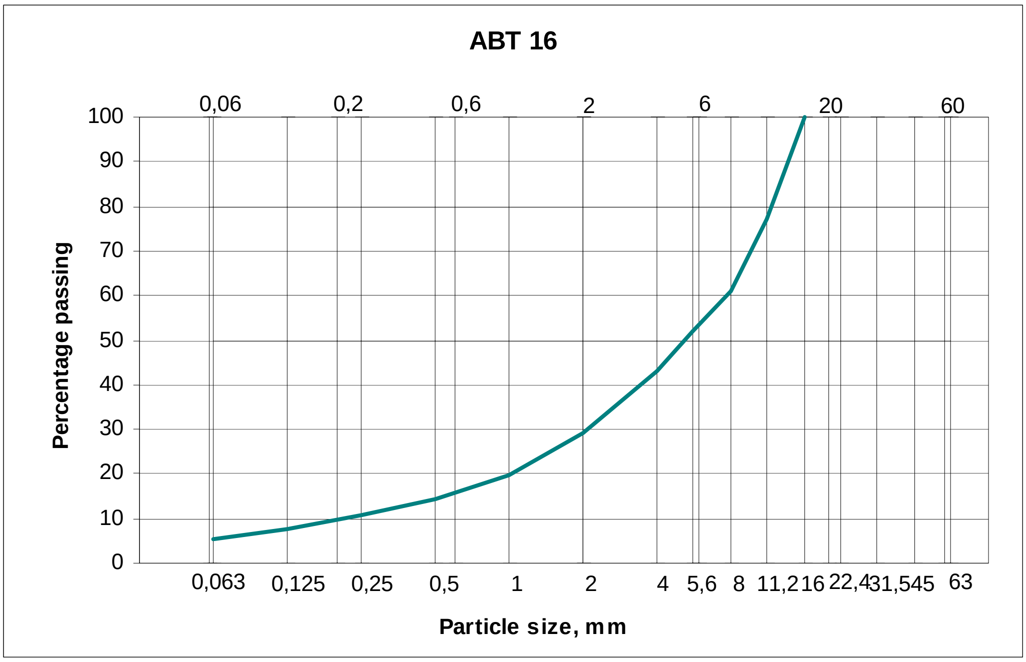


Figure 19 Particle size distribution of dense graded asphalt concrete. ABT16.

Table 10 Properties of the SE06 asphalt concrete surface layer from core samples after the test.

Property	SE06 asphalt concrete surface layer	
	Test area	Outside test area
Binder content (percent weight of total)	6.04	
Softening point: Ring & Ball Penetration. 25°C	50.6 (°C) 56 (0.1 mm)	
Void content, %	3.8	3.8
Bulk Density, g/cm^3	2.409	2.404
Density,. g/cm^3	2.505	2.498
E-modulus. MPa Indirect tensile test, +10°C	7,450	7,756

FWD tests were carried out on the pavement surface before the HVS test, when it was resumed, and on its conclusion.

The SE06 test was interrupted for 10 months due to other tests outside the VTI facility (as mentioned in the introduction).

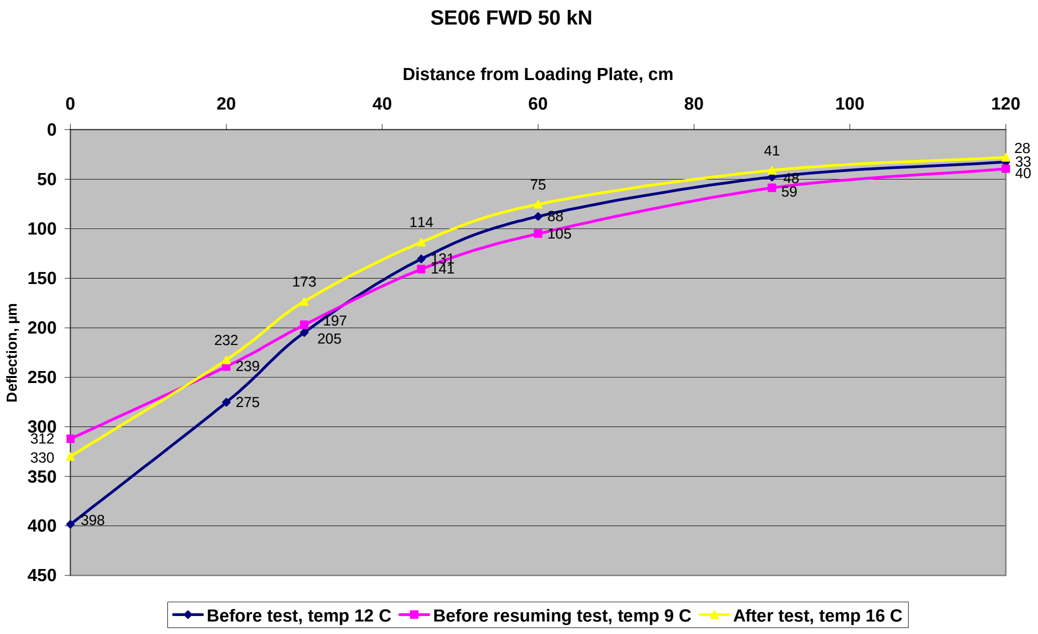


Figure 20 FWD test on pavement surface before test SE06 began, between the test periods, and after the test. The deflections shown are mean deflections from seven positions in the HVS loading centre line.

4 Accelerated load testing

Details about the HVS-machine and the full scale pavement test facility at VTI can be found in Appendix B.

4.1 General test procedure

Before the accelerated loading test, a pre-loading and a comprehensive response measurement programme were performed.

The pre-loading was done in order to relieve possible residual stresses and cause some post-compaction. This was done by 20,000 passes during one day with a lower wheel load (30 kN single wheel load) with an even lateral distribution. The size of the single wheel was 425/65R22.5.

The response measurement programme embraced considerable measurement of stresses, strains, and deflections at different positions in the test structures and at different test-loads, lateral positions, speeds, and temperatures, and with different test-wheels and tyre pressures.

After the response measurement programme, the accelerated loading test was begun. Normal running was day and night five days a week with interruptions only for daily service of the machine, which means about 22,000 loadings per day including both directions. The following standard set of test parameters was used in the main tests:

- Dual wheel load 60 kN
- Tyre pressure 800 kPa
- Wheel size 295/80R22.5
- Wheel speed 12 km/h
- Bidirectional loading
- Pavement temperature +10 °C
- Lateral distribution.

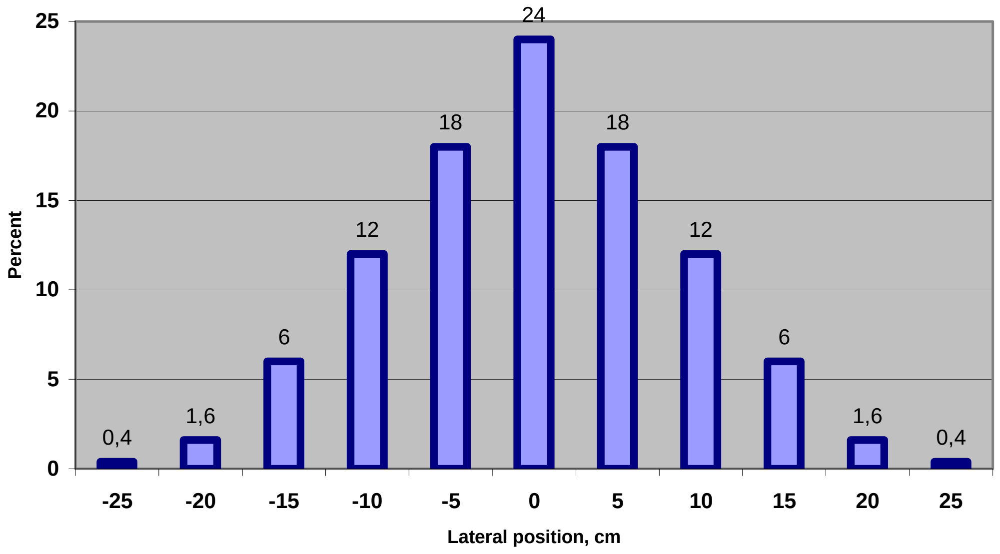


Figure 21 Lateral distribution used in main test with dual wheel load.

Pavement performance has been studied by visual inspections and measurements of cross profiles at fixed locations on the test structures for rut depth calculations.

All collected data will be stored in a common Finnish-Swedish database with information on test sites, pavement structures, sensors, materials, and response and performance measurement results.

4.2 SE05 test procedure

After pre-loading and the response measurement programme, the accelerated loading test, SE05, was begun on February 4, 2003. The test was divided into two phases: the first in dry condition and the second in wet condition. When the test began, there was no water standing in the subgrade but after about 350,000 loadings, the test was stopped and the subgrade and structure were filled with water. The water level was raised to the top of the pavement and then lowered to 30–40 cm below the subgrade surface.

4.2.1 Pre-loading

Before the response measuring programme and the main test in dry condition, the test structure was pre-loaded by 20,000 passes of a 30 kN/700 kPa single wheel load at 10°C pavement temperature and with an even lateral distribution.

Before beginning the main test in wet condition, a reduced pre-loading was done by 2,000 dual wheel load passes of 30 kN/500 kPa evenly distributed laterally.

4.2.2 Response measurements

The response from the different sensors in the test structure, (see instrumentation above), were measured for different sets of test parameters before the main test in dry condition began. The extensive response measuring programme can be seen in Table 11 below. A reduced response measuring program with only dual wheel load was carried out before the main test in wet condition started. Response measurements were also performed during the main test with load index P16 in dry condition and load index P45 in wet condition almost once a week.

Table 11 Response measuring programme SE05. Index S1–P36 in dry condition and index P38–57 in wet condition.

	Single wheel						
Index	Tire pressure	Load	Speed	Lateral position (cm)*			Pavement
	(kPa)	(kN)	(km/h)	0	-15	distribution	temp. (^{o}C)
S1	500	30	12	x			+10
S2	500	50	12	x			+10
S3	500	80	12	x			+10
S4	500	60	12			x	+10
S9	800	30	12	x			+10
S10	800	50	12	x			+10
S11	800	80	12	x			+10
S12	800	60	2	x			+10
S13	800	60	4	x			+10
S14	800	60	8	x			+10
S15	800	60	12	x			+10
S16	800	60	12			x	+10
S17	900	30	12	x			+10
S18	900	50	12	x			+10
S19	900	80	12	x			+10
S20	900	60	12			x	+10

	Dual wheel						
Index	Tire pressure	Load	Speed	Lateral position (cm)*			Pavement
	(kPa)	(kN)	(km/h)	0	-15	distribution	temp. (^{o}C)
P1	500	30	12	x	x		+10
P2	500	50	12	x	x		+10
P3	500	80	12	x	x		+10
P4	500	60	12			x	+10
P9	800	30	12	x	x		+10
P10	800	50	12	x	x		+10
P11	800	80	12	x	x		+10
P12	800	60	12			x	+10
P13	800	60	2	x	x		+10
P14	800	60	4	x	x		+10
P15	800	60	8	x	x		+10
P16	800	60	12	x	x		+10

Table 11 Continued.

	Dual wheel						
Index	Tire pressure (kPa)	Load (kN)	Speed (km/h)	Lateral position (cm)*			Pavement temp. (°C)
				0	-15	distribution	
P17	900	30	12	x	x		+10
P18	900	50	12	x	x		+10
P19	900	80	12	x	x		+10
P20	900	60	12			x	+10
P21	800	30	12	x	x		+0
P22	800	50	12	x	x		+0
P23	800	80	12	x	x		+0
P24	800	60	12			x	+0
P33	800	30	12	x	x		+20
P34	800	50	12	x	x		+20
P35	800	80	12	x	x		+20
P36	800	60	12			x	+20
Wet condition							
P46	500	30	12	x	x		+10
P47	500	50	12	x	x		+10
P48	500	80	12	x	x		+10
P38	800	30	12	x	x		+10
P39	800	50	12	x	x		+10
P40	800	80	12	x	x		+10
P41	800	60	12			x	+10
P45	800	60	12	x	x		+10
P54	900	30	12	x	x		+10
P55	900	50	12	x	x		+10
P56	900	80	12	x	x		+10
P57	900	60	12			x	+10
*)Lateral position:		0 = Centre line					
		Single wheel lateral disribution: from -35 to +35 cm in steps of 5 cm					
		Dual wheel lateral distribution: from -25 to +25 cm in steps of 5 cm					

4.2.3 Performance measurements

During the main test, surface cross profiles were measured at three fixed longitudinal locations on each structure. From these cross profiles, rut depths were calculated as the vertical maximum difference from the first measured profiles. Preliminary results from these measurements (mean rut depths on each structure) were reported during the test by e-mail to people with an interest in the test. These reports were sent on a weekly basis and called “HVS Nordic Weekly Report”. The final weekly report from SE05 can be seen below.

Table 12 Final weekly report from SE05.

HVS Nordic weekly report							
Test SE05			**Test structure**				
			Layer 1	40 mm	Asphalt concrete, (AB16T/B85)		
			Layer 2	450 mm	Granular base, natural gravel and crushed aggregate		
Main Test Parameters			Layer 3	2500 mm	Fine sand subgrade		
Speed:	12 km/h			Rigid bottom	Cement concrete		
Temperature:	10 C						
Tyre:	Dual tyre						
Tyre pressure:	800 kPa		**Objective**				
Wheel load	60 kN		To compare two different unbound base layer materials				
Load direction	Both		Half of the testarea has a natural gravel base layer and the other half a crushed aggregate base layer				
Date	**Load repetitions**	**Mean Rut depth** Natural gravel mm	**Mean Rut depth** Crushed aggregate mm	**Wheel load** kN	**Cracking** Natural nr / length	Crushed	**Remarks**
2003-01-23	0	0,0	0,0	30(Single)			Preloading started
2003-01-24	20000	3,3	3,0	30			Preloading finished
2003-02-03	26740	4,5	5,0	30, 50, 60, 80			Response finished
2003-02-04	26740	4,5	5,0	60 (Dual)			Main Test started, dry condition
2003-02-05	46850	5,4	6,0				
2003-02-06	70486	6,0	6,8				
2003-02-07	93580	6,5	7,4				
2003-02-10	135000	7,0	8,1				
2003-02-11	153178	7,3	8,0				
2003-02-12	171240	7,5	8,6				
2003-02-14	217800	7,9	9,0				
2003-02-16	261526	8,2	9,7				
2003-02-17	282450	8,6	9,7				
2003-02-19	303816	8,7	10,1				
2003-02-21	347630	9,2	10,6				Test in dry condition stopped
2003-02-21	#SAKNAS!	#SAKNAS!	#SAKNAS!				Filling water in subgrade started
2003-02-24	#SAKNAS!	#SAKNAS!	#SAKNAS!				Upgrading of HVS software/Hardware
2003-02-28	#SAKNAS!	#SAKNAS!	#SAKNAS!				**GWL at pavement surface**
2003-03-11	#SAKNAS!	#SAKNAS!	#SAKNAS!				Upgrading interrupted
2003-03-05	#SAKNAS!	#SAKNAS!	#SAKNAS!				**GWL at -30 cm in subgrade**
2003-03-12	347630	9,0	10,2	30 (Dual)			Preloading started
2003-03-12	349395	8,8	10,7	30 (Dual)			Preloading stopped
2003-03-13	349395	#SAKNAS!	#SAKNAS!	30, 50, 60, 80			Response meas. GWL -40 cm
2003-03-17	361992	9,4	10,9				Response meas. Stopped
2003-03-17	361992	#SAKNAS!	#SAKNAS!	60 (Dual)			Main test restarted, wet condition
2003-03-19	381134	9,5	12,1				GWL at -40 cm
2003-03-22	415908	10,0	13,6				
2003-03-26	458000	10,2	14,6				
2003-03-27	483221	10,6	15,1				
2003-03-28	503959	11,0	15,9				
2003-03-31	532720	11,3	16,3				
2003-04-02	573030	11,8	17,1				
2003-04-04	613447	12,0	17,6				Main test in wet condition stopped

4.3 SE06 Test procedure

The SE06 test was started in dry condition on April 17, 2003.

After about 205,000 load repetitions, the test was stopped for 10 months due to other tests outside VTI at two sites in rural areas in Sweden. The test was then resumed on March 15, 2004 and after a total of about 530,000 load repetitions, water was added to the subgrade.

The water level was this time raised to 30 cm below the subgrade surface, not to the top of the pavement and back as in the previous test, SE05.

4.3.1 Pre-loading

Before the response measuring programme and the main test in dry condition, the test structure was pre-loaded by 20,000 passes of a 30 kN/700 kPa single wheel load, evenly distributed laterally, at 10°C pavement temperature.

No pre-loading was done before beginning the main test in wet condition.

4.3.2 Response measurements

The response from the different sensors in the test structure, (see instrumentation above), were measured for different sets of test parameters before the main test in dry condition started.

The extensive response measuring programme can be seen in Table 13 below. A reduced response measuring programme with only dual wheel load was carried out before the main test in wet condition started. Response measurements were also performed during the main test with load index P16 in dry condition and load index P45 in wet condition almost once a week.

At the end of test SE06, response measurements were carried out with load index P38–P41 and P45.

Table 13 Response measuring programme SE06. Index S1–P36 in dry condition and index P38–45 in wet condition.

	Single wheel						
Index	Tire pressure (kPa)	Load (kN)	Speed (km/h)	Lateral position (cm)*			Pavement temp. (^{o}C)
				0	-15	distribution	
S1	500	30	12	x			+10
S2	500	50	12	x			+10
S3	500	80	12	x			+10
S4	500	60	12			x	+10
S9	800	30	12	x			+10
S10	800	50	12	x			+10
S11	800	80	12	x			+10
S15	800	60	12	x			+10
S16	800	60	12			x	+10
S17	900	30	12	x			+10
S18	900	50	12	x			+10
S19	900	80	12	x			+10
S20	900	60	12			x	+10

	Dual wheel						
Index	Tire pressure (kPa)	Load (kN)	Speed (km/h)	Lateral position (cm)*			Pavement temp. (^{o}C)
				0	-15	distribution	
P1	500	30	12	x	x		+10
P2	500	50	12	x	x		+10
P3	500	80	12	x	x		+10
P4	500	60	12			x	+10
P9	800	30	12	x	x		+10
P10	800	50	12	x	x		+10
P11	800	80	12	x	x		+10
P12	800	60	12			x	+10
P13	800	60	2	x	x		+10
P14	800	60	4	x	x		+10
P15	800	60	8	x	x		+10
P16	800	60	12	x	x		+10

Table 13 *Continued.*

	Dual wheel						
Index	Tire pressure	Load	Speed	Lateral position (cm)*			Pavement
	(kPa)	(kN)	(km/h)	0	-15	distribution	temp. (^{o}C)
P17	900	30	12	x	x		+10
P18	900	50	12	x	x		+10
P19	900	80	12	x	x		+10
P20	900	60	12			x	+10
P21	800	30	12	x	x		+0
P22	800	50	12	x	x		+0
P23	800	80	12	x	x		+0
P24	800	60	12			x	+0
P33	800	30	12	x	x		+20
P34	800	50	12	x	x		+20
P35	800	80	12	x	x		+20
P36	800	60	12			x	+20
Wet condition							
P38	800	30	12	x	x		+10
P39	800	50	12	x	x		+10
P40	800	80	12	x	x		+10
P41	800	60	12			x	+10
P42	800	60	2	x	x		+10
P43	800	60	4	x	x		+10
P44	800	60	8	x	x		+10
P45	800	60	12	x	x		+10
*)Lateral position:		0 = Centre line					
		Single wheel lateral disribution: from -35 to +35 cm in steps of 5 cm					
		Dual wheel lateral distribution: from -25 to +25 cm in steps of 5 cm					

4.3.3 Performance measurements

During the main test, surface cross profiles were measured at five fixed longitudinal locations. Rut depths were calculated from these cross profiles as the vertical maximum difference from the first measured profiles. Preliminary results from these measurements (mean rut depth) were reported during the test by e-mail to people with interest in the test. These reports were sent on a weekly basis and called “HVS-Nordic Weekly Report”. The final weekly report from SE06 can be seen below.

Table 14 Final weekly report from SE06.

HVS Nordic weekly report					
Test SE06			**Test structure**		
			Layer 1	40 mm	Asphalt concrete, (AB16T, 70/100)
			Layer 2	60 mm	Bituminous base, (AG 22, 160/220)
Main Test Parameters			Layer 3	110 mm	Granular base
Speed:	12 km/h		Layer 4	130 mm	Granular sub-base
Temperature:	10 C		Layer 5	2500 mm	Fine sand subgrade
Tyre:	Dual tyre			Rigid bottom	Cement concrete
Tyre pressure:	800 kPa				
Wheel load	60 kN		**Objective**		
Load direction	Both		This test will be compared with two earlier test (SE01, SE02)		
			in a series with increasing bearing capacity		
Date	**Load repetitions**	**Mean Rut depth**	**Wheel load**	**Cracking**	**Remarks**
		mm	kN	no. / length	
2003-04-17	0	0,0			
2003-04-22	20000	1,3	30 (single)		Pre-loading
2003-05-06	35965	2,8	30,50,60,80		Response Measurements
2003-05-08	73180	3,7	60		Main Test
2003-05-09	95213	3,8	60		
2003-05-12	129341	4,1	60		
2003-05-16	205577	5,0	60		Main Test Temporarily Stopped
2004-03-15	205577	4,8	60		Main Test Resumed
2004-03-16	215900	4,7	60		
2004-03-18	239049	5,0	60		
2004-03-22	259959	4,9	60		
2004-03-26	292225	5,4	60		
2004-03-31	328650	5,5	60		
2004-04-06	365839	5,4	60		
2004-04-15	403385	5,4	60		
2004-04-20	487986	6,0	60		Adding water from bottom started
2004-04-22	530000	#SAKNAS!			Test stopped, adding water continued
2004-04-26	530126	6,0	60		GWL at 30 cm below subgrade surface
2004-04-27	552193	6,6	60		GWL at 30 cm below subgrade surface
2004-04-29	581550	7,3	60		GWL at 30 cm below subgrade surface
2004-05-04	608176	7,8	60		GWL at 30 cm below subgrade surface
2004-05-05	630740	8,8	60		GWL at 30 cm below subgrade surface
2004-05-06	650556	9,2	60		GWL at 30 cm below subgrade surface
2004-05-07	671179	9,3	60		GWL at 30 cm below subgrade surface
2004-05-10	700000	9,8	60		GWL at 30 cm below subgrade surface
2004-05-12	746539	10,8	60		GWL at 30 cm below subgrade surface
2004-05-15	786532	11,1	60		GWL at 30 cm below subgrade surface
2004-05-17	810000	11,5	60		GWL at 30 cm below subgrade surface
2004-05-19	852930	12,0	60		GWL at 30 cm below subgrade surface
2004-05-24	875000	12,4	60		GWL at 30 cm below subgrade surface
2004-05-26	915771	12,8	60		GWL at 30 cm below subgrade surface
2004-05-28	940000	13,0	60		GWL at 30 cm below subgrade surface
2004-06-01	965000	13,3	60		GWL at 30 cm below subgrade surface
2004-06-03	1000000	13,7	60		Test stopped

5 Test results

The results presented in this report are limited to performance data as surface rut depth propagation from cross profile measurements and pavement layer deformations as static values from inductive coil measurements.

The results from the response measurement programmes, such as dynamic stress, strain, and deflection data, will be analysed and reported elsewhere.

5.1 SE05 Performance test result

5.1.1 Surface rut depth

Surface rut depths were calculated from cross profile measurements at three fixed longitudinal positions on each structure. The equipment used was a beam with a moving laser, taking readings every 2 mm over a total length of 2,500 mm.

Rut depth was defined as the maximum difference between the first measured cross profile before the test and the cross profile in question.

As mentioned above, the test started in dry condition and after about 350,000 passes, water was added to the subgrade and the structures. The rest of the test was performed in wet condition with ground water level at 30–40 cm below the subgrade surface.

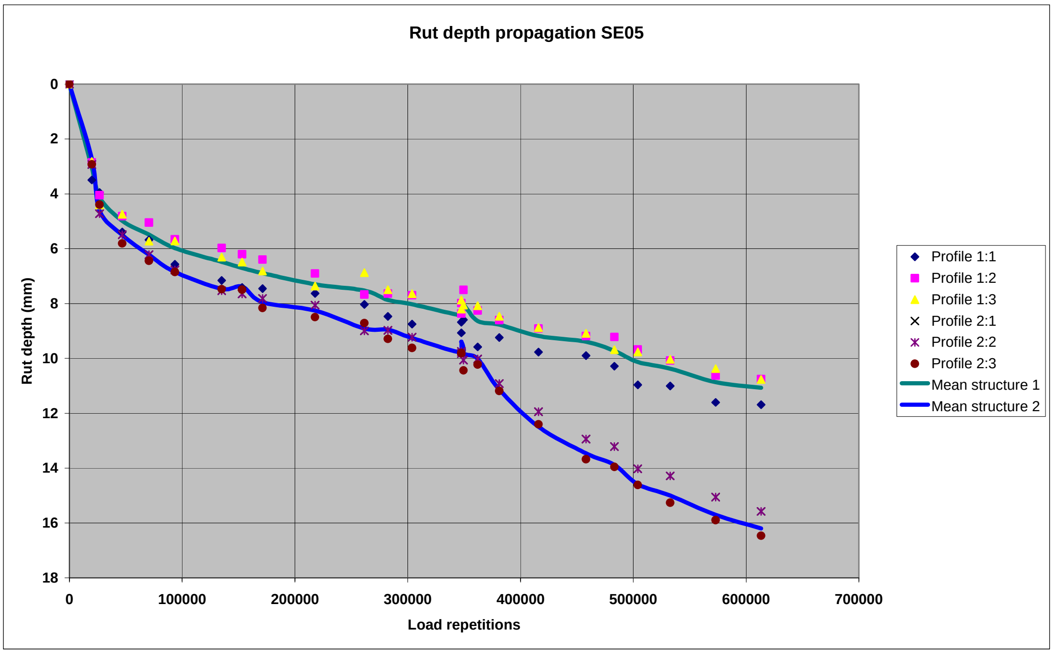


Figure 22 Rut depth propagation in test SE05, structure 1 (Natural granular material) and structure 2 (Crushed rock aggregate).

In the following figures, the results from cross profile measurements are shown as the average of the three cross profiles on each structure before and after the test.

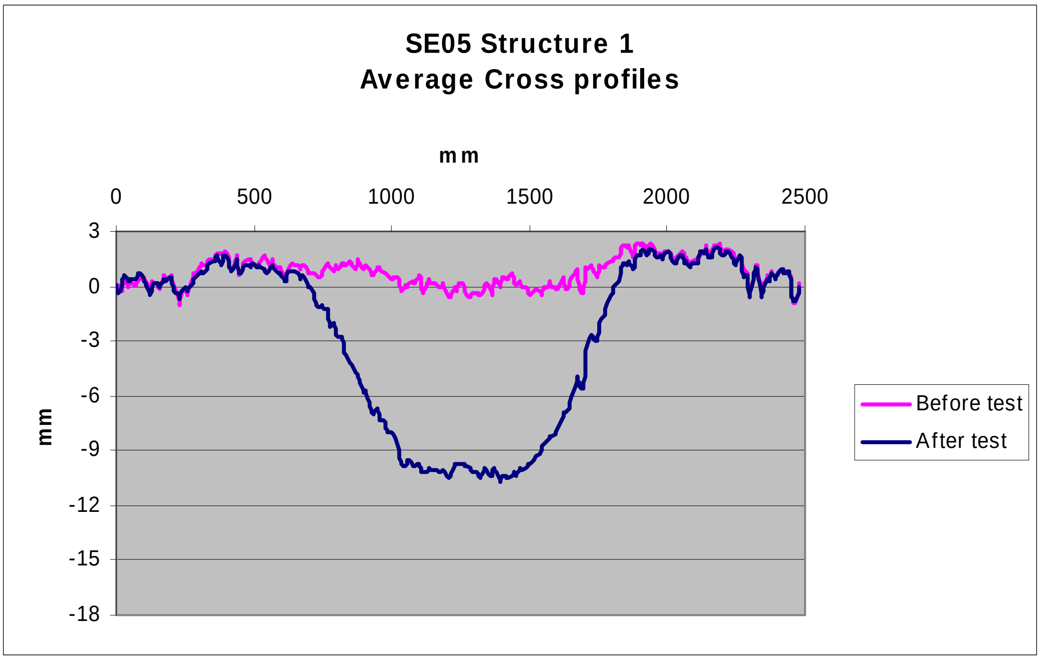


Figure 23 Average cross profile before and after test of Structure 1. The profiles are the averages from cross profile measurements at three fixed longitudinal positions.

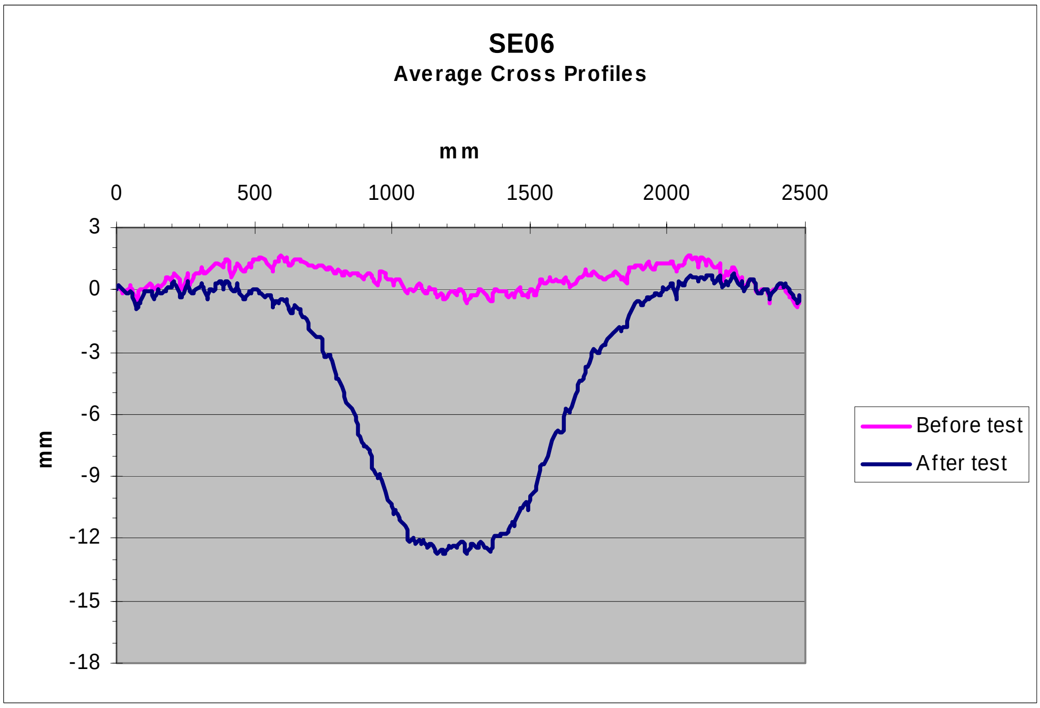


Figure 24 Average cross profile before and after test of Structure 2. The profiles are the averages from cross profile measurements at three fixed longitudinal positions.

As stated earlier, water was added to the subgrade and pavement structure after a period of testing in dry condition. The volumetric water content was measured using WCR-sensors (Water Content Reflectometers) at different depths in the test structures. These volumetric water contents have been converted to water content by weight by dividing the measured values by the dry densities of the base layer materials.

Figure 25 shows the results from two of these sensors placed at a depth of 15 cm from the base layer surface during the period when ground water level was raised from the bottom of the subgrade to the top of the pavement and then lowered to 30–40 cm below the subgrade surface.

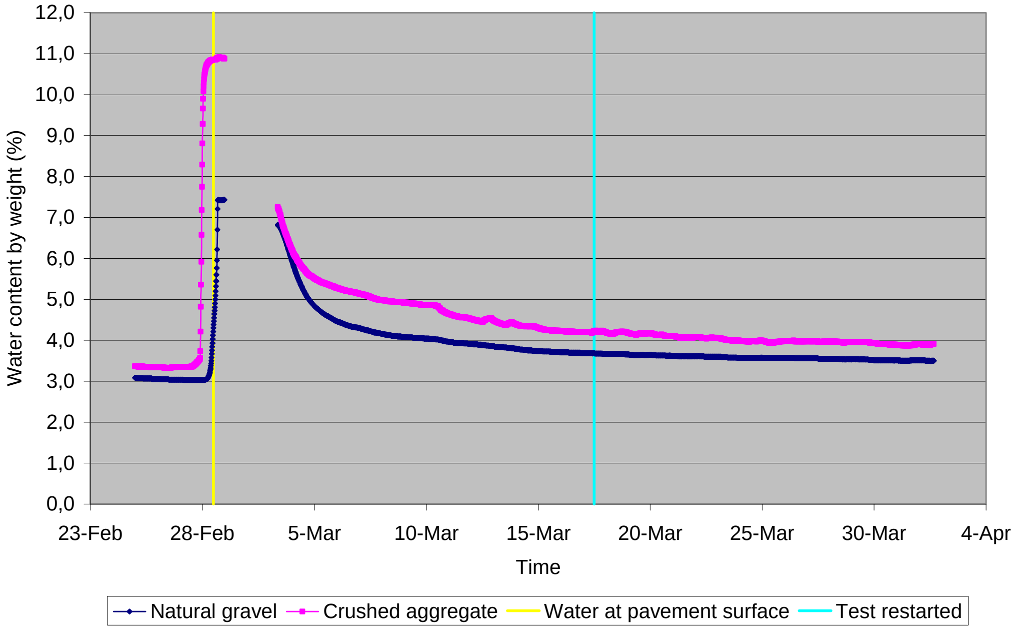


Figure 25 Water content by weight, at a depth of 15 cm from the base layer surface, during raising and lowering of the ground water level.

As can be seen, the water content was only raised 0.5% for both materials, from 3.0% to 3.5% for the natural gravel and from 3.4% to 3.9% for the crushed aggregate.

5.1.2 Unbound base layer deformation

The nominal thickness of the unbound base layers was 450 mm. The change in thickness due to the loading was measured using inductive coils (εMU-coils). The measurement was subdivided into three thirds of the thickness, 0–150 mm, 150–300 mm, and 300–450 mm. The measurements of the change of these thickness at the end of the test (573,000 wheel passes) are compared with the surface rut depth measured at the same time.

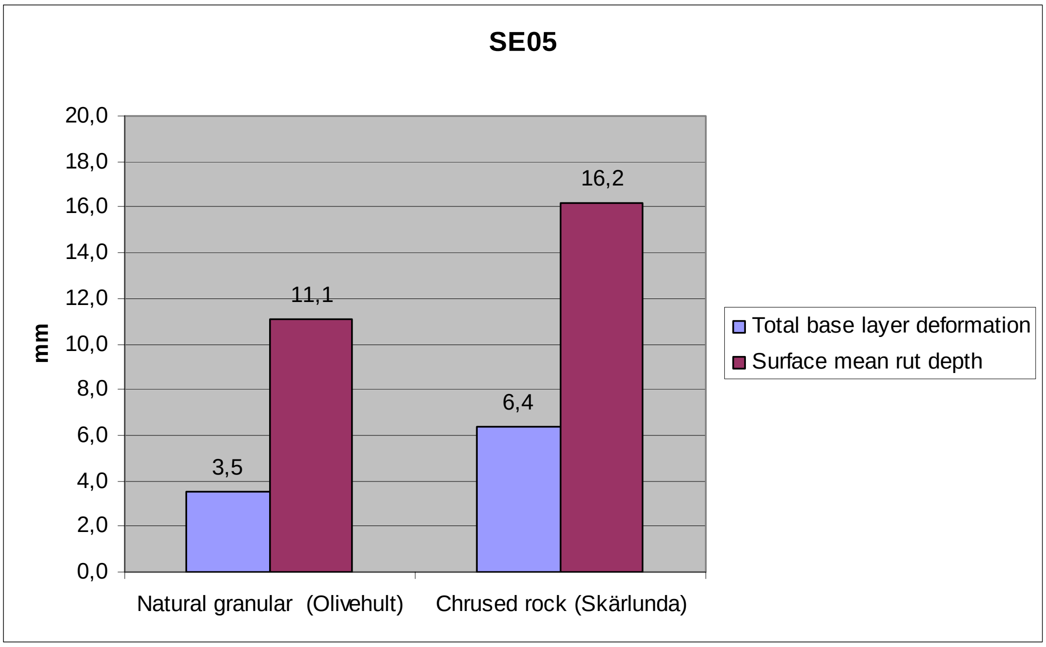


Figure 26 Surface mean rut depth and total base layer deformation at the end of the test (573,000 wheel passes).

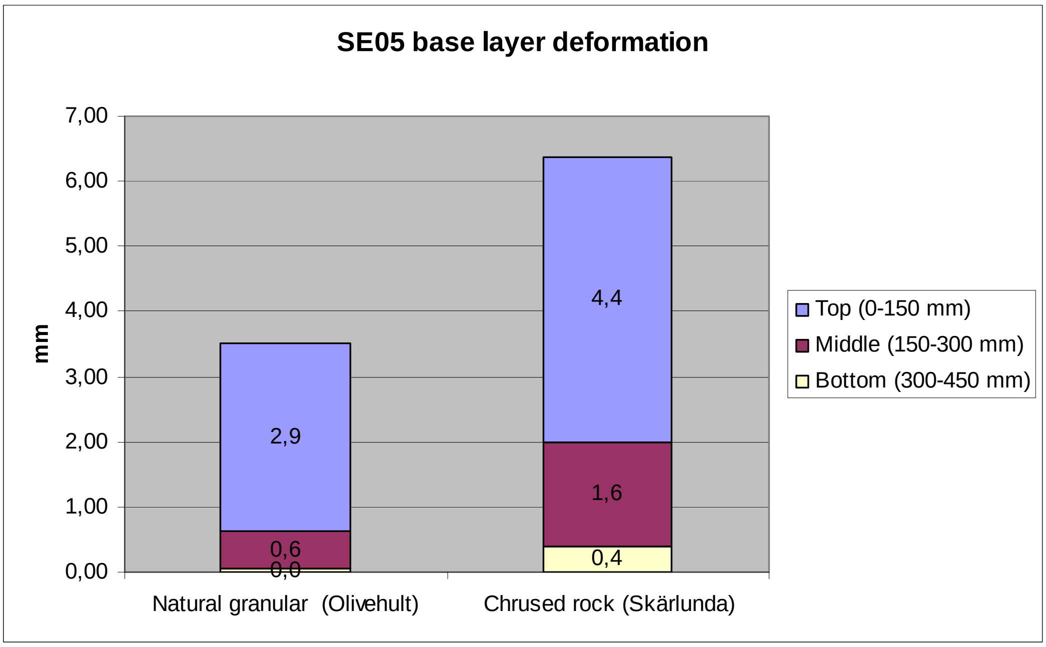


Figure 27 Base layer deformation, variation with depth.

More than half of the difference in rut depth on the surface can be found in the difference in the base layer deformation, and most of the deformation of the base layers are related to the upper part (0–150 mm) of these layers.

5.2 SE06 Performance test results

5.2.1 Surface rut depth

Surface rut depths were calculated from cross profile measurements at five fixed longitudinal positions.

The test started in dry condition and after about 205,000 load repetitions, the test was stopped for 10 months due to other tests outside VTI. After this interruption, the test was continued and after a total of about 530,000 load repetitions, water was added to the subgrade.

The water level was this time raised to the level 30 cm below subgrade surface, not to the top of the pavement and back as in the previous test, SE05.

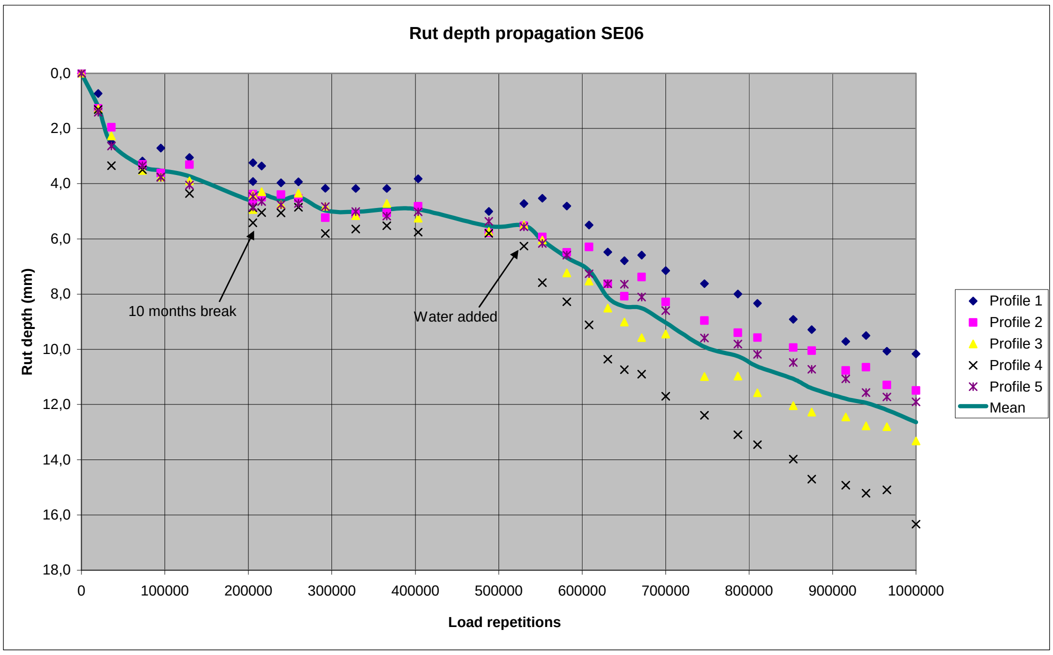


Figure 28 Rut depth propagation in test SE06.

As can be seen from figure 28, there is a fairly large scatter in rut depth propagation in wet condition. The large rut depth propagation at cross profile number 4, (and also number 3), could possibly be explained by insufficient compaction around the steel rods, used to measure base layer and subgrade surface deformation. These steel rods are located between profile 3 and 4 (see instrumentation plan in figure 20).

In the following figure, the results from cross profile measurements are shown as the average of the five cross profiles before and after the test.

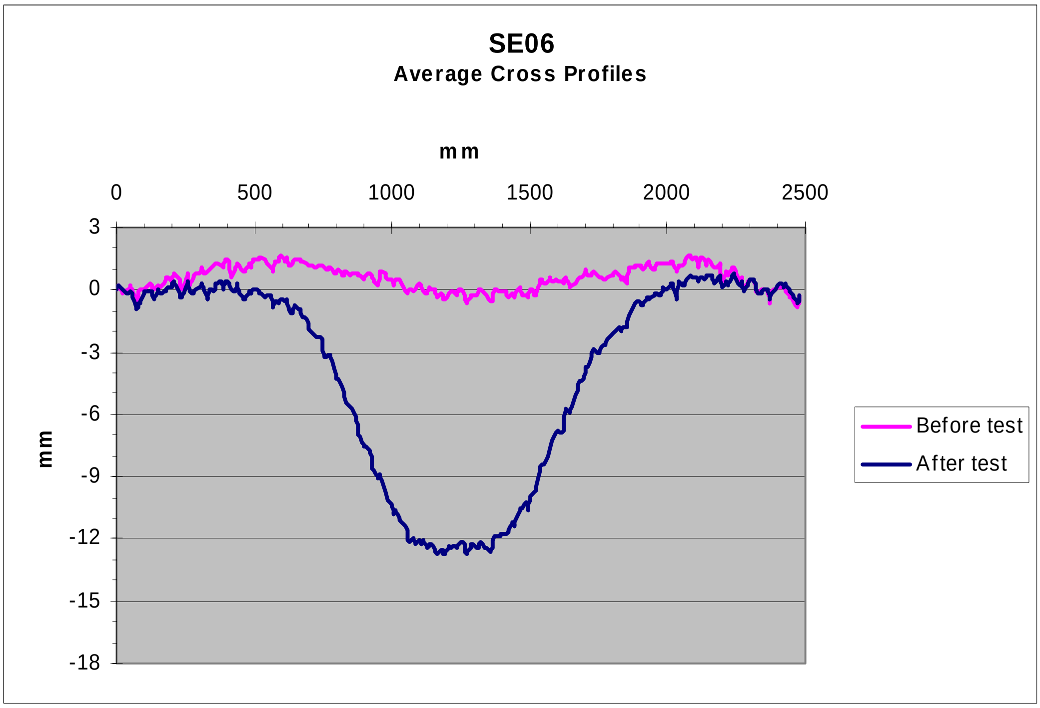


Figure 29 Average cross profile before and after test SE06. The profiles are the averages from cross profile measurements at five fixed longitudinal positions.

5.2.2 Deformation of unbound layers

As in the previous test, the changes in thickness of the unbound pavement layers were measured by inductive coils (εMU-coils). The base layer, the sub-base layer, and the upper part of the subgrade (divided into two layers) were measured separately. The accumulated results from these measurements after the first period in dry condition, and after completion of the test, both dry and wet conditions, are shown below.

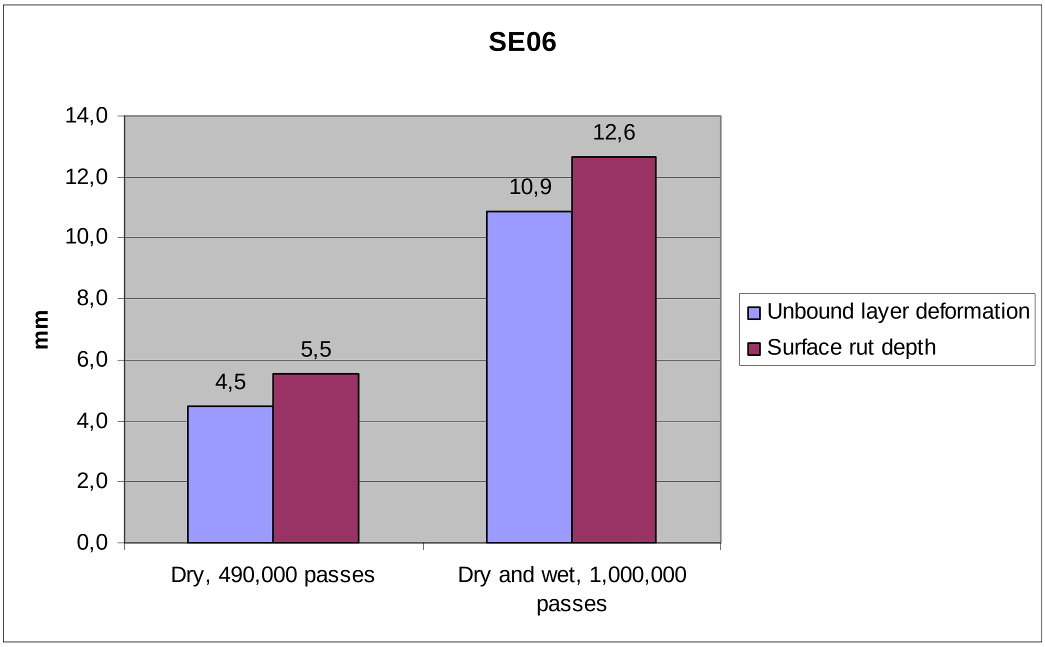


Figure 30 Total deformation of unbound layers compared to pavement surface rut depth. Unbound layers include base, sub-base, and the upper 300 mm of the subgrade.

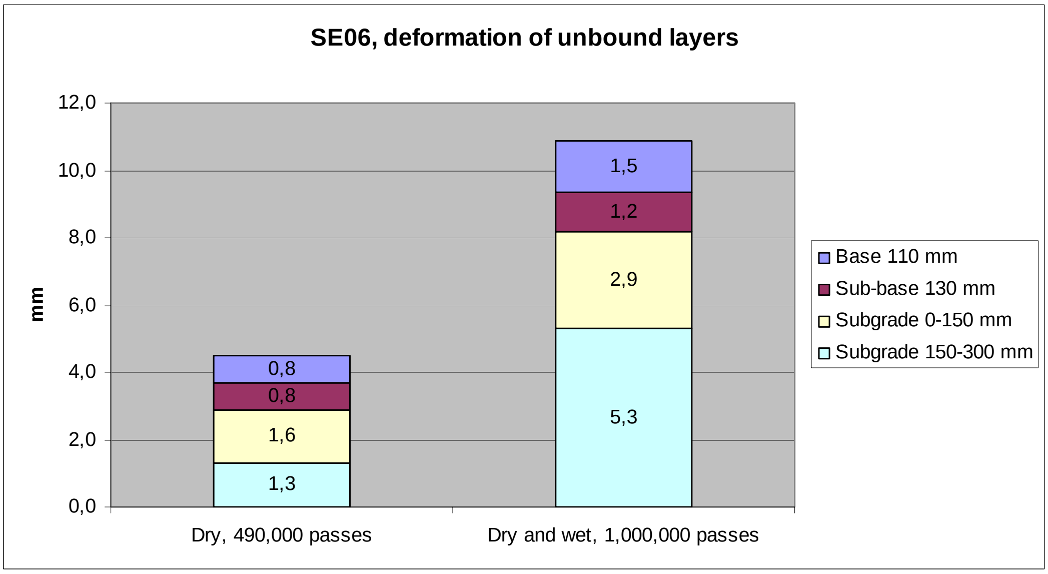


Figure 31 Total deformation of unbound pavement layer divided into the deformations of the individual layer.

Most of the rut depth on the pavement surface can be related to the deformation of the unbound pavement layers and the upper part (300 mm) of the subgrade. Furthermore, most of the deformation of the unbound layers can be related to the upper part of the subgrade. This means that about 65% of the rut depth on the pavement surface can be related to the deformation of the subgrade.

6 Findings and conclusions

6.1 Unbound base material test SE05

The objective of the unbound base material test was to study the behaviour of two pavement structures with different base layer materials. Both structures were constructed on the same fine sand subgrade and with the same asphalt surface layer. The base layer materials were natural granular material (Structure 1) and crushed rock aggregate (Structure 2) and the thickness was 450 mm. The surface rut depth propagation during the accelerated load testing was greater on the structure with crushed rock aggregate in the base than on the structure with natural gravel in the base, especially in wet condition. This was not expected and more than half of the difference in surface rut depth was found in the difference in the base layer deformations.

One main reason for this unexpected behaviour is believed to be unsatisfactory compaction of the crushed rock aggregate base.

In these tests, the degrees of compaction were correlated to modified Proctor tests. The degree of compaction was the same (close to 100%) for both base layers. However, there are indications that this is not enough to obtain a sufficient degree of compaction for crushed materials. Greater compaction might probably be necessary to reduce the pore volume and obtain the density needed for good performance. For the crushed material, an increase in compaction energy will also increase the density. For the natural gravel, the increase in compaction energy will probably not result in as high an increase in density. This means that also in laboratory tests, the density of crushed rock is probably more sensitive to compaction energy than that of the natural gravel.

To obtain sufficient compaction with the crushed material, two approaches could be used. One is to require a higher degree of compaction for crushed materials in the specifications, perhaps more than 100% of modified Proctor test. The other is to use higher compacting energy in the laboratory than the modified Proctor to determine the degree of compaction.

After construction of the base layers, the water content, as an average for the upper 30 cm of the base, was 2.4% by weight in the natural gravel measured by isotopic measure and 2.7% for the crushed rock. This is below the optimum water content for both materials, which is 3.7% for the natural gravel and 4.7% for the crushed rock.

In the modified Proctor tests, the crushed material showed a steep increase in the maximum density for the moisture content interval of 2–4.5% compared to the more moderate increase for the natural gravel. This also means that the crushed rock had insufficient compaction at the start of the HVS test. This probably insufficient compaction at the start of the test might explain the faster increase in permanent deformation for the crushed rock.

When raising and lowering the water table, the water content in both materials raised with 0.5% towards the optimum water content. Again, the steeper increase in the maximum density for a change in moisture content might explain why the deformation rate for the crushed rock increased further. (Odermatt, 2003 and Odermatt et al., 2004).

6.2 Structural design test, SE06

The objective of this structural design test was that it should constitute the third test in a series of three with gradually increasing bearing capacity. The results from the two previous tests, SE01 and SE02, are reported in Wiman, 2001. Materials and actual layer thickness for the three structures are shown in figure 32 below.

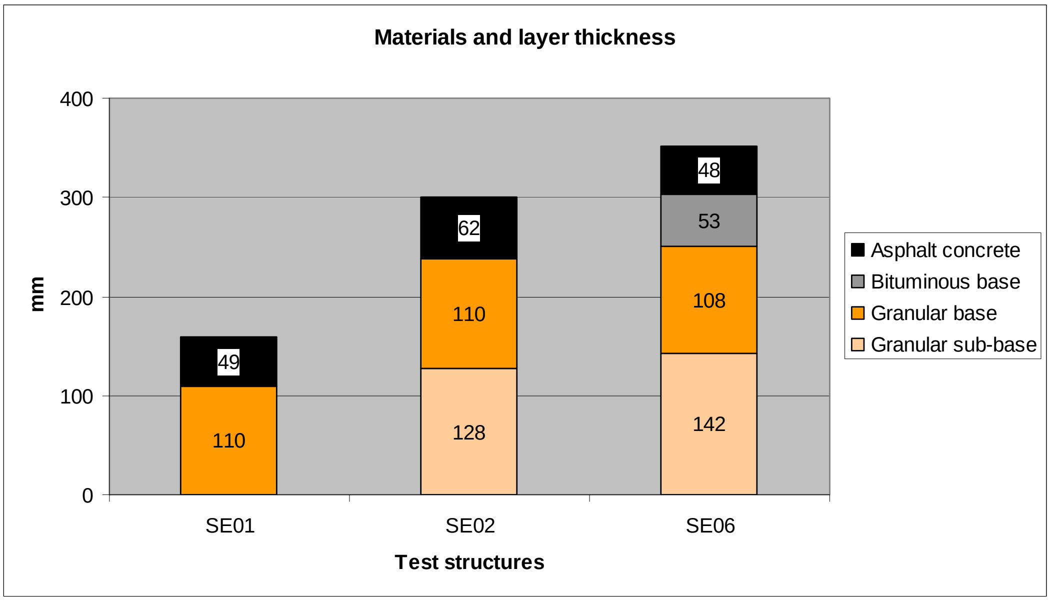


Figure 32 Pavement test structures with increasing bearing capacity.

The performance of these pavement structures during the accelerated load testing will be analysed in more detail in future projects. One preliminary conclusion is that there seems to be a fairly strong correlation between the rut depth propagation in dry condition and surface deflections from falling weight deflectometer (FWD) measurement.

The rut depth propagation during the first phase, in dry condition, for these three tests showed a good fit with exponential regression lines.

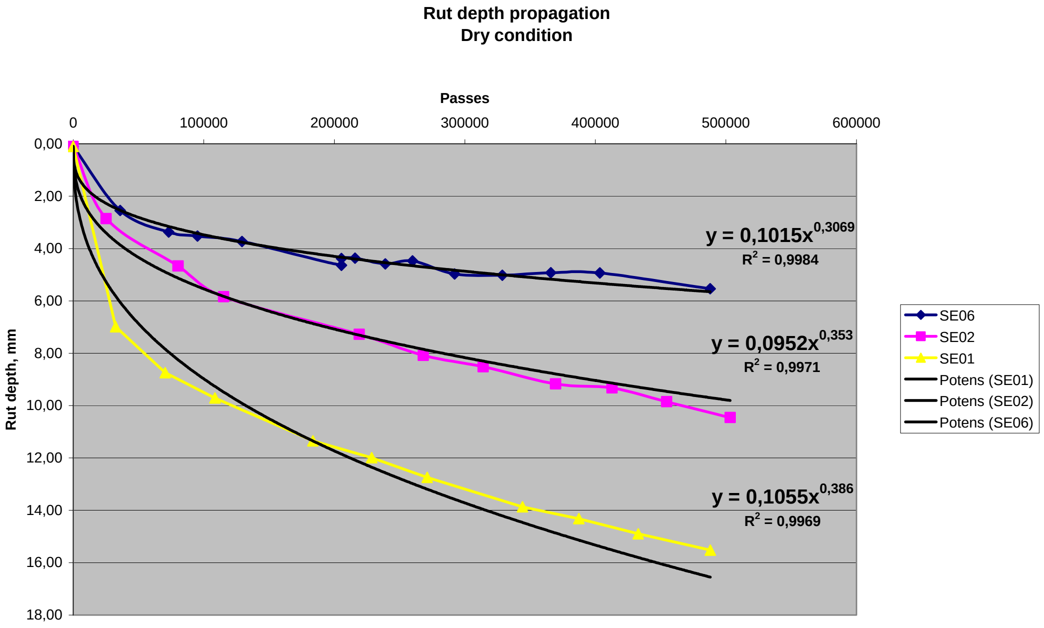


Figure 33 Rut depth propagation in dry condition and regression lines for the pavement test structures with increasing bearing capacity.

In an attempt to find a relation between pavement structure and pavement performance, the relationship between surface deflections from FWD and the exponents in the rut depth propagation regression lines was used. The exponents were related to the surface curvature index SCI 300 from FWD (deflection at the centre of the loading plate minus deflection 300 mm from the loading plate) measured before the tests and a good linear relationship was found. This was a first attempt and no corrections, for example for temperature, have been made. The pavement surface temperatures during the FWD measurements were 8–9°C in SE01 and SE02 and 12°C in SE06.

In this first attempt, the A-factor in the equation, $y = A*x^{B}$, was set to 0.10 which is the average value for the three regression lines.

Table 15 A-factor, exponent B and SCI 300 from tests SE01, SE02 and SE06.

Test	*A-factor*	*Exponent B*	*SCI 300*
SE01	*0.1055*	*0.386*	*317*
SE02	*0.0952*	*0.353*	*247*
SE06	*0.1015*	*0.3069*	*184*
Average	*0.1007*		

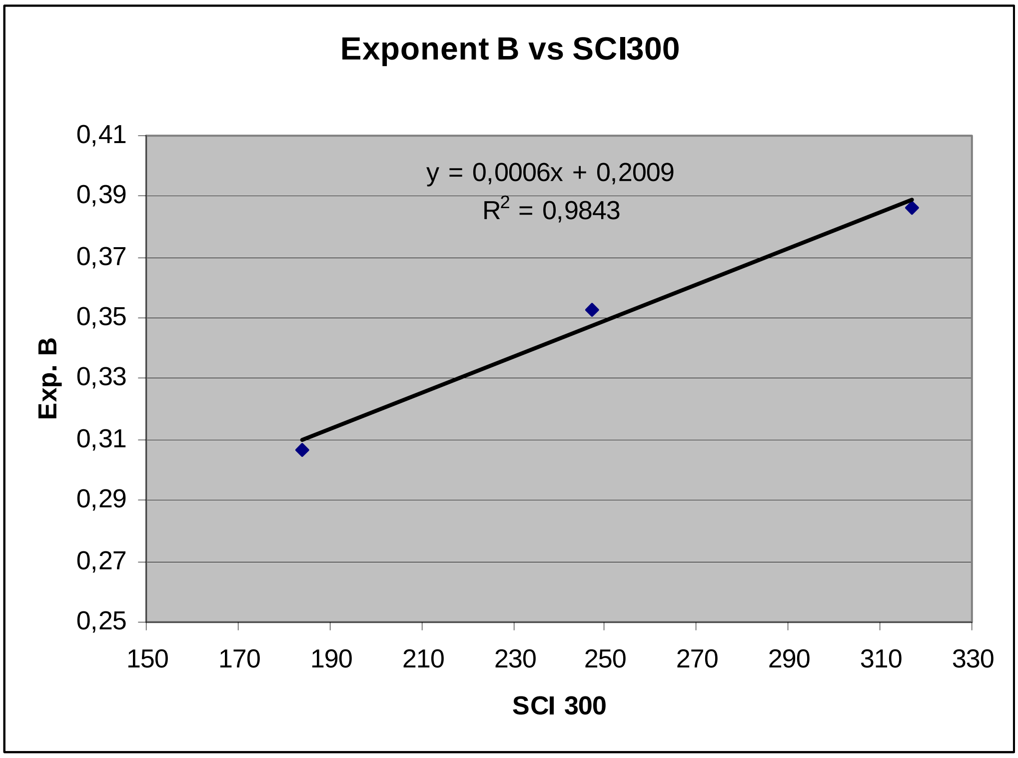


Figure 34 Relationship between exponents in regression lines and SCI 300 from FWD measurements before tests.

Based on these findings, a preliminary prediction model for the rut depth propagation in dry condition can be formulated as follows:

$RD = 0.10 * N^B$

Where:
RD = Rut depth propagation (mm)
N = Number of wheel loadings (60 kN)
$B = 0.0006 * SCI + 0.2009$
$SCI = D_0 – D_{300}$ (µm)
D_x = Surface deflections from FWD (50 kN) measurements

These results and findings will be added to and studied further in other, future tests. A similar relationship was also found with data from the Swedish LTPP (Long Term Pavement Performance) sections, which indicates a possible link between ALT (Accelerated Load Testing) and RLT (Real-time Load Testing).

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Provväg E6, *Glimmerrika bärlager och vägkonstruktioner med lättklinker.* Provsträckor och mätresultat, Vägverket 2004:84.

Thøgersen F., Busch C. and Henrichsen A.: *Mechanistic Design of Semi-Rigid Pavements,* Vejdirektoratet Denmark, 2004, VI rapport 138.

Wiman. L.G.: *Accelerated Load Testing of Pavements – HVS Nordic tests* in *Sweden 1999.* VTI report 477A, Swedish National Road and Transport Research Institute, Linköping, Sweden, 2001.

Overview of HVS tests in Finland and Sweden 1997–2004

Test	Start, yy/mm, duration	Total number of loadings (10^3)	Description	Reference
FIN01	97/	1,710	Base course test with low quality base	Finnra report 30/2001 Matti Huhtala, Jari Pihlajamäki and Janne Sikiö
FIN02	97/	170	Base course test with high quality base	
FIN03	97/	1,400	Loading mode test, single wheel, bi-directional	
FIN04	97/	318	Loading mode test, single wheel, uni-directional	
FIN05	97/	Not started	Loading mode test, dual wheel, bi-directional	
FIN06	98/04 1 month	4.9	Thawing test, frost-susceptible subgrade	Finnra report 31/2000 Heikki Kangas, Heikki Onninen and Seppo Saarelainen
FIN07	98/05 1 month	8.1	Thawing test, frost-susceptible subgrade	
FIN08	98/05 1 month	6.5	Thawing test, frost-susceptible subgrade, steel grid in base course	
FIN09	98/06 2 months	130	Heavy traffic road, traditional structure	Finnra reports 29/2001 Jari Pihlajamäki and Janne Sikiö
FIN10	98/08 2 months	500	Heavy traffic road, high resistance to fatigue structure	
SE01	98/12 6 months	2,296	The first test in a series of three with gradually increasing bearing capacity. SE01, SE02, SE06	Accelerated load testing of pavements VTI Report 477A Leif G Wiman, 2001
SE02	99/06 2 months	1,135	The second test in a series of three with gradually increasing bearing capacity. SE01, SE02, SE06	
SE03	99/09 2 months	800	Maintenance treatment on SE01. ”Milling and filling”.	
SE04	99/12 1 month	165	Maintenance treatment on SE02. ”Milling and filling”.	

Test	Start, yy/mm, duration	Total number of loadings (10^3)	Description	Reference
IS02	00/03 1 month	480	Surface treatment (double) on unbound base and sub-base material from Iceland	HVS-testing of Icelandic low volume road structures Thorir Ingason Leif G. Wiman Hreinn Haraldsson ISAP 2002, Danmark
IS03	00/04 1 month	475	Surface treatment (double) and bituminous base layer on unbound base and sub-base material from Iceland.	
RX01	00/06 0.1 month	39	Flow rutting test. Effect of steel mesh on pavement deformation at high AC-layer temperature	REFLEX Final Report T4:02 Full Scale Accelerated Tests Jari Philajamäki, Leif G Wiman, Kent Gustafson EU Brite/Euram III RTD Programme, 2002
RX02	00/08 3 months	852	Bearing capacity test. Effect of steel mesh in bituminous base on bearing capacity at ”normal” temperature (10 °C)	
FIN11 (Reflex03)	01/ 1 month	111	Bearing capacity test. Effect of steel grid #75/75 in crushed rock at ”normal” temperature (10 °C)	
FIN12 (Reflex03)	01/ 1 month	111	Bearing capacity test. Effect of steel grid #150/150 in crushed rock at ”normal” temperature (10 °C)	
FIN13 (Reflex03)	01/ 1 month	68.8	Bearing capacity test. Un-reinforced reference structure	
FIN14	01/ 1 month	23.1	EPS-structure. Effect of lightweight material	Jukka Elomaa, Helsinki University of Technology, Master’s thesis, 2002
FIN15	01/ 1 month	23.1	EPS-structure. Effect of lightweight material + steel grid in crushed rock	
FIN16 + FIN17	01/08 0.5 month	16.1	Sloped structure (reference structure no slope)	Finnra report 19/2003 L. Korkiala-Tanttu, P. Jauhiainen, P. Halonen, R. Laaksonen, M. Juvankoski, H. Kangas and J. Sikiö
FIN18	01/09 0.5 month	17.9	Sloped structure slope 1:3	
FIN19 + FIN 20	01/11 0.5 month	17.9	Sloped structure slope 1:1.5	

Test	Start, yy/mm, duration	Total number of loadings (10^3)	Description	Reference
FIN21	02/03 0.5 month	70	Low-volume road, high level of ground water, load 70 kN	Finnra report 22/2003, L. Korkiala-Tanttu, R. Laaksonen and J. Törnqvist
FIN22	02/02 0.5 month	70	Low-volume road, high level of ground water, load 50 kN	
FIN23	02/04 0.5 month	70	Low-volume road, lower level of ground water, load 70 kN	
PL01/02	02/07 2 months	1,200	Verification of an alternative semi-rigid pavement structure and comparison with Polish standard design.	Verification of Pavement Structure Design on A2 Toll Motorway in Poland using Heavy Vehicle Simulator (HVS NORDIC) Ao. Univ. Prof. Dipl.-Ing. Dr. Ronald BLAB o. Univ. Prof. Dipl.-Ing. Dr. Johann LITZKA Dipl.-Ing. Peter GIRKINGER STRASSENBAU DER TECHN. UNIVERSITÄT WIEN
FIN24	02/10 0.5 month	39	Steep reinforced slope rehabilitated structure, reference structure without reinforcement	Finnra report 38/2003, L. Korkiala-Tanttu and R. Laaksonen
FIN25	02/10 0.5 month	39	Steep reinforced slope rehabilitated structure, steel grid B500H - 5/6 - 200/150	
FIN26	02/11 0.5 month	39	Steep reinforced slope rehabilitated structure, steel grid B500H - 5/8 - 200/150	
FIN27	02/11 0.5 month	39	Steep reinforced slope rehabilitated structure, fibreglass grid	
FIN28	02/11 0.5 month	39	Steep reinforced slope rehabilitated structure, steel grid B500H - 5/6 - 200/150	
FIN29	02/11 0.5 month	39	Steep reinforced slope rehabilitated structure, reference structure without reinforcement	

Test	**Start, yy/mm, duration**	**Total number of loadings (10^3)**	**Description**	**Reference**
SE05	03/01 2 months	613	Unbound base layer study. Crushed rock material compared to natural gravel	Accelerated load testing of pavements VTI Report 544A Leif G Wiman, 2006
SE06	03/04 and 04/03 4 months	1,000	The third test in a series of three tests with gradually increasing bearing capacity. SE01, SE02, SE06	
SE07A	03/06 1 month	400	Different Mica content in unbound base layers. 4 tests at a construction site in the west of Sweden (E6 Uddevalla).	Provväg E6, glimmerrika bärlager och vägkonstruktioner med lättklinker. Provsträckor och mätresultat. Vägverket Publ. 2004:84
SE07B	03/08 1 month	366	Different base layer thickness on light fill material. 4 tests at a construction site in the west of Sweden (E6 Uddevalla).	
SE08	03/09 and 03/12 3 months	800	Different particle size distribution in crushed rock material in sub-base. Test sections at a construction site in the south of Sweden (E4 Markaryd).	
DK01	03/11 1 month	388	Semi-rigid pavement design tests. Different quality of the cement bound base layers. Danish test sections at a construction site in the south of Sweden (E4 Markaryd).	Mechanistic Design of Semi-Rigid Pavements - An Incremental Approach Road Directorate, DRI Report 138, 2004 www.vejdirektoratet.dk

Testing machine and test site at VTI

The HVS-NORDIC is a mobile linear full-scale accelerated pavement-testing machine (HVS Mark IV), figure 1. The machine can be run over a short distance by itself at walking speed and can be moved as a semi-trailer over longer distances. Its speed during transportation by road is about 50 km/h but special permits are needed. Because it has steering wheels, it can, in spite of its length, negotiate even relatively sharp corners.

Figure 1 Transportation of HVS-NORDIC.

The HVS-NORDIC has a heating/cooling system and temperature can thus be held constant. The air inside the insulated box is heated or cooled and controlled in order to keep the pavement temperature constant. The standard pavement temperature is set at +10°C. The HVS can be run on diesel fuel or by electric power. The diesel engine also provides power for the heating/cooling system and the machine is thus independent of external power.

Its main technical characteristics are:

- Loading wheels, dual or single
- Loading can be in one or both directions
- The number of loadings is about 22,000 in 24 hours, (including daily maintenance), when loading in both directions.
- The lateral movement of the loading wheel centre is up to 0.75 m

The HVS is 23 m long, 3.5 m wide, 4.2 m high, and weighs 46 tonnes. The wheel load can be varied from 30 kN to 110 kN (corresponding axle loads 60...220 kN) at speeds up to 12 km/h. The machine can be run 24 hours a day, even during the night with no staff present.

Figure 2 HVS-NORDIC ding wheel.

Figure 3 Inside view of test-carriage and loading wheel.

At VTI there is an indoor full-scale pavement test facility where pavements can be constructed by ordinary road construction machines. This facility comprises three test pits and two of these are used for the accelerated pavement testing, figure 4. The test pits are 3 m deep, 5 m wide, and 15 m long. Using two test pits means that one test section can be constructed while the test is running on the other. See figure 5.

Figure 4 Full-scale pavement test facility at VTI, Linköping.

Figure 5 HVS machine during test.

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VTI är ett oberoende och internationellt framstående forskningsinstitut som arbetar med forskning och utveckling inom transportsektorn. Vi arbetar med samtliga trafikslag och kärnkompetensen finns inom områdena säkerhet, ekonomi, miljö, trafik- och transportanalys, beteende och samspel mellan människa-fordon-transportsystem samt inom vägkonstruktion, drift och underhåll. VTI är världsledande inom ett flertal områden, till exempel simulatorteknik. VTI har tjänster som sträcker sig från förstudier, oberoende kvalificerade utredningar och expertutlåtanden till projektledning samt forskning och utveckling. Vår tekniska utrustning består bland annat av körsimulatorer för väg- och järnvägstrafik, väglaboratorium, däckprovningsanläggning, krockbanor och mycket mer. Vi kan även erbjuda ett brett utbud av kurser och seminarier inom transportområdet.

VTI is an independent, internationally outstanding research institute which is engaged on research and development in the transport sector. Our work covers all modes, and our core competence is in the fields of safety, economy, environment, traffic and transport analysis, behaviour and the man-vehicle-transport system interaction, and in road design, operation and maintenance. VTI is a world leader in several areas, for instance in simulator technology. VTI provides services ranging from preliminary studies, highlevel independent investigations and expert statements to project management, research and development. Our technical equipment includes driving simulators for road and rail traffic, a road laboratory, a tyre testing facility, crash tracks and a lot more. We can also offer a broad selection of courses and seminars in the field of transport.

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