

# **PROVISIONAL RESULTS FROM ACCELERATED TESTING OF ULTRA THIN-LAYER REINFORCED CONCRETE IN SOUTH AFRICA**

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## **ABSTRACT**

The CSIR Built-Environment, in conjunction with the University of Pretoria and the Cement and Concrete Institute of South Africa, developed a low cost option for the upgrading of unsurfaced (gravel) roads. The proposed solution is the placing of a thin layer of normal concrete reinforced with 5.6mm diameter steel with a mesh grid size of 200mm. This thin layer is placed on top of the existing unsurfaced road with minimal preparation to the existing road surface using labour-intensive construction methods.

Through full-scale trials this type of upgrading proved to be adequate for low-volume traffic applications (e.g. residential streets) as well as for higher-volume applications (e.g. bus routes). During the trials test sections were subjected to a total of over 700,000 ESALs over a period of 5 years without showing any deterioration.

In order to determine the structural capacity of this type of overlay full-scale Heavy Vehicle Simulator tests were conducted. This paper summarizes the initial results from the accelerated pavement testing (APT) tests and is aimed at building confidence in the use of thin-layer CRCP, with cognizance being taken of the pavement structure, support conditions, construction, climate and traffic.

## **INTRODUCTION**

The upgrading of unsurfaced residential roads has become a priority for many metropolitan areas in South Africa. Coupled with this is the need to construct roads using labour-intensive construction techniques. One solution is the use of an ultra thin reinforced concrete pavement (UTRCP). UTRCP has been shown to offer good performance during a previous trial study (1,2) but a number of questions still remain to be answered, particularly with regard to the limits of application of this technology.

The primary objective of this project is to assess the performance of 50-mm thick CRCP placed on various support conditions through accelerated pavement testing (APT), coupled with a laboratory-testing programme. The aim is to determine the limits for safe application of the technology in South Africa. The outcomes of the project will also be used to update the South African design method for rigid pavements (cncPAVE) (3).

This study is aimed at building confidence in the use of UTRCP, taking cognizance of the pavement structure, construction, climate and traffic, by providing practitioners with reliable design information.

## Expected Benefits

The use of UTRCP on roads offers multiple benefits by comparison with more conventional approaches. The benefits include:

- UTRCP is labour-friendly and is highly suitable for labour-based construction;
- Only simple, inexpensive construction equipment is required;
- Existing subgrade and alignment can be used;
- It can be used as an overlay on existing roads;
- It requires less lighting energy at night by comparison with bituminous surfaces because of the reflectivity of the surface; and
- Significant reduction in construction energy can be realised as the mix is hand-placed at ambient temperatures.

## **THE CONSTRUCTION OF THE UTRCP SECTIONS**

The Ultra Thin Reinforced Concrete Pavement sections were constructed on a 130m long test section using a mix of 13mm and 9mm quartzite aggregate to achieve a dense aggregate packing. A high-strength cement (CEM I - 42.5N) was used and the mix was reinforced with a steel mesh consisting of a 200 x 200mm grid size using 5.6mm diameter steel wire. The total thickness of concrete was 50mm and the steel was placed on the neutral axis, 25mm from the surface using plastic chairs. The mix was hand placed using shutters to control the width and thickness of the concrete. A double vibrating roller screed was used for compaction and the pavement was cured under plastic for 7 days to minimize differential shrinkage. The sections were constructed on the R80 Highway north-east of Pretoria, South Africa and Figure 1 shows some aspects of the construction process.



**Figure 1: The UTRCP construction process**

The average 28-day cube crushing strength was 37.5 MPa (without the steel).

The UTRCP was placed on a prepared road bed consisting of various support types, which included a granular base section, a cemented base section, and sections with a 50mm of emulsion-treated base. One section was constructed using bottom dump ash (from a coal-fired power station) as a replacement for the quartzite aggregate. The aim of this was to determine the structural bearing capacity of the UTRCP under various support conditions with the aid of the HVS.

## ENVIRONMENTAL INFLUENCE ON SLAB CURL AND WARPING

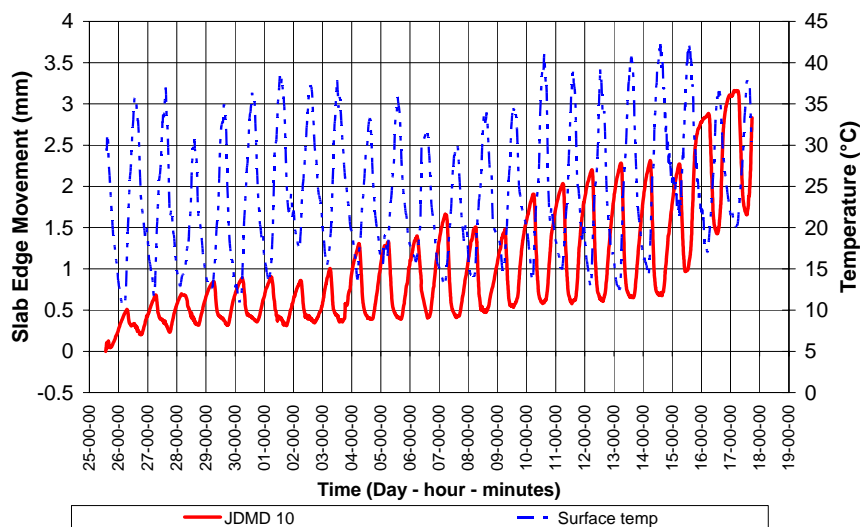
Prior to the start of APT loading (during the curing period), a set of measurements was taken to measure the slab curl and warping movements as a result of daily temperature fluctuations and differential shrinkage under the influence of the environment. Joint Deflection Measuring Devices (JDMDs) were installed immediately after placement of the concrete to record the vertical movements of the edges of the concrete slab.

Thermocouples (TCs), which measured both top and bottom temperatures were also installed in the concrete at each JDMD location. The data captured during the first 23 days are graphically represented in Figure 3. This graph shows the maximum movements as captured by instrument JDMD 10. The instruments were installed as soon as the concrete had developed enough strength to carry the weight of the slugs of the various LVDTs.

Two distinct edge movements were identified:

- a) The daily (elastic) up/down movement due to daily temperature variations.  
As the temperature increased during daytime, the concrete expanded elastically but, because the surface was hotter at the top (being exposed to the sun) than the bottom, the top expanded at a faster rate than the bottom, causing the longitudinal edge of the slab to curl downwards. This process was reversed at night when the top was cooler than the bottom, causing upwards slab movement along the edge of the concrete slab.
- b) Slab warping.  
During the initial curing period in particular, a significant amount of shrinkage in concrete took place but, because the top was exposed to the environment, the degree of hydration was greater towards the top than the bottom of the slab. This differential shrinkage caused the longitudinal edge of the slab to curl upwards. This permanent non-recoverable movement is termed 'slab warping'. The degree of slab warping depends on environmental factors such as humidity, temperature and wind, as well as on the type of concrete and of the reinforcement.

Both these movements can be identified in Figure 3. Analysis of the first 23 days of curing showed that the maximum separation of the concrete from the base was 1.6mm during the day and increased to 3.1mm during the night. The data are summarized in Table 1.



**Figure 3: Maximum slab edge movements and associated surface temperatures**

**Table 1: Summary of slab edge movements due to environmental influences**

Instrument	Permanent Warp (upward)	Daily Curl		Total daily elastic curling movement
	(mm)	up (mm)	down (mm)	(mm)
JDMD 10	2.30	0.80	0.70	1.50
Maximum surface temperature (Deg C)				42.40
Minimum surface temperature (Deg C)				10.50
Maximum positive temperature differential (top - bottom) (Deg C)				3.60
Maximum negative temperature differential (top - bottom) (Deg C)				-3.40

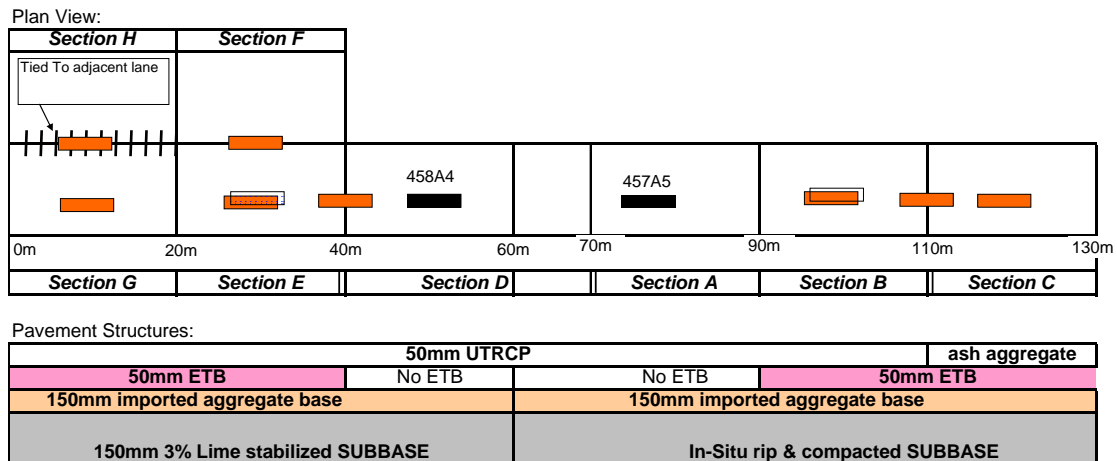
  

The diagram illustrates the slab edge movements with three curves: a blue curve (top), a black curve (middle), and a red curve (bottom). The vertical dimensions are labeled as 3.1, 2.3, and 1.6, representing different levels of movement or depth from the surface.

Unfortunately data collection was stopped after 23 days to accommodate the HVS tests which followed directly afterwards.

**APT TESTING PLAN**

In order to address the aims of this study a series of Heavy Vehicle Simulator tests (HVS) were planned as shown in Figure 4. The rectangular boxes indicate possible HVS testing areas



**Figure 4: Planned HVS testing areas**

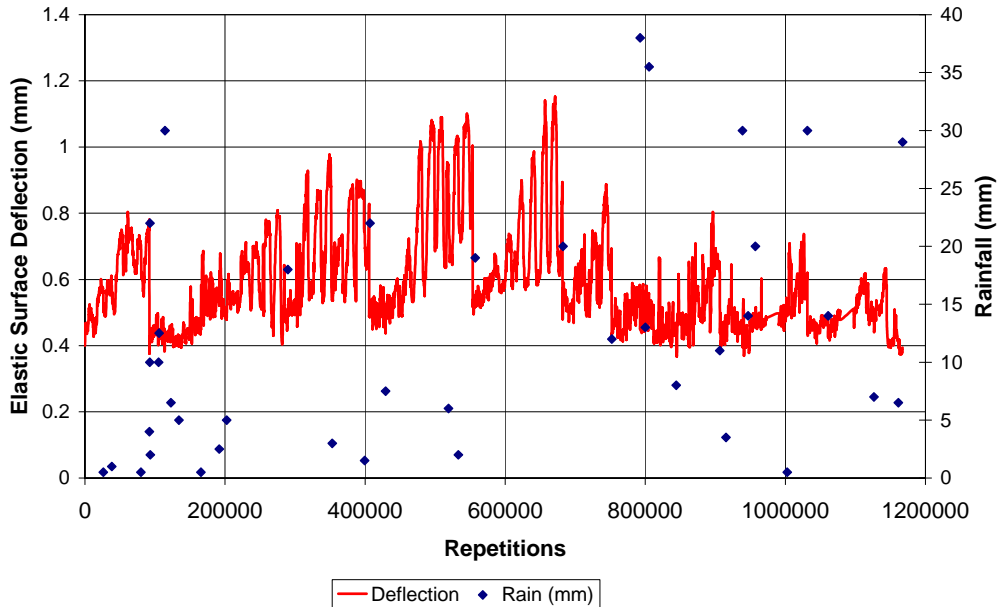
The main objectives of these tests can be summarized as:

- To assess the effects of various input parameters (i.e. type of aggregate, support conditions, longitudinal joints, traffic loading) on the structural integrity and performance of the UTRCP layer;
- To determine the structural strength across joints and transverse cracks as these are believed to be the weak areas in the UTRCP system; and
- To establish the success of patchwork and rehabilitation options in the event of the early UTRCP layer failure.

In order to address the last mentioned point, certain HVS testing will be conducted until complete failure has been observed. Those failed areas will then be patched using the standard fixing techniques for continuously reinforced pavements. The same areas will then be subjected to a second round of accelerated loading.

## LATEST HVS RESULTS

To date only two tests have been conducted. These tests (457A5 and 458A4) are according to the layout in Figure 4. A total of over 1.3 million standard axle loads (80kN) were applied to each of the sections without any signs of structural failure. Only two small transverse cracks had appeared after 5 days of trafficking but no signs of pumping or any other form of deterioration could be detected, despite the fact that over 540 mm rain fell on the test pavement during the test. The pavement has been subjected to accelerated trafficking for 3 months and loading will continue until structural failure. Figure 5 shows the peak deflection with repetitions.



**Figure 5: 40kN deflections and rainfall data**

The variations in the data are due to daily temperature and rainfall effects. From the graph it is evident that no significant degree of deterioration in terms of deflections can yet be detected. After 1.2 million load applications the deflection values are very similar to those recorded at the beginning of the test.

From this it is concluded that very little damage has been done to the pavement under loading. This conclusion is supported by the results of visual inspections.

## MODELING THE BEHAVIOUR OF THE PAVEMENT

The purpose of modelling was to develop a model which could be used for the design of a UTRCP and to update the design procedures in cncPAVE (3).

cncPAVE is a mechanistically based design method developed in South Africa to facilitate interaction with the mechanistic flexible pavement design methods currently in use and to promote the use of concrete to rehabilitate flexible pavements. cncPAVE, a user friendly computer program, is based on models developed from finite element and multi-layer evaluations. The design method has been calibrated against actual performance of different concrete pavement sections (roads and streets) under normal traffic loading, as well as under the HVS.

The UTRCP pavement that was modelled and tested consisted of a thin reinforced concrete pavement on top of a layered system. Properties of the model include:

- Generation of a generic finite element model of a representative piece of road provided with a reinforced concrete slab on top and various layers underneath;

- Application of wheel loads as circular patches of constant pressure moving at a given speed; and
- Non-linear dynamic FE analyses using explicit time integration.

The results from the analyses included principal stress values at the top and bottom of the concrete, as well as vertical deflections of the concrete. The results were presented as contour fringe plots as well as in tabular form.

The mesh of the model was selected per layer to be finer at the top and coarser at the bottom in order to reduce computational effort. The finest mesh was directly in the wheel path. At both ends of the wheel path, for a distance of about 1m, the mesh was coarser, allowing basically for the wheel speed to increase to a constant value in these areas.

The boundary conditions were such that all displacements at the bottom (x, y and z directions) were fixed. On the plane of symmetry at  $y=0$ , the displacement in the y direction was constrained to zero. At the ends, as well as along the sides, non-reflective boundaries were prescribed, meaning that pressure waves that propagated radially outwards from the wheel positions were not reflected back into the modelled part.

Two circular load patches, 200mm in diameter, simulated the dual-wheel loading of a typical truck. A surface pressure of 700 kPa was applied to the top concrete surface along a path that ran at a distance of 900mm from the plane of symmetry.

In the dynamic analysis the wheel load together with the gravity load of the concrete was first applied in 0.1 seconds from 0 to 700 kPa at an axle position close to one end of the model (145 mm). Thereafter it was accelerated for a distance of 855 mm along the path up to its ultimate speed. Thereafter the wheel load moved at a constant speed along the wheel path.

A transverse crack in the concrete was modelled at the center of the wheel path over the full width of the model. The crack was through the total thickness of the concrete and was modelled in such a way that compression forces, but not tension forces, could develop on the two adjacent surfaces of the crack. Vertical shear could also be carried in the crack, which meant that there was no vertical slip between the surfaces of the crack. The reinforcement was modelled as a continuous sheet of steel in both the x and y directions.

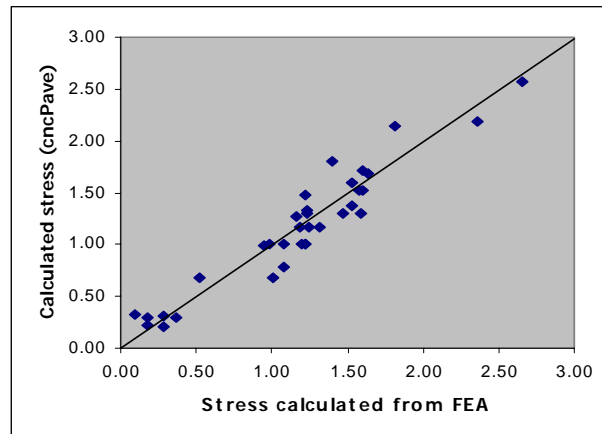
In order to create a void below the slab, the interlayer stiffness was reduced to practically zero and, for the transition areas at both ends of the void area, reduced stiffness were introduced by linear interpolation.

The explicit time integration of the dynamic process was quite time-consuming, and parallel processing with multi processors and about 400 MB of memory was required. An eight processor server with 3.66 GHz 64bit Xeon processors was used. The time required for a run using four processors was typically was three to nine hours, depending on the size of the smallest element in the model and the stiffness of the material. The analysis was done stepwise in time, with extremely small time steps, typically 2 to 3 microseconds. With the duration of the wheel passing process from end to end being about 2 seconds, about 800 000 solution cycles were required.

A non-linear dynamic analysis was required since the wheel patches are moving objects in the wheel path and sliding contact is defined between the wheels and the concrete surface. At the simulated crack in the concrete non-linear contact was also defined between the surfaces of the crack.

The results of the analyses were available after a run as time history displacements, strains and stresses. These could be presented as time history plots or as fringe or contour plots at selected time intervals. Deformed plots scaled to enlarge the actual deformation were also generated.

In view of the time and cost of using sophisticated Finite Element Analysis (FEA), a limited number of cases were evaluated. The data generated by the FEA was used to re-calibrate the equations used in cncPAVE and cncPAVE was subsequently used as a tool to illustrate the relative effect of different parameters on the performance of a UTCRCP. Figure 6 shows the reliability of the predicted maximum tensile stress on the surface of the pavement using cncPAVE compared to the values generated by FEA. The correlation coefficient  $R^2$  for the data in Figure 6 is 0.91.



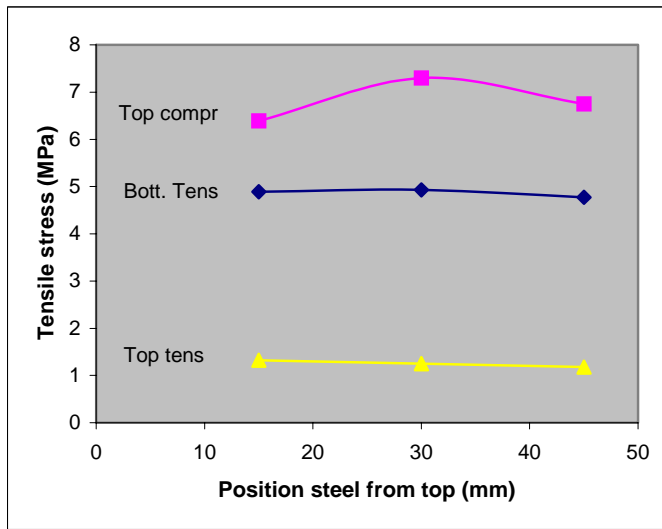
**Figure 6: Comparison between FEA and cncPAVE calculated tensile stress.**

## MODE OF FAILURE

Combinations of FEA results and cncPAVE equations can now be used to explain the behaviour of UTCRCP as observed on the test sections under HVS testing and to establish the consequences if parameters that may vary during the design, construction and loading of a UTCRCP.

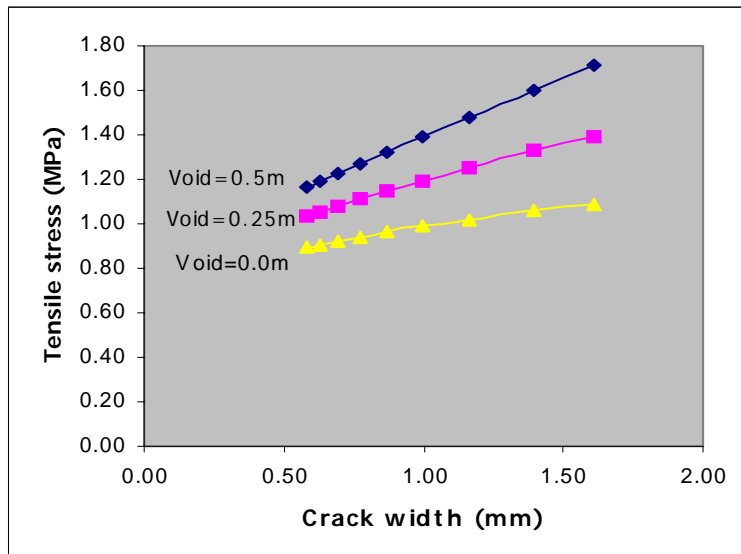
The modelling and the output of program cncPAVE can be used to establish the possible mode of failure and to demonstrate the sensitivity of certain characteristics of UTCRCP:

1. Transverse cracks will develop as a result of shrinkage. It is also inevitable that transverse construction joints will be introduced into the pavement. Since steel bar reinforcement will be going through this joint, the joint or crack can be regarded as a hinge that allows shear but no moment to be transferred across.
2. High stresses develop when a wheel load crosses from one side of the crack or joint to the other side. According to FEA analyses the critical stresses are tensile stresses at the bottom of the pavement about 450mm from the crack, those between the wheel loads at the top of the pavement and the compression stress at the top of the crack when the wheel is crossing the crack. A plot of these stresses is shown in Figure 7 where the stress has been calculated for a 60mm slab with the longitudinal steel bar reinforcement placed at different levels in the slab. It was found that the tensile stress is at its greatest about 450mm away from the crack and that a second crack will rapidly develop due to the high tensile stress at that point. The crack itself may initially not be visible but the stiffness of the slab is reduced, resulting in an increase in deflection and in a greater vertical stress at the top of the supporting layer. At the same time high compression stresses develop at the top of the slab in the crack, resulting in spalling and a risk of loss of shear resistance, as well as in a risk of water entering the slab (see Figure 7). The crack between the wheels will later extend from the surface into the pavement itself.



**Figure 7: Stress in a 60mm slab as a function of the position of the reinforcement**

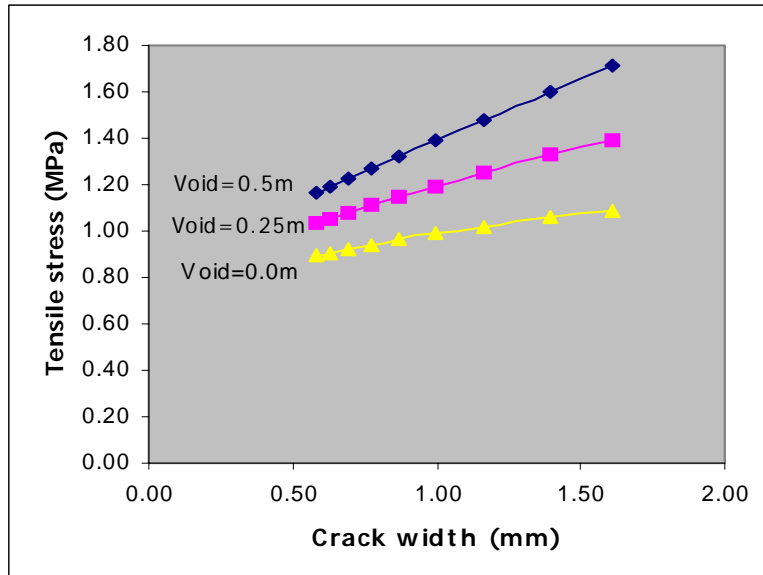
- Water that enters the supporting layer through the spalled crack results in a loss of bond and, with an increase in deflection, a void will develop between the slab and the supporting layer. The effect of a loss of bond is shown in Figure 8 below where the maximum stress at the surface of the slab, calculated with cncPAVE, is plotted as a function of bond and crack width. Figure 9 indicates the effect of the void size once bond between the slab and the supporting layer is lost. The crack widths in both Figures 8 and 9 are used to indicate the loss of shear and thus load transfer at the crack.



**Figure 8: Maximum tensile stress at the surface as a function of crack width and bond between slab and support layer.**

The FEM analysis shows that the estimated pavement life for this type of structure is approximately 2 million 80kN load applications.





**Figure 9: Maximum tensile stress at the surface as a function of crack width and the size of the void between the slab and the supporting layer.**

## CONCLUSIONS

This aim of this study was to characterize the structural performance of a 50mm thick Ultra Thin Reinforced Concrete Pavement under various types of realistic support conditions with the aid of the Heavy vehicle Simulator.

Early indications are that this type of structure is prone to curling and warping. Separation of over 3 mm between the bottom of the slab and the base along the longitudinal edge of the test section was recorded. Special attention will be required to mitigate the harmful effects of the loss of bond between the concrete and the support structure.

Although APT testing has not been completed, the visual and structural evaluation of the current state of the pavement ties in with the predictions from the dynamic Finite Element Analysis.

## ACKNOWLEDGEMENTS

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