Accelerated Dynamic Loading of Flexible Pavements at the Canterbury Accelerated Pavement Testing Indoor Facility

BRYAN D. PIDWERBESKY

New Zealand pavement design and construction practices are significantly indigenous, having evolved to suit the local conditions. Asphalt-bound aggregate systems are used for some urban streets and interurban motorways, and some rigid pavements were constructed 50 years ago, but virtually all highway traffic is carried by thin-surfaced unbound granular pavements. The need to ensure that designs and materials are adequate for modern vehicles provided the impetus for developing an accelerated pavement testing facility that reproduces vehicle dynamics. First, the development of the Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) is described. The main feature of CAPTIF is the Simulated Loading and Vehicle Emulator, which can apply a myriad of loading conditions via an array of tire and load configurations at high rates of accelerated loading. Second, research projects conducted since 1986 are discussed and the significant results are presented. The research conducted at CAPTIF has contributed to the understanding of the behavior and performance of thin-surfaced, unbound granular pavements and the effect of vehicle dynamics on pavement wear.

The New Zealand road network totals nearly 100 000 km in length, of which 55 000 km have all-weather surfaces, and serves a population of 3.3 million over an area of 268 675 km^2. The typical pavement consists of a sprayed chip seal over unbound granular base and subbase layers. The pavement engineering design and construction practices used in New Zealand are described elsewhere (*1–3*).

The thickness design procedure for thin-surfaced, unbound granular flexible pavements is based on multilayer linear elastic theory. The procedure assumes that surface thicknesses of less than 35 mm do not contribute to the structural capacity of the pavement and that the stresses are dissipated through the depth of the granular cover layers above the subgrade. The design theory presupposes that the primary mode of structural failure is permanent deformation in the subgrade, so the main criterion is to limit the vertical compressive strain in the subgrade to acceptable magnitudes (*3*). The New Zealand subgrade criteria are derived from the *Shell Pavement Design Manual* (*4*).

At present, the maximum gross vehicle weight permitted on national highways is limited to 430 kN, and the maximum loads permitted for single-, tandem-, and triple-axle groups are 80, 145, and 175 kN, respectively. The New Zealand term for equivalent single-axle load is equivalent design axle (EDA); one EDA is defined as an 80-kN axle load on dual tires inflated to 550 kPa. Typically, the maximum design life would be on the order of 10^6 EDA.

Because of New Zealand's unique situation with respect to both the road user charges incurred by heavy vehicles and the dependence on thin-surfaced flexible pavements, research has been undertaken to isolate the influence of various components of the vehicle-pavement interaction system, such as the static and dynamic components of vehicle loading, and the relative effects of vehicles, the environment, and the pavement materials. Laboratory testing and computer analysis alone are inappropriate. Thus, trials using full-scale equipment and pavements are necessary, either in the field or in a test track under controlled conditions. Therefore, the first New Zealand accelerated loading facility was constructed in 1969 (*5*).

The first machine was used for a number of pavement research projects and finally became unserviceable in 1983. An assessment of the need for a new, improved accelerated pavement loading facility identified four primary research priorities:

- Evaluation of the performance of aggregates, such as marginal materials;
- Modified designs for surfacings, especially chip seals;
- Evaluation of pavement design assumptions by collecting data describing the long-term performance of pavements; and
- Investigation of the relationship between vehicle loading conditions and the deterioration of pavements for a wide spectrum of pavement and loading characteristics.

Accelerated pavement testers have been constructed in a variety of configurations (*6–8*). The facilities are generally classified as being circular or linear test tracks. A circular test track in which full-scale pavements could be constructed and a loading apparatus capable of imposing realistic dynamic heavy vehicle loading were selected because

- The machines can be operated continuously without being interrupted for direction changes, thereby greatly increasing the rate of load cycling;
- After initial acceleration, the speed of the loading system can be kept constant for long periods of time or varied, depending on the requirements of specific projects;
- Circular tracks can be divided into a number of either annular rings or longitudinal segments, each containing a pavement with some unique characteristics, and all segments can be tested simultaneously under the same or varying loading conditions;
- The configuration of each loading assembly in a multiarmed machine, such as tire types and pressures, axle numbers and weights, suspensions, and loads, can be altered so that the response of the same pavement under various loading conditions can be determined; and
- The interaction of pavements and vehicle dynamics can be examined using a combination of unsprung and sprung masses possessing realistic damping characteristics.

University of Canterbury, Private Bag 4800, Christchurch, New Zealand.

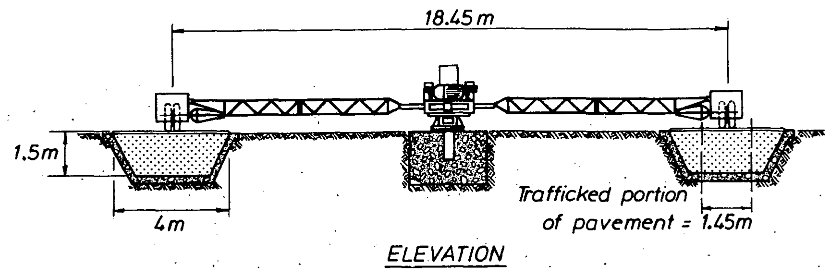

FIGURE 1 Elevation view of SLAVE and cross section of track.

DESCRIPTION OF FACILITY

The Canterbury Accelerated Pavement Testing Indoor Facility (CAPTIF) is housed in a hexagon-shaped building that is 26 m wide and 6 m high. An annular concrete tank, 1.5 m deep and 4 m wide, confines the bottom and sides of the track (Figure 1), enhancing the control of moisture contents in the subsurface systems and drainage. The track has a median diameter and circumference of 18.5 and 58.1 m, respectively. Normal field construction and compaction equipment is used in the facility. The main feature of CAPTIF is the Simulated Loading and Vehicle Emulator (SLAVE).

Simulated Loading and Vehicle Emulator

SLAVE was designed for the accelerated testing and evaluation of subgrades, pavements, and surfacings by replicating the effect on the pavement of actual road traffic conditions. An elevation view of SLAVE is presented in Figure 1. A sliding frame within the central platform is moved horizontally a maximum of 1 m (from stop to stop) by two hydraulic rams; this radial movement produces multiple wheel paths. The base elevation can be altered by up to 150 mm, to maintain the dynamic balance of the machine if the pavement surface level changes due to rutting or an overlay being applied.

Each vehicle consists of the axle, which is driven by a hydraulic motor, a suspension, a frame, instrumentation, and standard wheel hubs and truck tires (Figure 2). SLAVE vehicles can carry single or dual tires; their loads can be adjusted to between 21 and 60 kN (42 to 120 kN axle loads) by adding or removing steel weights. The suspensions can be multileaf steel spring, a parabolic steel leaf spring, or an air spring; each vehicle can carry the same or a different suspension for simultaneous testing. The speed can be any value between 0 and 50 km/hr and can be varied while running. The vehicles can be moved slowly and positioned at any location on the track, using a handheld, infrared remote control.

SLAVE operations are controlled directly by its internal electronics. The external or onshore computer is an IBM-compatible personal computer. Whenever a parameter is to be altered, the new command is sent by the external computer through a communications link under the track and a slip ring within the central pedestal. SLAVE and the computers can safely be left running without supervision.

Testing routines can be programmed in terms of start-stop times, distance or revolutions to be run, traveling speeds, and tracking pattern of wheelpath positions, and so forth. Any combination of these may be included in a programmed testing routine because the SLAVE software will use default values for those items not defined in the shore computer program. Manual control can be imposed when desired to override the current program. In addition to conventional hydraulic pressure, electrical current, and motor overload devices, the SLAVE electronics continually scans the safety monitors, and if a condition occurs that requires human inspection, brakes the vehicles to a stop.

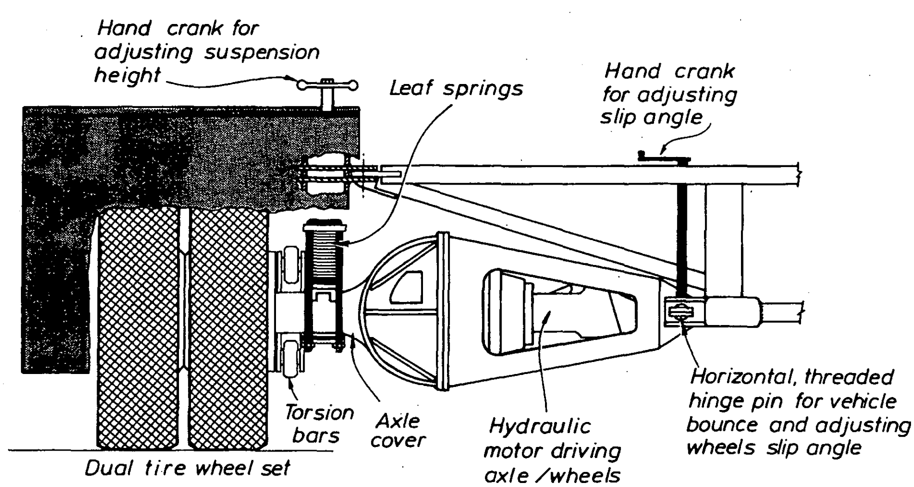

FIGURE 2 Cross section of one SLAVE vehicle.

Instrumentation and Data Acquisition

Since SLAVE was commissioned in 1987, electronic systems have been introduced that measure dynamic and residual strains and displacements, surface profiles, rebounds, and temperatures in the pavement and subgrade. The CAPTIF deflectometer, which is a modified version of the geobeam device developed by Tonkin and Taylor Ltd. of Auckland and resembles a Benkelman beam, measures the surface deflection of a pavement under a wheel load. The deflectometer probe is positioned between the tires of a dual-tired wheel and, as the wheel is moved away, the rebound of the pavement is measured to the nearest 0.01 mm, every 50 mm of horizontal movement. There are no moving parts on the device; an electromagnetic gap-measuring sensor at the end of the beam measures the vertical distance between the sensor and a steel disk placed on the pavement surface. A separate, associated device measures the horizontal movement of the wheel.

The CAPTIF profilometer measures transverse surface profiles using similar electronics. The profilometer consists of a braced aluminum beam, 4.4 m long, supported at each end by adjustable feet. An aluminum carriage is driven along the beam by an electric motor and drive chain. The carriage holds a linear variable displacement transducer with a jockey wheel riding along the pavement surface. Vertical displacement is recorded every 25 mm of horizontal travel of the carriage.

The output signals from the foregoing are digitized by electronics contained within the devices, and the digital data are captured by a Psion handheld computer. A DIPStick profiler is used to measure the longitudinal surface profiles for roughness surveys. The output from temperature probes installed in the pavements are automatically recorded hourly by a Taupo F-10-24K-48A data logger. A Hewlett Packard 3852S microprocessor-based unit and computer capture data signals from accelerometers and displacement transducers mounted on the chassis and axles of each vehicle, for measuring the dynamic loads being applied by the axles, and transmit the data to a trackside computer via radiowaves, while the vehicles are running at speeds of up to 50 km/hr.

The soil strain measuring system determines minute strains (100 μm/m) with good resolution (±50 μm/m) using Bison soil strain sensors. The sensors use the principle of inductance coupling between two free-floating, flat, circular wire-wound induction coils coated in epoxy, with a diameter of 50 mm (*9*). One of the two disks acts as the transmitter coil, creating an electromagnetic field that induces a current in the receiving coil. The magnitude of the induced current is inversely proportional to the spacing between the two coils (Figure 3). The gauge length is the separation distance between each paired coil. The Bison disks are installed during the formation of the subgrade and the overlying layers to minimize the disturbance to the materials.

The CAPTIF strain-measuring system is a modified prototype of the Saskatchewan soil strain displacement-measuring system developed by Saskatchewan (Canada) Highways and Transportation. The CAPTIF system uses a dedicated computer containing a specially built general-purpose input-output board, circuit boards, rectifiers, amplifiers, and assembler code written specifically for this application. Each sensor in an array is scanned simultaneously when triggered, every 30 mm of vehicle travel, so that a continuous bowl shape of strain versus distance traveled is obtained.

PAVEMENT RESEARCH PROGRAM

The research projects conducted at CAPTIF since 1986 are summarized in Table 1. The major findings are discussed in this section. In

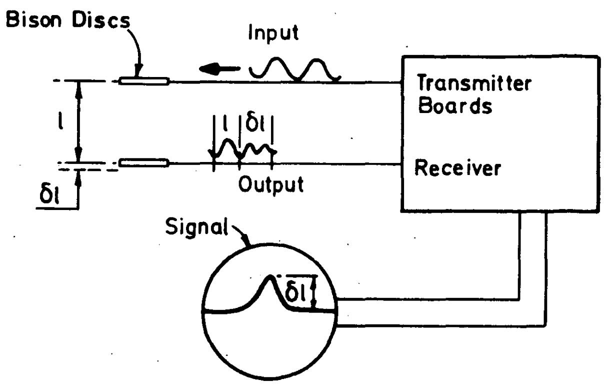

FIGURE 3 **Principle of Bison strain sensors.**

all the projects, the subgrade and the granular layers were spread by a small bulldozer and compacted by a 40-kN dual-drum roller. The surface of the base course is finished with a pneumatic-tired roller.

Inaugural Project

The purpose of this project was (a) to commission the SLAVE and evaluate its capabilities and (b) to monitor the performances of four granular pavements to provide an initial evaluation of the construction and operation techniques required for the accelerated trafficking facility. The average California bearing ratio (CBR) of the clayey loess subgrade was 30 percent. The pavement thicknesses ranged from 150 to 300 mm, in 50-mm increments; the pavement material for all four was a well-graded aggregate with a maximum particle size of 40 mm, except the uppermost lift had a maximum size of 18 mm. The surfacing was a double seal coat; soon after loading began, the seal began flushing, even though there was no loss of chip and the base course was firm. After flushing became severe, the initial coats were removed and the base course lightly releveled. A single coat of bitumen sprayed at a lower-than-normal rate was coated with a first layer of larger stone chips (A.L.D. of 12 mm) interlocked with smaller chips (A.L.D. of 8 mm).

Each SLAVE vehicle applied a wheel load of 40 kN to represent an equivalent design axle (EDA) SLAVE applied 1.53 million EDA loads to the pavement during the project. There was no significant difference in the performances of the four pavements; even the thinnest unbound granular pavement of compacted, well-graded crushed aggregate can sustain at least 1.5×10^6 80-kN axle load repetitions in the absence of deleterious ground moisture and environmental factors (*10*). The pavement thickness design procedure should be modified to explicitly consider the effect of such factors.

Comparative Rutting of Tire Types

The vertical deformation caused by a single low-profile radial tire (14.00/80 R 20 on Vehicle B) and dual standard radial tires (10.00 R 20 on Vehicle A) was compared. The load applied by each wheel set was 40 kN. The clayey loss subgrade material had an average CBR of 30 percent. The pavement consisted of a 40-mm-thick surfacing of an open-graded bituminous mix, a 150-mm-thick base course of a high-quality crushed aggregate, and a 150-mm-thick subbase of coarse aggregate with a maximum particle size of

TABLE 1 Summary of Projects at CAPTIF

Project and Variables	Load Repetitions (EDA)	Wheel Loads (kN)	
		Veh. A	Veh. B
Inaugural: 4 thicknesses unbound granular pavements under chip seals	1.5 x 10^6	40	40
Comparative Rutting: duals and wide-base single tires	94,700	40	40
Effect of Particle Shape and Gradation on Basecourse Performance: 9 pavements	54,300	40	40
Lime-stabilised subbases: 3 thicknesses	30,500	21, 40	21, 40
Strain response of subgrades and unbound granular pavements: wheel load, tire pressure and tire type	51,000	40	21-46
Modified Binders in Asphalt Mixes: 6 modified binders	3.2 x 10^6	40-46	40-46
Life-cycle performance of a thin-surfaced unbound granular pavement	740,000	40	40
Dynamic wheel loads and pavement wear: single unit and multi-leaf spring suspensions	35,000	38	38
DIVINE* (Element 1): air bag and multi-leaf suspensions		50	50

* Dynamic Interaction of Vehicles and Infrastructure Experiment

65 mm. Further information about the pavement and temperatures are provided in Table 2. After 16,000 loading cycles, the average permanent deformation (as measured by the transverse profilometer) created by the single low profile radial tire was 92 percent greater than that of the dual radial tires, as shown in Figure 4 (*11*).

Effect of Particle Shape and Gradation on Unbound Base Course Performance

The study evaluated the effect of particle shape and gradation on the performance of unbound base course aggregates constructed according to a revised specification (*12*). Aggregates consisting of different combinations of rounded and angular crushed particles were created for three different particle size distributions using Talbot's equation.

$$P_d = 100\left[\frac{d}{D}\right]^n \qquad (1)$$

where

P_d = percentage of sample passing sieve size d,
d = sieve size (mm),
D = largest particle size in sample (mm), and
n = gradation exponent.

The values for the gradation exponent (n), 0.4, 0.5, and 0.6, represent the lower limit, midpoint, and upper limit of the gradation envelope for New Zealand primary base course aggregate, respectively (*13*). Nine base course aggregates were created, as shown in Table 3. The base course aggregates were placed in nine sequential segments in the track, with an average depth of 108 mm ± 7 mm; the maximum dry density varied according to the gradation. Segments A, B, C, and I could not be compacted, so they were removed and replaced with a local aggregate; the four segments, which were adjoining, were combined into one segment designated A1. The 48-mm-thick (± 6 mm) surfacing was an open-graded bituminous mix (porous asphalt) with the same properties as described in Table 2.

After 54,000 EDA cumulative loadings, the subgrade deformation under loading was similar for all test segments, and base course deformation differed (Table 3). Particle shape had the greatest effect on the performance of the aggregates, compared with gradation. Aggregates consisting of 30 percent or less angular particles could not be compacted, and the best performance was achieved with aggregates of 70 percent or more angular particles, which is required by the New Zealand base course aggregate specification (*13*).

Behavior of Lime-Modified Subbases

Three pavements were constructed, two with lime-stabilized clay subbases of thicknesses 150 and 250 mm, and the third with an unmodified high-quality, well-graded, crushed aggregate, as shown in Figure 5. The laboratory CBR of the unstabilized and stabilized clay specimens were 5 and 20 percent, respectively. For all three pavements, the surfacing was a 30-mm-thick layer of asphaltic concrete and the base course was a 150-mm-thick layer of high-quality, well-graded crushed aggregate (*13*). The subgrade had a CBR of 3 percent, which represents the worst possible case, and a compacted dry density of 1 700 kg/m^3 ± 4 percent at a moisture content

TABLE 2 Asphalt Properties and Temperatures for Comparative Rutting of Tire Types

Mix Properties		Temperatures (°C)	Min.	Max.
Bitumen penetration grade (100 g, 5 sec, 15°C)	80/100			
Binder content (%)	5.5	Air	10	23
Air voids (%)	23	Tire Tread (A)	11	33
Hydrated lime (%)	2	Tire Tread (B)	11	33
		Pavement	10	22
Aggregate Gradation (% passing by mass)				
13.2 mm (sieve size)	100			
9.5	92			
4.75	25			
2.36	10			
1.18	7			
600 μm	5			
300	4			
150	2			
75	1			

of 20 percent. Laboratory tests showed that the optimum lime content for the subbase material was 4 percent. The maximum dry densities (at optimum moisture contents) of the unstabilized and lime-stabilized subbase material were 1 680 kg/m^3 (at 18 percent) and 1 520 kg/m^3 (at 25 percent), respectively. A geotextile (Typar 3407) was placed on top of the subbase to separate the base course aggregate material and the subbase, therefore enhancing the measurement of the layer profiles without interfering with the stress development and distribution within the pavement. The minimum temperature during curing was +6°C; during loading, the pavement temperature ranged between −3°C and +20°C.

Elastic deflections and permanent deformation of the pavement surface were measured; some results are presented in Table 4. Pavement failure was defined as vertical surface deformation of 25 mm. The pavement containing the 150-mm-thick lime-stabilized layer performed substantially better than the same thickness of unstabilized aggregate. Increasing the stabilized subbase thickness by 100 mm yielded a 15-fold increase in the life of the pavement. The moduli of the lime-stabilized layers were lower than that predicted by laboratory testing and computer analyses, primarily because the pavement could not be fully compacted on such a weak subgrade (*14*).

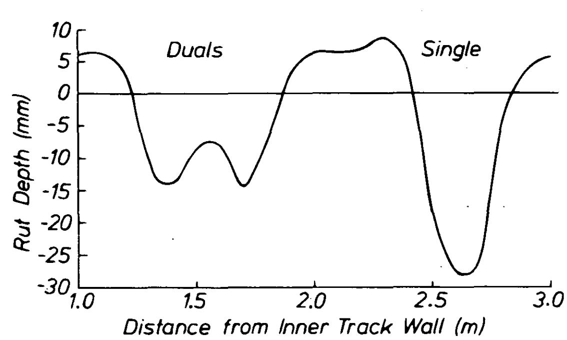

FIGURE 4 Pavement surface deformation under single- and dual-tire wheel loads.

Effect of Binder Modification on Asphalt Pavement Performance

The trial involved constructing six test sections of various asphaltic concrete mixes over 200 mm of unbound granular base course and a silty clay subgrade possessing a CBR of 13 percent. The base course aggregate was a well-graded, crushed gravel, compacted at a moisture content of 4 percent to a maximum dry density of 2 150 kg/m^3. The design life of all test sections was 1×10^6 EDA, so the depth of the asphalt concrete varied from 80 to 125 mm, depending on the characteristics of the different mixes. The bitumens used for the test sections were

- Standard paving grade (conforming to a German specification for B80 Grade),
- Binder modified with a plastomeric polymer,
- Binders modified with three types of elastomeric polymer, and
- High-stiffness (pen. grade 21 @ 25°C) binder.

TABLE 3 Properties and Performance Data for Particle Shape and Gradation Experiment

Segment	Angular Particles (%)	n	Maximum Surface Rebound (mm)	Maximum Surface Rut Depth (mm)	Subgrade Dry Density (kg/m³)	Subgrade Deformation (mm)	Basecourse m/c (%)	Basecourse Dry Density (kg/m³)
A	0	0.6	--	--	2190	--	--	2060
B	0	0.5	--	--	2160	--	--	2060
C	0	0.4	--	--	2200	--	--	2070
D	100	0.4	1.6	25	2210	10	2.7	1930
E	100	0.5	1.7	36	2250	10	2.7	1990
F	100	0.6	1.6	18	2210	7	2.7	1920
G	50	0.5	1.3	28	2280	7	2.4	2080
H	70	0.5	1.9	14	2220	8	2.9	2040
I	30	0.5	--	--	2240	--	2.2	2090

-- The surfaces of Segments A, B, C and I could not be compacted properly for surfacing

The surface deflection bowls, the vertical strains at various depths in the pavement and subgrade, longitudinal and transverse profiles, and temperatures in the bottom of the asphalt layer and in the base course were measured after specified intervals of loading cycles. A falling weight deflectometer was also used to measure the pavement structural capacity for the first part of the experiment. Data collected at CAPTIF were electronically transmitted daily to British Petroleum International in England. The wheel load was 40 kN for both vehicles for the first 920,000 loading cycles and 46 kN for the remaining 1.2 million loading cycles. The dual radial tires in both vehicles were inflated to 700 kPa, and the vehicle speed was 40 km/hr. Altogether, SLAVE applied 3.2 million EDAs to the test pavements. Details of the project and results are provided elsewhere (*15*). The rut depth was only 4 mm, indicating negligible compaction in the subsurface layers. The project concluded before the predefined failure criterion of a maximum surface rut depth of 25 mm occurred because the pavement design was conservative (pavements designed for 1×10^6 EDA should have exhibited greater deterioration after 3.2×10^6 EDA) and because the project costs exceeded the budgeted funds. The test sections exhibited negligible deterioration in their structural condition and minimal surface distress. It was concluded that the thinner asphalt concrete layers constructed with modified binders and the high-stiffness binder provided performance equivalent to that of the thicker layer containing a conventional binder (*15*).

Dynamic Wheel Forces and Pavement Wear

The objective of the current research program (1992–1997) is to compare the pavement deterioration caused by dynamic loads generated under different types of suspensions: steel parabolic leaf spring and shock absorber, multileaf steel suspension, and air bag suspension with shock absorber. By using the accelerometers and displacement transducers fitted to the SLAVE vehicles, vertical dynamic loads created by the vehicle bounce are related to subsur-

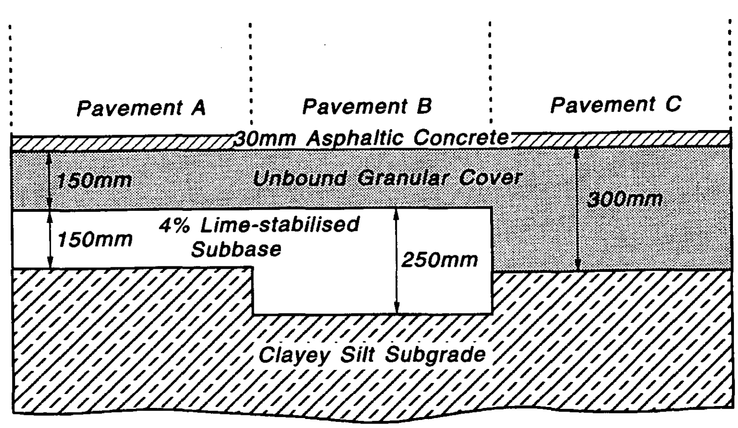

FIGURE 5 Cross section of pavements with lime-stabilized subbases.

TABLE 4 Properties and Performance Data for Lime-Stabilized Subbase Experiment

		Pavement Design		
		A	B	C
Subbase Dry Density (kg/m^3)		1490 ± 5%	1540 ± 4%	--
Moisture Content at Construction (%)		23.5	24.5	--
Basecourse Dry Density (kg/m^3)		2100 ± 2%	2070 ± 2%	2095 ± 2%
Moisture Content at Construction (%)		4	5	5
Surface Deflection[a] before Loading (mm)		4.5	1.4	9.7
Surface Deflection[a] at Failure (mm)		8.5	6.0	9.7
Cycles to Failure (21 kN wheel Load)		4400	30500	30
Asphaltic Concrete Mix				
Asphalt Binder Content (%)	6.5			
Bulk Density (kg/m^3)	2242			
Air Voids (%)	7.0			
Marshal Stability (kN)	15.36			
Marshal Flow (mm)	2.8			

[a] Benkelman Beam deflection test with 21 kN wheel load

face strains and longitudinal surface profiles measured by the DIP-Stick profiler and a laser device mounted on one vehicle. Altogether, five pavements will be constructed and tested sequentially. Sufficient subgrade soil and base course aggregate were procured for five pavements and have been stockpiled to ensure that the material properties of the pavement are the same for each suspension. The base course aggregate of well-graded crushed gravel was produced to stringent specifications (*13*) using a portable aggregate blending plant.

SUMMARY AND CONCLUSIONS

The development and operation of the CAPTIF, including SLAVE and the instrumentation systems, have been described. Research projects conducted since 1986 have been discussed, and the significant results were presented.

The CAPTIF SLAVE was designed to generate realistic dynamic wheel loads instead of attempting to eliminate them. The SLAVE vehicles that apply the loads are fitted with suspensions based on actual heavy vehicle components.

The facility has been beneficial in evaluating the performance of aggregates and pavement design assumptions by collecting data describing the long-term performance of pavements and investigating the relationship between vehicle loading conditions and the deterioration of pavements for a wide spectrum of pavement and loading characteristics.

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