THE ROLE OF THE MMLS DEVICES IN APT

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1 INTRODUCTION

Metcalf (1) defines full scale accelerated pavement testing (APT) as "…the controlled application of a prototype wheel loading, at or above the appropriate legal load limit to a prototype or actual, layered, structural pavement system to determine pavement response and performance under a controlled, accelerated, accumulation of damage in a compressed time period." For small scale APT, the definition must include wheel loading below the legal load limit.

Scaled testing of pavement structures and materials provides an alternative means for preliminary indicator or ranking tests prior to, or in place of, expensive full scale APT. Hugo (2) was the first to show the relationship between accelerated pavement testing and other pavement engineering methodologies (see Figure 1).

Figure 1 illustrates that APT forms an essential bridge between laboratory testing and Long Term Pavement Performance (LTPP) studies. The use of APT complements LTPP studies as pavement response, subsequent performance under controlled load, and environmental conditions can be monitored in a relatively short period with significant lifetime cost benefits. The authors have superimposed the relative position of model APT testing into the benefit-cost diagram (dotted line).

The immediate benefit of scaled APT is that testing can be done at a fraction of the cost of full-scale APT. Furthermore, testing can be done either in the laboratory or in the field under controlled environmental and testing conditions. This allows many of the variables impacting pavement systems to be controlled directly. Examples are the control of pavement temperature and trafficking speed. These factors have a direct influence on the stiffness of asphalt layers and hence the response of the pavement under loading. Controlling these variables eliminates uncertainties often associated with the development of APT performance models. In the development of APT performance models, a large number of tests are necessary to evaluate impacting variables and this has necessitated finding means whereby it would be possible to expedite the testing of the different variables, prior to conducting full-scale APT. Accelerated scaled testing provides a cost efficient and effective means of doing this.

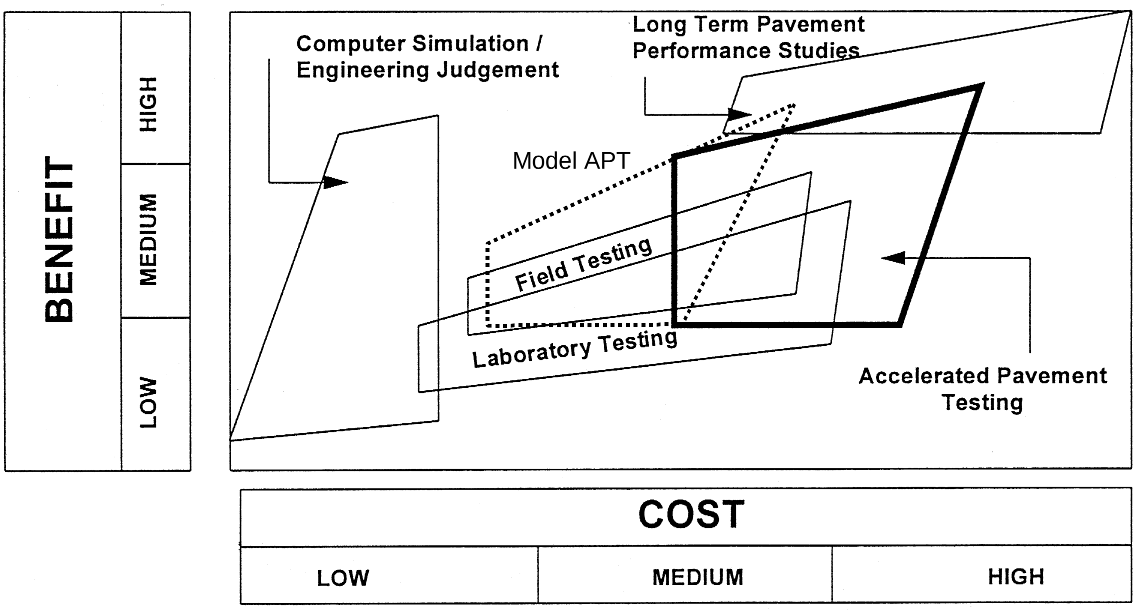

Figure 1. The Place of APT in Pavement Technology [after (2)]

Because of the possible role of model testing in APT, MMLS research initially focused on scaled testing of pavement structures with scaling of the materials and the pavement structure. More recently, the focus has shifted to the testing of in-situ conventional pavements. This became possible with the development of the MMLS Mk.3 as will be shown later. To understand the suite of available applications it is necessary to give a brief overview of the MMLS devices. It is also important to gain insight into the constraints that have to be considered in (some of the) model tests.

The options for testing with the MMLS equipment are shown in Table 1 and will be discussed throughout this paper. The table indicates links between different applications. For the first case, for example, pavement structures in the field comprising full-scale materials may be tested.

Table 1. Possible MMLS applications of structures and materials

STRUCTURES			**MATERIALS**	
Pavement structure in the field	**Scaled pavement structure**	**Laboratory model structures**	**Scaled materials**	**Full scale materials**
X				X
	X		X	
	X			X
		X	X	X

2 THE MMLS FAMILY

At the moment two devices are members of the model MMLS family, the MMLS Mk.1 and MMLS Mk.3. The MMLS Mk.1 was introduced as a scaled down 1:10 APT device for use in a controlled environment (3). A schematic of the MMLS Mk.1 is shown in Figure 2. The development of the full-scale MLS in Texas was based on the 1:10 scale prototype MMLS. The latter was later utilised for testing model pavements with scaled down materials. The main advantages of this type of scaled APT device are that:

1. The load is always moving in one direction.
2. Many repetitions are possible in a short period.
3. A relatively high trafficking speed is possible.

Many practical difficulties were experienced with the scaling down of material properties and the thickness of model pavement layers by 1:10. To overcome some of the scaling constraints experienced with certain tests using the MMLS Mk.1 and to facilitate a wider spectrum of applications, a larger, more robust machine was developed i.e. the MMLS Mk.3. The relative scale of the MMLS Mk3 allows pavement structures to be scaled down by a factor 3 - 4.5. In many cases this is more practical than scaling down pavement layers by a factor 10, for example, the thickness of a full-scale layer of 200 mm can be scaled down to 50 mm. Figure 3 shows a schematic of the wheel configuration of the MMLS Mk3.

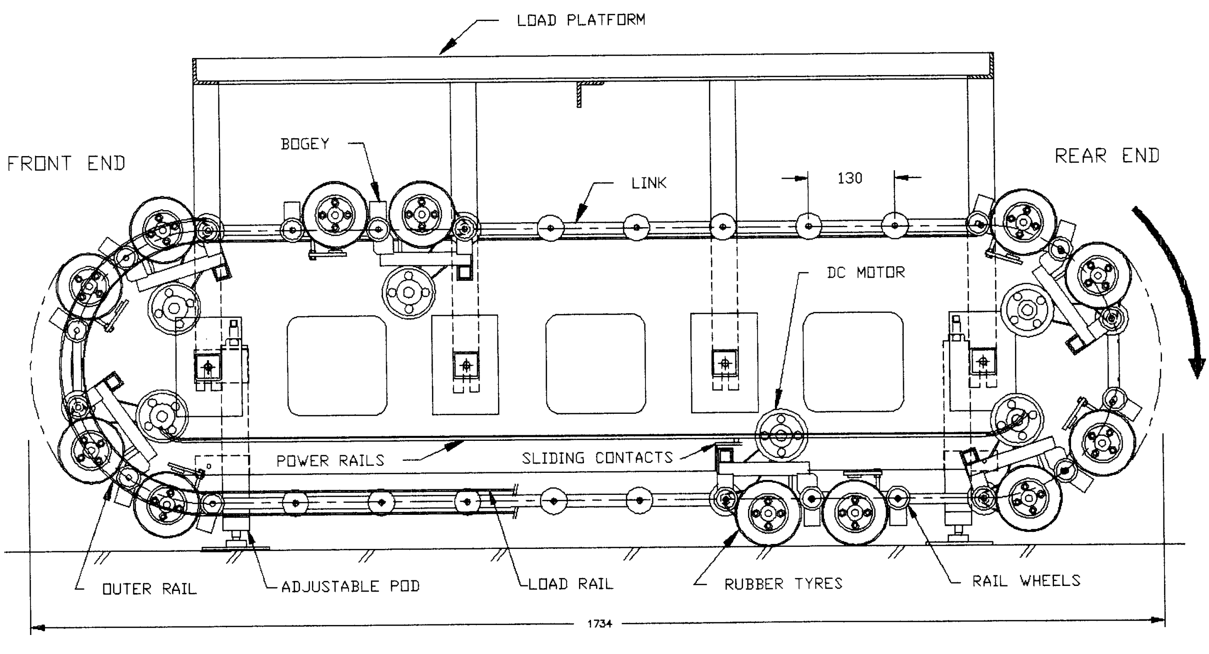

Figure 2. The MMLS Mk.1 with a complete dual wheel axle

An advantage of the MMLS Mk.3 is that it can be used for doing field tests on conventional pavements (provided the maximum particle size is less than 25 mm). The device has four wheels (300 mm diameter and 80 mm wide) and these can be laterally displaced across 150 mm in a triangular distribution about the centre-line. Alternatively, the lateral wheel load distribution can be done by displacing the machine transversely intermittently during trafficking. In this way the distribution can be controlled to a predetermined distribution pattern. The MMLS Mk.3 is able to apply 7200 wheel loads per hour. The wheel load can be set to 2.1 kN or 2.7 kN and tyre pressures may be varied up to 900 kPa.

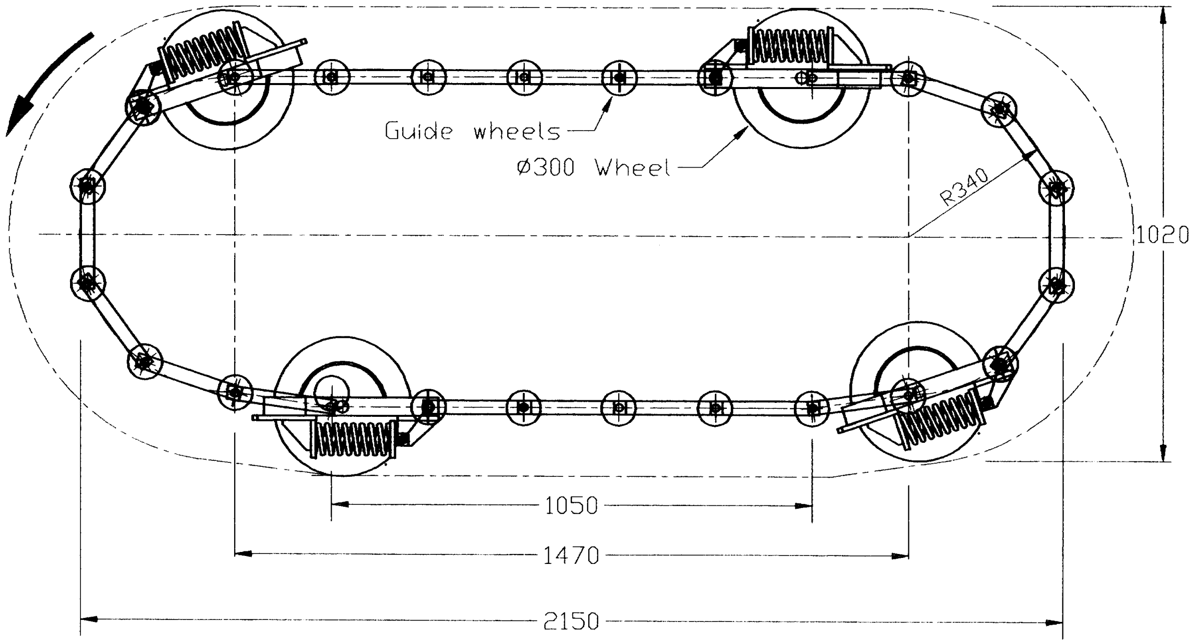

Figure 3. Wheel Configuration of the MMLS Mk.3 with a single wheel configuration

3 BASICS OF MODELING

Scaled down APT testing requires consideration of the following differences between scaled down and normal trafficking:

1. loading functions (rate, mode and magnitude),
2. dimensional and material properties,
3. transfer functions (scaled down to full-scale),
4. time domains, and,
5. environmental influences.

<u>3.1 Loading Considerations</u>

If one assumes an elastic pavement response, then the fundamental principle underlying model testing is that a pavement's structural composition, when scaled down, is subject to the same stresses and strains as a full-scale pavement under equivalent loading and assuming the same material properties i.e. stiffness and Poisson's ratio. In the case of the MMLS MK.1, this is valid provided the load contact pressure of the scaled down (1:10) vehicle is the same as the full-scale vehicle, and the total applied load is one hundredth the full-scale load. This is shown as follows:

$$P_F = \frac{F_F}{\pi \cdot r_F^2} = P_S = \frac{F_S}{\pi \cdot r_S^2} \text{ but } r_S = \frac{r_F}{10} \text{ therefore } F_S = \frac{F_F}{100}$$

where:

P_F = Full-scale tyre pressure
P_S = Scaled down tyre pressure
F_F = Full-scale wheel load
F_S = Scaled down wheel load
r_F = Full-scale contact area
r_S = Scaled down contact area

The rate and mode of loading is an important consideration when testing visco-elastic materials such as asphalt at elevated temperatures. This is discussed in greater detail later.

3.2 Physical Dimensional and Material Properties

The visco-elastic response of scaled down asphalt pavements under MMLS loading prompted research into the dimensional effects of loading functions with respect to full-scale testing. Kim *et al*. (4) have shown that for extrapolation from scaled to full-scale to be valid, the laws of the theory of similitude must be satisfied. This means that all variables with given physical dimensions must be reproduced at exactly the same proportions and with the same properties from the full-scale to the model. Complete similitude may not be possible in most cases. The use of scaled models will still be valid if one can ensure that the variables that are not properly scaled have a negligible effect on the measured response both in the field and in the laboratory. This is a difficult task requiring theoretical knowledge and expert engineering judgement.

Dimensional analysis considerations have been used to assess whether the results of laboratory tests can be extrapolated to predict the response observed in full-scale testing. In the mathematical modelling of any physical phenomenon, it is necessary to first select the parameters that control the behaviour one is attempting to predict. Once these parameters have been selected, dimensional analysis allows their combination in terms of dimensionless quantities that must have the same values in model and full-scale in order to satisfy laws of similitude. The three dimensions involved in most mechanics problems are length (*L*), mass (*M*) and time (*T*). If the material properties are influenced by temperature, as is the case for asphalt, temperature would be a fourth dimension which would need to be considered. An overview of the laws of similitude as they relate to scaling down is beyond the scope of this paper and the reader is referred to the work of Kim *et al*. (4). To summarise, they found that the response of the full-scale pavement is identical to the model if the following parameters (N is the scaling factor) are used and the materials are linear elastic:

Material properties	(Stiffness, Poisson's ratio)	1:1
Length	(Thickness, Particle size)	1:N
Load amplitude	(Force)	1:N^2
Stress on the surface	(Tyre pressure)	1:1
Velocity of loading	(Speed)	1:N

For visco-elastic materials, inertia effects resulting from dynamic loading require that the velocity of the bogies should be the same in the model and the full-scale for pavements with the same properties. The MMLS models do not have a suspension system (only quasi-static loading) and hence inertia effects under MMLS testing are ignored. It should be noted that visco-elastic response under transient loading is accounted for under model testing, as the rate of loading corresponds to the full-scale. The 1:10 scale parameters are illustrated in Figure 4.

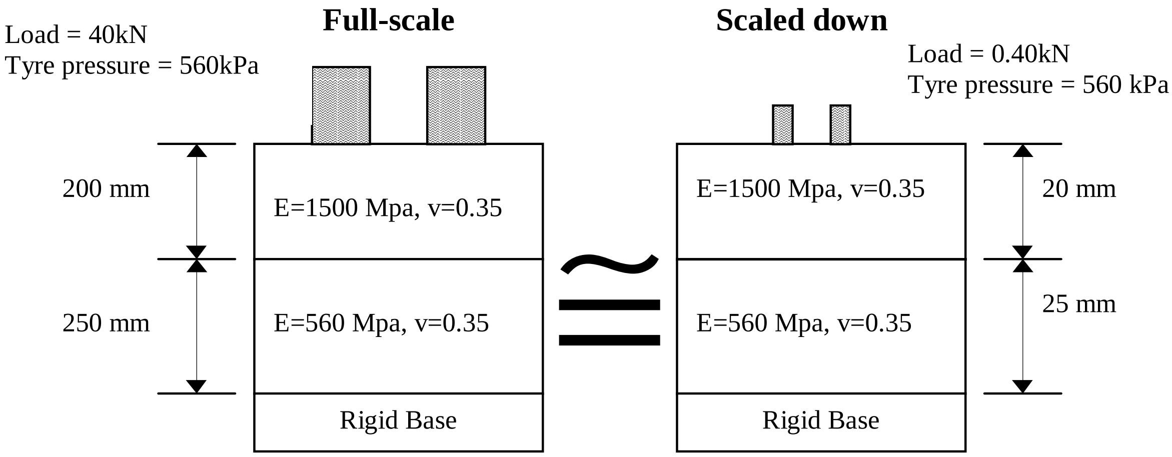

Figure 4. 1:10 Scaling of a full-scale pavement

4 SCALING DOWN OF MATERIALS

MMLS studies have shown that a scaled model could be used to reproduce at least some aspects of real pavement behaviour. More research is necessary, especially regarding the material properties of the scaled pavement. For visco-elastic full-scale and scaled down materials it is considered important to at least analyse the following mechanical properties:

1. Stiffness,
2. Strength and fatigue behaviour, and
3. Permanent deformation behaviour.

The volumetric differences between full-scale and comparable scaled down materials must also be considered. It was found that when scaling down pavement materials, the initial difference between the full-scale and comparable scaled down materials is noted with the filler content of the mix. It is practically difficult to scale down the fraction of the mix finer than 0,075 mm. The resultant filler fraction of the scaled down materials may be double that of the full-scale equivalent. Due to specific surface considerations for the fine fraction, a higher filler content requires a higher binder content. If cognisance is not taken of this detail, the mastic of the full-scale and comparable scaled down mix may differ significantly, which will influence the mix response.

Mix stiffness at lower temperatures is influenced by the bitumen properties and macro volumetric properties (voids in the mix, volume of bitumen and volume of aggregate) of the mix. In order to achieve comparable scaled down and full-scale stiffness properties, the binder content of a scaled down mix has invariably been considerably higher than that of the full-scale mix. Assuming that the voids in the mix of the full-scale and scaled down mixes should be the same, an increase in binder content for the scaled down mix must be countered by a decrease in the volume of aggregate in the mix. This will normally result in a lower mix stiffness at higher binder contents. The resultant difference in stiffness between full-scale and scaled down mixes will impact on the fatigue and permanent deformation characteristics of the mixes, and this should be accounted for when comparing full-scale and scaled down performance relationships. At higher test temperatures it is not enough to only look at macro-volumetrics with relation to mix stiffness as is illustrated in Figure 5.

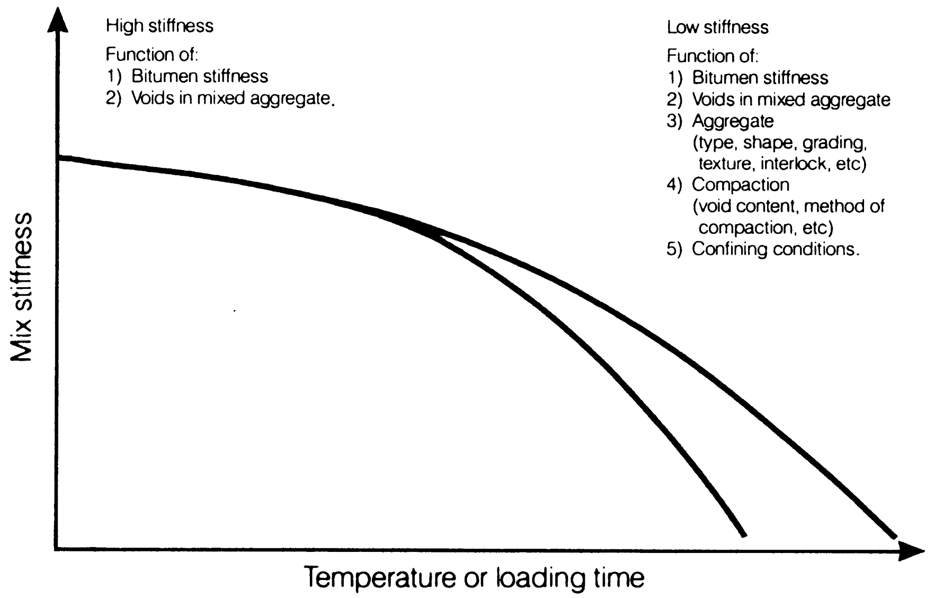

Figure 5. Mix stiffness as a function of temperature or loading time [after (5)]

At higher testing temperatures, the stiffness and permanent deformation characteristic are, to a great extent, influenced by the stiffness of the aggregate structure of the mix. Scaling may influence this stone skeleton, in that the larger filler fraction could break the aggregate interlock. Aggregate angularity and fractured faces should not be allowed to vary between full-scale and scaled down gradations.

Triaxial testing of full-scale and comparable scaled down granular materials to implement model testing (6) has shown that:

1. equivalent dynamic stiffness can sometimes be achieved for full-scale and scaled down mixes for a variety of materials,
2. the shear strength parameters may be kept acceptably constant for continuously graded mixes if attention is given to cohesion values. In particular, the clay content and plasticity of the material requires analysis,
3. materials such as Waterbound Macadam (large aggregate gap-graded mixes) do not provide very similar shear strength parameters when scaled down; however, scale test results will provide conservative assessments,

In the light of this, positive possibilities exist for APT on scaled down granular materials.

5 APT APPLICATIONS WITH THE MMLS MK.1

In light of the possible role of model testing in APT, attention has been given to the following fields:

1. Performance modelling
2. Validation of asphalt mix design
3. Ranking of candidate blends

Details of the different studies are beyond the scope of this paper and the reader is referred to the references for specifics on pavements structures, materials, ageing protocols etc.

5.1 Performance Modelling

The MMLS Mk.1 has been used to evaluate scaled asphalt pavements in terms of asphalt permanent deformation or rutting (3, 7, 8), and fatigue failure (9, 10). These model tests were all done on scaled down pavement structures. The effects of scaling down on material properties are discussed and examples of the MMLS performance testing are presented to give the reader a broad overview of the research undertaken.

Permanent Deformation Tests

The MMLS Mk. 1 has been used to investigate the effect of variation in binder content on the long term rutting performance of scaled down large aggregate asphalt pavements (8). It was found that the binder content of the pavement had a notable effect on its rutting performance. Pavements constructed at a lower than optimum binder content performed considerably better than those constructed at or above optimum.

A typical MMLS rutting profile measured under MMLS loading on a high binder content pavement is shown in Figure 6. Permanent deformation testing was carried out at a temperature of 40 C. Use was made of artificial ageing of the asphalt to simulate long-term environmental ageing.

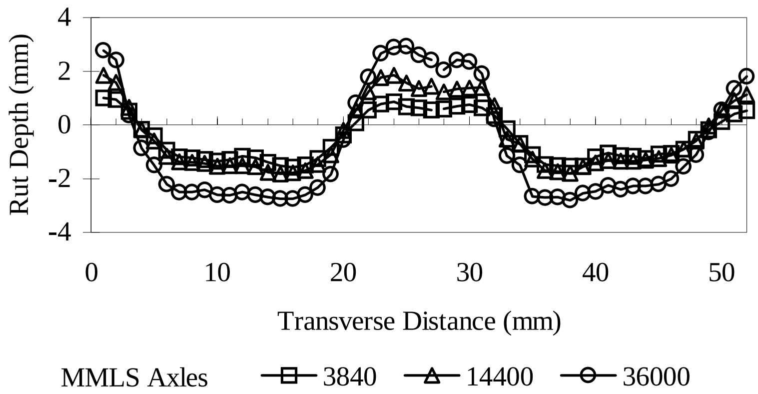

Figure 6. MMLS Mk.1 Rutting Profile for a High Binder Content Pavement [after(8)]

Fatigue Tests

MMLS Mk. 1 fatigue testing has been carried out at a temperature of 5 C. In one particular test, the influence of ageing on the fatigue performance of a scaled asphalt pavement was evaluated. One half of the trafficked model pavement was artificially aged by heating the pavement surface to 100 C and maintaining this temperature for an extended period. The remaining half was unaged. Use was made of Spectral Analysis of Surface Waves (SASW) techniques to allow a non-destructive means of determining in-situ pavement stiffness (9). A decrease in stiffness is indicative of pavement deterioration, in this case, fatigue distress. Figure 7 illustrates this for the MMLS pavement in question. Cumulative cracking of the MMLS pavement was also measured with trafficking as shown in Figure 8.

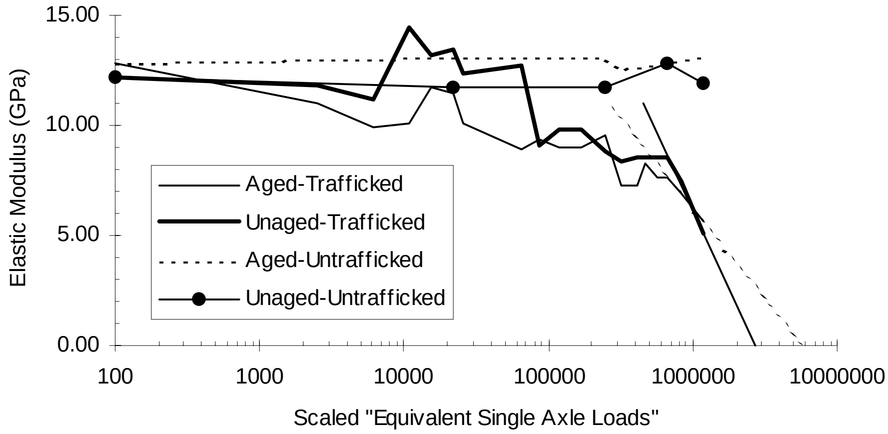

Figure 7. MMLS Mk. 1 Pavement stiffness measurements at 5 C using SASW [after (10)]

5.2 Validation of Asphalt Mix Design

The recent trend in asphalt mix design is to move from empirical towards more performance-based methodologies. In addition to assessing the volumetric properties, the SHRP Superpave mix design method incorporates accelerated performance-related tests for asphalt-aggregate mixes (11). A major shortcoming of the test procedure is that specimens for performance testing should be got from rolling-wheel compaction for it's obvious similarity to field compaction processes. Model testing with the MMLS Mk.3 can be done directly in the field. Furthermore, model testing allows a direct evaluation of the performance-related properties of asphalt mixes as actual transient wheel loads are applied.

As part of a research study initiated to validate Superpave mix design parameters (12), the MMLS Mk.1 was used and it was found that model testing had the ability to assess the influence of aggregate properties such as fine aggregate angularity on pavement performance where other laboratory mechanical tests such as the simple shear test (SST) failed. The model has also been instrumental in determining the significance of gradation restriction zones implemented in the Superpave design methodology.

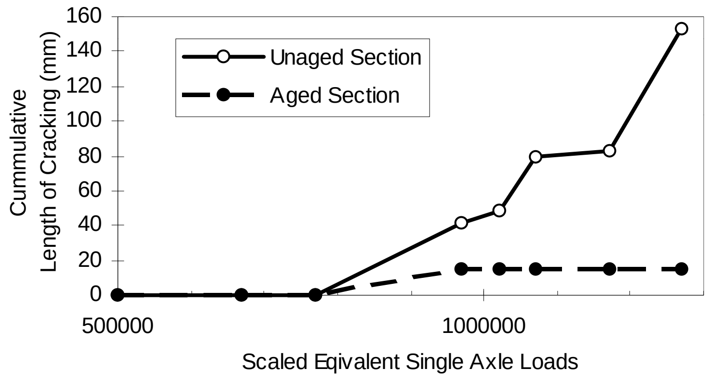

Figure 8. Cumulative total crack length measured under MMLS Mk. 1 trafficking [after (10)]

5.3 Ranking of Candidate Blends

The cost of full-scale APT is such that any reduction in the number of test variables is beneficial. As scaled APT allows a direct assessment of the performance-related properties of materials, it can be used to rank components such as binders for candidate asphalt mixes prior to full-scale testing. This allows full-scale testing to be done on performance optimised blends.

It has been shown by van de Ven *et al*. (12) that the MMLS Mk.1 is able to rank scaled asphalt mixtures in terms of rut susceptibility and as such serves as a wheel tracking test. Furthermore, it has been shown that the MMLS is able to rate the rut susceptibility of asphalt mixtures in a relatively short time; about three hours or after 30 000 MMLS axle loads (8). It is therefore recommended that all candidate blends be ranked using model testing prior to full-scale APT.

6 APT RESEARCH APPLICATIONS WITH THE MMLS MK.3

As mentioned previously, the results of scaled testing can be difficult to interpret. This is especially the case when materials are scaled down. In such cases, the question could be asked whether scaled modelling could assist in the identification of performance indicator characteristics or in the ranking of materials prior to expensive full scale APT. Prediction of the behaviour of pavement types based on theoretical/empirical and structural criteria, as outlined in the South African mechanistic design manual, could be validated using scaled APT testing. This could be a most powerful role the MMLS could play in this field.

There are, however, other areas of APT in which specifically the MMLS Mk.3 can play an important role. The MMLS Mk.3 has some advantages over the MMLS Mk.1. The device has a single tyre that can be inflated up to 1000 kPa. The load for the one wheel of the MMLS can be related to the scaled version of a so-called super single. The loads and tyre pressures associated with super-singles are higher than those for conventional tyres with the consequence that the potential for rutting and fatigue damage in pavements is greater. A super-single wheel on an axle with a load of 80 kN can be scaled down by approximately 1:4 using the MMLS Mk.3. The MMLS-MK3 has potential for many other APT applications. These will be discussed briefly.

6.1 Laboratory testing with the MMLS Mk.3

Wheel tracking test

In many countries in the world rutting tests are carried out on slabs to rank mixes with regards to their rutting resistance or as a specification requirement in the mix design. Many devices are available such as the Hamburger rut tester, the French rut tester, the Transportek wheel tracking device etc. The MMLSMk.3 can also be used as a rut testing device for mix design. The fact that one works with real tyre pressures and that the number of wheel repetitions can be as high as 7200 per hour opens a huge perspective for this testing device. The loading of a material in the form of a layer by an inflated tyre is close to reality and gives a good indication of the performance of the mix at high temperatures. Tests in the laboratory have shown that the MMLS loading will indicate rut susceptible mixes. After one hour testing at 50 C or 60 C a comparison can easily be made between mixes. The influence of reinforcement in pavements can also be measured (13). No standardised testing procedure has been developed as yet.

Testing on seals

Presently, research is underway to test several seal systems in the laboratory (14). The possibility of changing the tyre pressure and to compare various seal systems over one run of the MMLS Mk.3 makes it an excellent tool to test different kinds of seal systems. The behaviour of the different seal systems can be compared with relation to traffic volume, quality of the base, type of materials, change in surface texture, etc. Specifically the influence of the tyre pressure and modified binders is under investigation. It is important to note that the contact area of the wheel must be great enough to cover a representative surface area of the seal under investigation.

Testing of block pavement structure

The MMLS Mk.3 has been used to evaluate the mechanistic and structural performance of an inverted roof insulated pavement structure for a parking terrace of a building complex in Century City outside Cape Town (15). The emphasis of the study was the behaviour of the insulation material under transient loading and the influence thereof on the performance of the block pavement. The structure was built and tested at the University of Stellenbosch. As with the testing of seals, the contact area of the loaded wheel must be high enough in relation to the dimension of the individual blocks. Calculations with finite element methods or multi-layer linear elastic theory may be done to predict the expected behaviour and to analyse the MMLS influence. Figure 9 shows the inverted roof structure and rutting profile measured after MMLS Mk.3 trafficking.

6.2 Field testing with the MMLS Mk. 3

The MMLS has potential as a field-testing device, both as a quality control test after construction and as a research tool in the field during in-service life. The possibilities can best be illustrated by giving possibilities and examples of case studies.

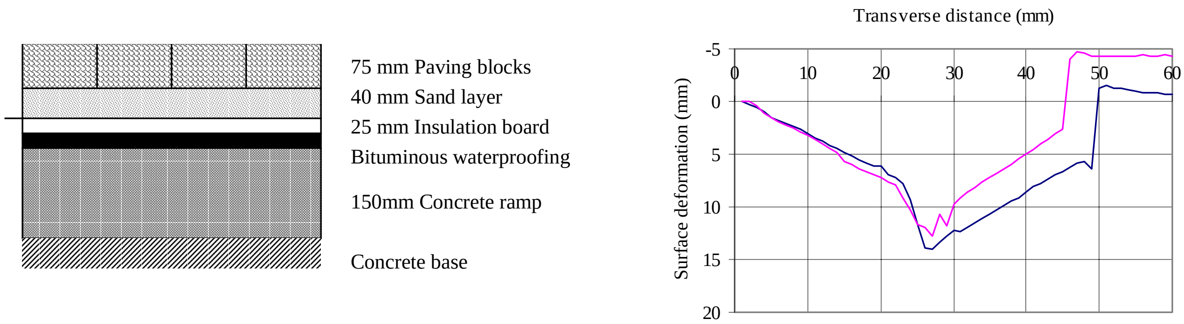

Figure 9. Inverted roof structure and MMLS Mk.3 rutting profiles [after (15)]

In-service pavements

The MMLS may be used to investigate the quality of an existing pavement. This may be necessary to provide information with regards to rehabilitation design, to find the cause of damage or to check assumptions made in performance models, etc. MMLS Mk.3 tests were done in-field on a road in Jacksboro, Texas. Dry, high temperature and wet tests were done to assess the rutting and moisture susceptibility of the in-situ mix (16, 17).

Recent research done in Texas (18) shows that it is possible to test different layers in a pavement structure. Initially, tests were done on the surface layer. Later this layer was milled and MMLS tests were done on the underlying layer. In this way, the effect of MMLS trafficking under different conditions (hot and wet) on the performance of selected layers was investigated. One objective of this particular study was to investigate the effectiveness of two different rehabilitation strategies i.e. Dustrol and Remixer used on the North and South lanes of US281 outside Jacksboro, Texas. The reduction in stiffness of the materials with MMLS Mk.3 testing was determined using SASW measurements and is shown in Figure 10.

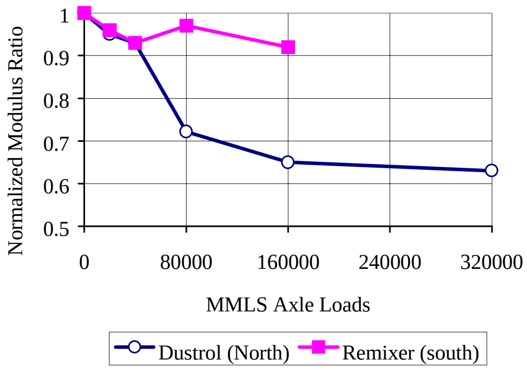

Figure 10. Stiffness reduction of rehabilitation materials with MMLS Mk. 3 trafficking [after (18)]

LAMBs mix design in the field for Cape Town International Airport

For very important projects, it may be sensible to test the asphalt mix as designed in the laboratory under field conditions before commencing the project. For the runway design of Cape Town International airport it was decided to test candidate mixes in the field on trial sections with the MMLS under hot and dry conditions and under wet conditions (19). Based on the results of the performance of the trial sections a final mix was chosen for the project.

Testing of seals in the field

In East London, field tests were done with the MMLS on seal trial sections to predict and compare the performance of several alternatives (20).

Early performance properties of a layer of recycled material with emulsion or foamed bitumen.

APT was performed on site with the MMLS as part of an investigation into the rutting potential during early life conditions of pavements with recycled material containing emulsion or foamed bitumen (21). The MMLS tests provided insight into the ravelling of foamed bitumen and emulsion treated layers under traffic as shown in Figure 11. The influence of slushing with water or diluted emulsion were also investigated and reported.

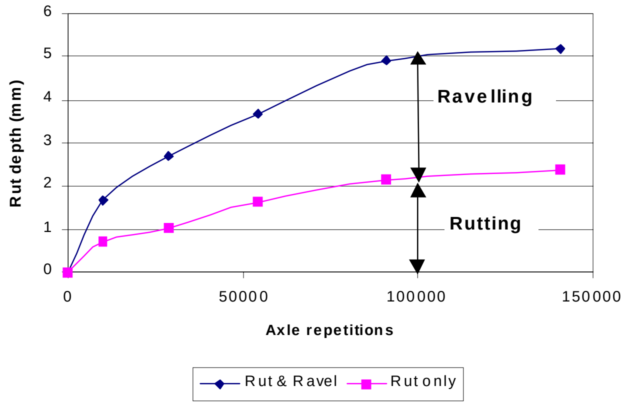

Figure 11. Ravelling and rutting of an emulsion treated base layer under MMLS trafficking [after (21)]

7 CLOSURE

Two model MMLS testing devices are described; the mechanisms of which mirror to an extent the full-scale MLS. The immediate benefit of these scaled APT devices is that testing can be done at a fraction of the cost of full-scale APT. Furthermore, testing can be done either in the laboratory or in the field under controlled environmental and testing conditions or directly in the field. This allows many of the variables impacting pavement systems to be controlled directly which expedites the testing of the different variables, prior to conducting full-scale APT.

The three main material response characteristics identified for scaled down performance testing are stiffness, strength (fatigue resistance) and permanent deformation. The volumetric differences between full-scale and comparable scaled down materials must also be considered.

Prediction of the behaviour of pavement types based on theoretical/empirical and structural criteria, as outlined in the South African mechanistic design manual, could be validated using scaled APT testing for different pavement structures.

Table 2 is a summary of the state-of-the-art of MMLS applications and areas to be explored.

Through the examples and case studies given in the paper, an indication has been given of possible APT testing with the MMLS, both in the laboratory and the field. It should be stressed, however, that any application in the field or in the laboratory with the MMLS must be supported by preliminary theoretical analysis. It must always be realised that the load applied by the MMLS is low and only has an impact on part of the structure. For this reason it will never replace full-scale testing or real trafficking.

Table 2. State-of-the-Art MMLS applications and areas to be explored

		Pavement structure in the field	**Scaled pavement structure in the laboratory**	**Laboratory model structures**	**Scaled materials**	**Full-scale materials**
MMLS Mk. 1	**Appli-cations**	None	Asphalt structures	None	Asphalt Granular materials: G1, ETB, WBM	None
	Areas to be explored	No	Validation of structural design models/criteria Dry/Wet High/Low Temperature	Ranking of binders Thin surfacing layers with fine material	Few: Scaling 1:10 has many problems	No
MMLS Mk.3	**Appli-cations**	Asphalt surfacing Asphalt bases Seals Dry/Wet	None	Block pavements Seal testing	None	Seals LAMBS Light weight asphalt Cold mix
	Areas to be explored	Many: Dry/Wet High/Low temperature	Validation of structural design models/criteria Dry/Wet High/Low Temperature	Many: Fatigue testing on slabs or beams Ravelling test etc	Scaling materials 1:3 may be feasible	many

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