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Accelerated pavement testing efforts using the Heavy Vehicle Simulator

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Abstract

This paper provides a brief description of the technological developments involved in the development and use of the Heavy Vehicle Simulator (HVS) accelerated pavement testing equipment. This covers the period from concept in the late 1960's, to the current state-of-the art HVS Mk-VI and highlights the development and improvements being built into the Mk VI. It also provides a brief overview of the research performed by the various accelerated testing programs currently using the HVS as their accelerated testing tool, which include the Gauteng Provincial Department of Transportation and the CSIR (South Africa), the UC Pavement Research Center (California), the U.S Army Corps of Engineers Engineering Research and Development Center (CRREL and WES), the Florida DOT HVS test program, the US Federal Aviation Administration (FAA), the HVS programs of the University of Costa Rica and the Mexico Institute of Transportation amongst others. Brief descriptions of HVS research and summaries of key results from these programs are provided. Planned research is covered where available.

1. Introduction

The need for accelerated testing of pavements arose from the uncertainty of design models and analysis techniques that could previously only be verified with performance observed under normal traffic in real time. Accelerated Pavement testing (APT) was developed to fill the important gap between mechanistic-empirical design models using laboratory materials testing characterization and real, long-term pavement performance monitoring and analysis data.

APT is a technique used to evaluate the performance of full-scale constructed pavements in an accelerated manner as opposed to long-term pavement performance monitoring. To study the negative impacts of the environment and traffic on the condition and performance of pavement structures can take years under true field conditions. APT utilises special full-scale mobile or fixed testing apparatus to simulate these effects in a shorter time period. APT is meant to provide results from full-scale constructed pavements and loading, but with damage accelerated through control of loading and environmental control in order to obtain results in weeks and months rather than the years and decades necessary to complete long-term monitoring.

APT came to the fore in the late 1950s with the AASHO road test in the USA and since then has played an important role in the elevation of road construction to a largely rational process. Metcalf [13] reported 28 active APT programs worldwide, and Hugo [10] lists significant findings from these full-scale APT programs. The philosophies

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behind – and the approaches to – APT in the various programmes vary considerably, imparting some degree of uniqueness to several of these experimental set-ups. In the case of the South African Heavy Vehicle Simulator (HVS), this uniqueness results primarily from the fact that it was designed to be used on real, in-service pavements.

1.1. Motivation for an HVS program in South Africa

Although empirical design procedures developed from the AASHO road test were originally incorporated in the South African design methods in use at that time, a great deal of effort was devoted to the development of design procedures to suit the local environment, materials and structures. APT appeared to have the capability of rapidly evaluating the performance of these developments and South Africa decided to pursue this approach.

Fixed-facility APT devices, and in some cases loop facilities, have the disadvantage that specially designed experimental pavement sections built at these facilities may not be typical of in-service pavements. In order to address the shortcomings of all the available APT technologies at that time, the former National Institute of Road Research (NIRR) of the Council for Scientific and Industrial Research (CSIR) (now CSIR-Built Environment Unit) developed a fully mobile APT device, the Heavy Vehicle Simulator (HVS). As stated above, the motivation for the development of the HVS was mainly because it could be used for evaluations on as-built mainline pavements throughout South Africa.

2. The start-up of the South African HVS programme

The South African pavement design approach during the 1960s was to develop an analytical design procedure in which the engineering characteristics of pavement materials could be used together with a mathematical model to predict or analyze pavement performance [30]. This led to the South African Mechanistic Design method [25]. However, confidence in these models could only be established by verifying their predictions against the performance of real pavements. In 1967 Van Vuuren [26] reported that there was no satisfactory procedure for the determination of the effects of abnormal vehicles on roads and he recommended that full-scale experimental test roads be built and trafficked with abnormal heavy vehicles. This lead to the construction of full-scale test section loops at the Silverton test site of the former NIRR. Heavy vehicles were used to apply the loads on these test sections. The low rate of load applications by using this approach became the motivation for the development of an accelerated loading testing facility.

The first HVS was designed to simulate the damage done to airport runways due to aircraft landing gear impact. This fixed facility was manufactured from Bailey Bridge components and subsequently became known as the HVS Mk I. The reaction force ballast) applied to the pavement utilized water tanks placed above the aircraft wheel supported by the Bailey Bridge structure. The facility produced useful results but was not mobile. As a result, Van Vuuren in 1972 [28,27] recommended that, due to atypical construction of test sections at the Silverton site, a mobile loading facility should be developed that could test real, in-service pavements.

The first fully mobile self-powered HVS Mk II) was commissioned in October 1970 [29]. The 30 ton machine could apply up to 800 repetitions per hour over a 6.2 m long test section. The initial maximum load applied to the pavement was 35 kN (1/2 axle), which was later increased to 75 kN (1 axle). By the end of 1972, 10 accelerated trafficking tests had been conducted with HVS Mk II. Data collected during the initial 10 tests included surface deflections, radius of curvature, permanent deformation, visual distress data, such as cracks, material loss, shear failures, etc.

Analysis of this data provided information on wheel load equivalency factors, rutting in untreated granular layers and load-associated cracking in cement-treated bases. By the end of 1975, 24 tests had been completed with HVS Mk II, nonetheless the main success and focus of the HVS programme began in 1972. A new coal delivery road, had been built between Witbank and Johannesburg between 1966 and 1969. Severe failures occurred on a 48 km section of this road within the first year of operation and major rehabilitation was necessary on certain sections. As a result 18 HVS tests were conducted on this road to investigate these problems [28,27].

The test results were so promising that in 1972 NIRR motivated the manufacturing of three additional improved HVS Mk III machines, which were designated as HVS 2, 3 and 4 [16,15]. The machines were financed by NIRR, the National Department of Transport (NDoT) and the Transvaal (now Gauteng) Department of Transport. Pictures of the South African Mk II and II can be seen in Fig. 1. The motivations for expansion of the HVS fleet are briefly summarized below:

- The desire was expressed by some road authorities to verify new pavement designs in the field before the beginning of any major construction, by constructing trial sections in the same area so that environmental and subgrade conditions would be similar. The objective would be to determine the mechanism of distress and remaining life (in terms of the number of load repetitions) to “failure” of the proposed pavement. To improve the South African new Pavement and Rehabilitation design procedures. The specific aims were:
  - To determine wheel load equivalencies;
  - To establish the effect of bi-directional trafficking;
  - To verify new designs proposed in the pavement design method;
  - To extend the data from above to four climatic regions in South Africa;

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Fig. 1. The South African HVS Mk II (1970) and III (1976).

- To verify the theoretical predictions of distress in cemented base pavements;
- To evaluate the prediction of fatigue cracking in bituminous pavements, and
- To evaluate stress-dependent response and deformation of existing pavement for overlay design purposes.

3. Significant outputs from the HVS programme in South Africa

Some of the most significant developments in the South African pavement design engineering field resulting from the use of the HVS are briefly mentioned.

3.1. Materials-based development

3.1.1. Large aggregate mix bases (LAMBs)

Preliminary results are reported elsewhere [18], which highlighted the promising behaviour and the technical benefits of this type of base course. Following an extensive laboratory study, the HVS was utilized to validate laboratory findings. The development work has since been completed and resulted in a design method [20].

3.1.2. Granular emulsion mixes (GEMs)

The use of emulsion-treated bases, primarily for rehabilitation and improvement of existing roads, remains a particular area for development in SA. The main objective was to compare GEMs using marginal parent in-situ material with imported aggregate crushed stone base materials. More recent HVS results [4] have provided additional input for the development of an appropriate design method [19].

3.1.3. Rehabilitation measures for cemented-base pavements

A long-term HVS investigation into the selection of rehabilitation measures for lightly cemented-base pavements was undertaken. The main findings of this investigation are reported elsewhere [23].

3.1.4. Treatments for phased upgrading of unpaved roads

HVS work in South Africa is closely aligned with the need for cost-effective improvements to unpaved roads, as

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part of a phased upgrading. Details of an HVS comparison of several bitumen- and tar-based treatment types were investigated during the 1990s [22].

3.1.5. *Comparison of bases constructed by labour-enhanced techniques*

The application of labour-enhanced, or labour-intensive, construction techniques is of special relevance to South Africa. The HVS programme for 1997 compared the behaviour of different base types constructed in this way. These include penetration macadam, emulsion treated natural gravel and slurry bound macadam.

3.1.6. *Porous asphalt*

The performance of porous asphalt, with void contents in excess of 20%, under accelerated traffic was investigated. The deformation characteristics of a porous asphalt with a bitumen-rubber binder were investigated with the HVS. This work has been incorporated into a porous asphalt design manual [21].

3.1.7. *Ultra thin reinforced concrete pavement (UTRCP)*

CSIR developed a cost-effective ultra-thin concrete pavement surface for the upgrading of unpaved roads to paved roads. The surface is more durable than many other pavement alternatives (such as asphalt). UTRCP is suitable for the building of residential and low-volume roads. The technology has been proof tested by the HVS and is now implemented in many township roads through the Gauteng province of South Africa [5].

3.1.8. *High modulus asphalt (HiMA) for base materials in South Africa*

The CSIR developed a high modulus asphalt base coarse material suitable for heavy traffic routes, airports and port terminals. The key performance characteristics of HiMA are high stiffness, superior resistance to permanent deformation/rutting and good resistance to fatigue cracking. Success of implementation of the technology is monitored through a long-term pavement performance evaluation project since 2011 [14].

3.2. *Developments in design, analysis and performance characterisation*

3.2.1. *South African pavement structural design method (Technical Recommendations for Highways, TRH4)*

The SA flexible pavement design method and catalogue has been developed over the years with major input from HVS data [3]. It has been revised to include certain additional refinements arising from the HVS programme [2]. Details of the underlying changes in the analytical evaluation the SA mechanistic design method, SAMDM) were given by [25].

3.2.2. *Improvements in the modelling of permanent deformation in pavements*

HVS performance data have been used in the investigation into the individual contributions of the various pavement layers to the overall deformation of the structure. A new approach to the estimation of these permanent deformations has been proposed, details of which are reported elsewhere [24].

3.2.3. *Improved modelling of pavement behaviour*

A back-calculation method for more realistically modelling in-depth and surface deflection bowls, based on actual responses measured during HVS testing, has been developed. Extremely good correlations were obtained using linear elastic layer theory to derive appropriate stiffness values [17].

3.2.4. *Mechanistic-empirical pavement design*

The development of an improved mechanistic-empirical South African Pavement Design Method SAPDM). Historical HVS material performance data has been used in the development, calibration and verification of the new recursive damage accumulation method in the revised SAPDM [11].

4. Further development of the HVS

Fundamentally similar to the Mk II, the Mk III machines had significant differences beyond simple cosmetic improvements: the test wheel carriage was now designed to take normal dual truck wheels only single wheels were used in the Mk II model), as well as aircraft wheels. Road transportation was changed to use a truck tractor for towing the HVS between remote locations at about 80 km/h. It was self-powered for on-site mobility and positioning. The design also allowed for both uni- and bi-directional trafficking [1,16,15]. The test section length remained at approximately 8 m and loads of up to 200 kN were possible. Test wheel speed was about 9 km/h, allowing approx. 20,000 bi-directional wheel load repetitions per day. At a test wheel load of 40 kN (half-axle) this produces 20,000 ESALs per day. Further acceleration is achieved by increasing the test wheel load. For instance, if a wheel load of 100 kN is applied the fourth power damage relationship suggests that each pass of the wheel produces 39 ESALs, for a total of about 781,000 ESALs per day. The design allowed for simulation of up to 1 m traffic wheel wander. Dimensions of the HVS were 23 m length × 3.7 m width × 4.2 height. The Mk III weighed about 57 tonnes.

In contrast to the Mk II, the three new production machines went into continuous use on public roads throughout South Africa from the outset. They were funded from grants received from the NDoT (for two machines) and from the Transvaal Provincial Administration (TPA) (for its machine) and were all operated and maintained by NIRR staff. This was done in close collaboration with the road authorities involved, and

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representative advisory committees were formed from the beginning. This relationship has been a significant factor in the undoubted success of the programme, ensuring the earliest possible application of important findings.

From the late 1970s and throughout the 1980s, the expanded HVS programme was able to underpin virtually all the advances and developments in South African pavement engineering, some of which are highlighted later. While South Africa's political status at that time undoubtedly restricted direct exposure of the HVS' work there were, nevertheless, significant numbers of overseas visitors during this time, notably from the United States, United Kingdom and Australia.

In 1994, after a successful pilot project demonstrating the HVS capabilities, the California Department of Transportation (Caltrans) decided to establish the CAL/APT programme and purchased two of the HVS Mk III machines. Both machines were refurbished in South Africa before being shipped to the USA. The machines were delivered in 1995 and immediately began testing pavements for the CAL/APT programme. This programme involved collaborative efforts between Caltrans, the University of California, Dynatest Consulting, Inc. and CSIR. This venture sparked international interest and by 2003, four additional new units had been sold internationally.

The rising interest in APT internationally has boosted further development in HVS technology and a new generation of HVSs, the HVS Mk IV was developed by Dynatest Consulting, Inc. under license from CSIR. The HVS Mk IV remains closely aligned to its forerunners, but was modernised and re-designed from the ground up, resulting in an improved and more efficient machine. Fully computer controlled, many machine functions are monitored and automatic shutdown occurs if these functions deviate beyond pre-set limits. Use of off-the-shelf running gear components and other improvements resulted in a weight reduction to approx. 46 tonnes. Height was further reduced to 3.9 m. Test wheel speed was increased to about 12 kph (20 km/h) allowing approximately 26,000 bi-directional wheel loads per day. Other test specifications are similar to the Mk III. The first HVS Mk IV was purchased by the Cold Regions Research and Engineering Laboratory (CRREL) of the US Army Corps of Engineers, who took delivery in early 1997. A second HVS Mk IV, was sold jointly to the national Road Research Laboratories of Finland and Sweden (VTT and VTI respectively), and was delivered in June 1997.

In a parallel development, a HVS for the testing of airfield pavements was designed for the Waterways Experiment Station (WES) of the US Army Corps of Engineers. Apart from its physical size (36.3 m × 4.23 m × 4.99 m, 102 tonnes), the fundamental difference between the new HVS–A (dubbed "Bigfoot") and the HVS Mk IV lies in the loading capability of the former – it can load the test wheel up to 440 kN over a 12 m test section whereas the HVS Mk IV can only apply 200 kN over 6 m. The HVS–A is also designed to utilise dual aircraft wheels. This machine was delivered to WES in 1998, and was designated a Mk V since there were significant changes made, particularly to the load carriage.

An improved version of the Mk IV, the HVS Mk IV$^+$ was also designed for CSIR and was delivered in March 1999. The HVS Mk IV+ is based on the HVS Mk IV, but the frame and loading beam have been strengthened in order to allow the simulation of full dynamic loading. The hydraulic systems of the HVS Mk IV$^+$ and the strengthened frame allows for a future hydraulic and systems upgrade to simulate dynamic loading at a frequency of 10 Hz. Three Mk IV+ were delivered, one to the Florida Department of Transportation in June 2000, a and the second one to the CSIR in South Africa, and the final one to the Central Road Research Institute (CRRI) in India in June, 2010.

In 2006 Dynatest was awarded a contract to provide a new HVS, the Mk VI, to Chang'An University in Xian, PRC. The Mk VI's main functional changes involved the ability to use a beam extension to allow an increased test section length of 12 m from the previous 6 m, or to apply higher wheel speeds (up to 20 kph) on the 6 m test section. The design also included changes that allow easier transportation of the HVS over the road network, or in containers for shipping. All HVS units delivered since Chang'An University have been Mk VI and include: KCIT, Korea (November 2014); IRE, Indonesia (November 2014); Lanname, Costa Rica (October 2012); IMT, Mexico (October 2015); MOT, Saudi Arabia (May 2015) and VDOT, Virginia (November 2015). The US Federal Aviation Administration (USFAA) purchased an airfield version of the Mk VI, which allows the use of aircraft wheel loads, and was delivered in November 2013.

To date 17 HVS units (Mk III to Mk VI) have been deployed worldwide. A comparison of the characteristics of the various HVS models can be seen in Table 1.

5. Other HVS programmes

The following is a brief indication of some APT efforts undertaken with the HVS outside South Africa.

5.1. California

In the nine 20 years between delivery of the two refurbished Mk III HVS's in 1994 and the end of 2014 (including new Mk VI HVS delivered in 2011 and retirement of one Mk III soon after), the California program applied approximately 85 million load repetitions and 2.8 billion 80 kN ESALs, averaging approximately 2.1 million repetitions and 70 million ESALS per machine per year and the end of 2004, these machines have applied about 60 million actual load repetitions, or approximately 6 billion ESALS if the fourth-power damage relationship is assumed. More than 70,100 pavement sections have been tested, including materials such as dense graded asphalt concrete DGAC), asphalt-rubber RAC-G), aggregate base AB), and subbase

Table 1
Comparison of the characteristics of the different HVS models.

HVS version comparison				
Characteristic	Mk III	Mk IV	Mk VI	HVS-A (Airport)
Wander control	Mechanical	Electronic/programmable	Electronic/programmable	Electronic/programmable
Wander width	1.4 m	1.4 m	1.4 m	2.0 m
Max speed	10 km/h	13 km/h	20 km/h	20 km/h
Bi-directional loading	Yes	Yes	Yes	Yes
Uni-directional loading	Yes	Yes	Yes	Yes
Test section dimensions	8 × 1.4 m	8 × 1.4 m	14 × 1.4 m	12.2 × 1.4 m
Loading range	40–150 kN	20–205 kN	20–205 kN	45–445 kN

ASB), asphalt treated permeable base ATPB), PCC, fast-setting hydraulic cement concrete FSHCC), modified binders and cement treated bases CTB), full-depth reclamation, interlocking concrete pavers and warm mix asphalt conventional and rubberized). Tests have evaluated rehabilitation and maintenance strategies including dowel bar retrofit, long life pavement designs asphalt and PCC), overlays for reflective cracking on concrete and asphalt, precast concrete, new composite pavement, fully permeable pavement and bridge deck joints. Performance of DGAC and RAC-G overlays on AC has been compared, and long-life flexible overlays of existing PCC have been developed and tested. Dowel bar retrofit DBR) of PCC for potential performance of this approach has been evaluated, as has deep in-situ recycling DISR) of AC pavements using foamed bitumen. Details have been published elsewhere [9] and in the proceedings of the international conferences on APT, or can be found at www.ucprc.ucdavis.com

As part of the ongoing assessment of the benefits and costs of the APT in California, a study was commissioned by Caltrans in 2009 to determine the benefit/cost ratio of using APT to speed the implementation of new pavement technology using a case study of long-life asphalt pavement [6,7]. The study approach had been previously developed for CSIR and applied to their program. The study showed benefit/cost ratios ranging from 2.8 to 17 depending on the opinions of Caltrans district engineers in terms of the contribution of APT results to their decision making, and the discount rate used in life cycle cost analysis calculations. Pictures of the two active HVS units in California can be seen in Fig. 2.

5.2. Mexican Institute of Transportation (IMT)

The Mexican Institute of Transportation (IMT) was aware of the importance of implementing an APT program to better asses the Mexican infrastructure and to implement an improved procedure into their pavement design and construction practices. Therefore, the acquisition of the HVS was done through a national roadway construction and management concession project. The HVS was received in October 2015 and since then two projects are being conducted. The first one is the evaluation of the impact of adding synthetic zeolites into Portland Cement Concrete on rigid pavement performance. Two test tracks were constructed and testing will begin early 2016. The second project will occurred approximately on the second quarter of 2016. This project will have the main objective to compare the rigid pavement performance when cement treated bases or aggregate bases are used as construction platforms (see Fig. 3).

5.3. University of Costa Rica (LANAMME-UCR)

The University of Costa Rica received their HVS in late 2012. The APT program also includes the construction of a state-of-the-art facility which includes the space to build eight test tracks and a water pit to control water table and monitor moisture content on the unbound layers. A newly design aging chamber with ultraviolet lighting has been implemented. Since the beginning of the APT program a series of experiments have been design and completed. As of August 2015 nearly 5 million repetitions have been applied to the test tracks which in turn represent approximately 11.5 million ESALs. See Fig. 4 for a picture of the HVS inside the testing facility in Costa Rica.

The experiments that had been undertaken involved the evaluation of flexible pavement performance with cement treated bases, polymer modified asphalts, aggregate bases and conventional pavement structures. In addition, construction variability was also evaluated. The main outcome of these experiments is the calibration of the national transfer functions that are part of the Mechanistic-Empirical Pavement Design Guide for Costa Rica [12].

5.4. Central Road Research Institute, India

The HVS has been used for comparison of uni and bi-directional rutting on a flexible pavement test section designed as per the Indian Design Guidelines i.e. Indian Road Congress (IRC)-37:2001. The finding of the study has been communicated to Flexible Pavement Committee of the IRC for possible inclusion in the revision of the guidelines. Permanent deformation of each layer was also measured using Multi-Depth Deflectometers (MDD) and the results, along with other APT data, have been published internationally. The HVS of the Central Road Research Institute is shown in Fig. 5.

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Fig. 2. The HVS Mk II and Mk VI units operational in California.

Fig. 3. The HVS Mk VI with extended beam in Mexico.

5.5. Ministry of Transport (MOT), Kingdom of Saudi Arabia

Current HVS testing is focussed on evaluating rutting performance of crumb rubber and polymer modified asphalt at high temperatures. It is also intended to evaluate the use of up to 30% sulphur as an asphalt modifier. The long term goals are to develop an MOT ME pavement design procedure, as well as construction specifications and guidelines. See Fig. 6 for a picture of the HVS in the Kingdom of Saudi Arabia.

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Fig. 4. The HVS Mk VI inside the testing facility of the University of Costa Rica.

Fig. 5. The HVS Mk IV^+ of the Central Road Research Institute, India.

5.6. US Federal Aviation Administration

Heavy Vehicle Simulator – Airfields Mark VI (HVS-A) is used for full-scale accelerated pavement tests to study the performance of greener/sustainable technologies and pavement surface layer materials (like Warm Mix Asphalt Stone Matrix Asphalt, Recycled Asphalt Pavement) at high aircraft tire pressures and pavement temperatures. The HVS-A is capable of applying a maximum wheel load of 100,000 lb 450 kN). It has a central controller that can be programmed to provide automatic test sequencing and interfacing with the pavement instrumentation and data acquisition system. It can accommodate a lateral wander pattern up to a maximum wander width of ±3 feet total wander 6 feet). HVS-A is equipped with heaters and insulation panels and is capable of heating the test pavement surface up to 150 °F. HVS-A is stationed at the FAA's National Airport Pavement and Materials Research Center NAPMRC) in Atlantic City, NJ (see Fig. 7). The facility has six test lanes 4 outdoors and 2 indoors). Currently, Test Cycle-1 TC-1) is under progress. The objective of TC-1 is to study the performance of different materials HMA and WMA with different binder grades) and the effect of tire pressure on pavement performance. The results from this facility will be used to develop FAA Standards/Specifications [8].

The HVS-A was also used on acceptance test strips to study the effects high tire pressures (1.45 and 1.75 MPa) on HMA rutting; to evaluate structured methyl methacrylate (MMA) for use as paint stripes; and to evaluate the performance of different 'rumble strip' configurations.

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Fig. 6. HVS Mk VI of the Ministry of Transport, Kingdom of Saudi Arabia.

Fig. 7. The HVS Mk VI – A of the FAA.

5.7. Virginia Department of Transportation (VDoT)

The HVS Mk VI is being used to evaluate reflection cracking performance of three modified binders viz. rubber (wet process), ground rubber blown in at plant and Kraton high polymer compared to a control SMA 76–22 binder. It is also being used to evaluate overlay performance on recycled CCPR pavement. Fig. 8 shows the VDoT HVS with its temperature control chamber.

5.8. Finland and Sweden (VTT & VTI)

The VTT/VTI Mk IV HVS was delivered to Finland in 1997 where it tested typical Finnish pavement structures (see Fig. 9). It was subsequently moved to Sweden where testes have included the evaluation of three pavements with gradually increased bearing capacities, as well as evaluation of mill & fill maintenance treatments for these sections. Innovative approaches such as the use of steel mesh in bituminous pavements have been evaluated. The performance of crushed rock compared to natural gravel have been studied, as well the effect of mica content in unbound base layers, and the effect of gradation variations in crushed rock subbases. Different base layer thicknesses on light fill material have been tested, and different quality cement-bound base layers comprising semi-rigid pavements have been evaluated. Collaborative studies have been performed with Iceland to evaluate Icelandic base- and subbase

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Fig. 8. HVS VI of the Virginia Department of Transportation fitted with its temperature control chamber.

Fig. 9. The HVS Mk IV of VTT.

performance, and a proposed warranty pavement structure for Poland was tested. Detailed reports are available at www.vti.se.

5.9. Florida DOT

In the first 3.5 years after receiving the HVS Mk IV+ in 2000, FDOT has applied 8.5 million uni-directional passes of a 40 kN wheel load (see Fig. 10). This would be 17 million passes if a bi-directional approach had been used. FDOT has evaluated the effects of polymer modification of Superpave mixtures, as well as the rutting performance of coarse and fine-gained mixtures. The early strength requirements for PCC slab replacement to minimize shrinkage have been studied and the feasibility of using composite pavements such as UTW and TWT in Florida has been investigated. The HVS has also been used to test the performance of raised pavement markers. Details can be found at: www.dot.state.fl.us/statematerialsoffice/pavementevaluation/peresearch/apt.

Fig. 10. HVS Mk IV$^{\pm}$ of Florida DOT.

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Fig. 11. HVS V – A of USACE waterways experimental station.

5.10. USACE CRREL

This HVS Mk IV programme specializes in APT at their frost-effect research facility which allows moisture and temperature control. A subgrade performance study evaluating moisture effects was initiated with FHWA and included collaboration with Denmark and Finland. This study continues as a pooled-fund approach led by NYDOT and includes 18 other States. CRREL also performed a tire-pressure effect study on low-volume road pavements for the USFS, and a thaw-effect study for the USAF. They have evaluated the use of geogrids to reduce base thickness requirements, and have evaluated utility cut repair performance. Details can be found at www.crrel.usace.army.mil/cerd/hvs.

5.11. USACE WES

The HVS-Airfield Mk V at WES is typically used for high wheel load short duration APT studies (see Fig. 11). For instance, the first test at WES was planned to involve 100,000 coverages of a B727 aircraft gear. Work has been performed on evaluating pavement structures for the new C-17 cargo aircraft including rapid repair strategies. Short term research has focused on wheel load interaction for new aircraft gear configurations. WES is unique in its evaluation of expedient airfield pavements for military use over very short periods, with durations of 4 weeks, 6 months or 2 years. The long-term efforts focus on pavement performance relationships. Details can be found at: http://pavement.wes.army.mil/at.

6. Conclusions

The South African HVS programme had a significant impact on the development of pavement engineering in South Africa over the past 40 years. The use of this technology has resulted in significant savings in road building and rehabilitation costs to the country. The successful use of the HVS in South Africa led to increasing international interest in the technology, and two HVS MK III's were acquired by Caltrans in 1994 for use in the Cal/APT research program. This extremely successful APT effort has evolved into the current PRC program, now using a MK VI HVS. The California success spurred further interest and the HVS technology was continually improved to the current MK VI version. Seventeen machines are in use worldwide for APT efforts on a wide variety of pavement types and concerns by the organizations listed in the paper. This makes the HVS the most successful and widely used APT device in the world, largely due to its reliability, durability and productivity. Further HVS improvements are under consideration by CSIR and Dynatest, and are likely to be implemented if the current high level of interest in APT continues into the future. Given the international acceptance of HVS technology, the next 40 years are likely to be equally successful.

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