Ultra-Thin Reinforced Concrete Pavements (UTRCP): Towards the development of a structural design guideline for South Africa

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Abstract

The design and use of Ultra-thin reinforce concrete pavements (UTRCP) are well known and are implemented successfully in residential streets and low volume roads in South Africa. Various authors and publications are available to assist engineers and contractors to successfully design and construct roads using this labor intensive construction technique. The current structural design of UTRCP is for low volume road applications with a total expected traffic of less than 1 million equivalent single 80kN axle loads. This paper deals with an analytical evaluation based on laboratory results and computer modeling to determine the stress condition under loading and to determine the design life of the UTRCP pavement system. The analysis showed that initial design guidelines for the design of UTRCP may have underestimated the required stiffness of the foundation for the pavements. These results are in agreement to visual observations of early failures at UTRCP constructed urban roads and streets. The use of mechanistic-empirical software is recommended for design of the pavements.

Background

The In recent years the CSIR has been involved with the development of innovative Ultra Thin Concrete Pavement (UTCP) solutions for both high-volume and low-volume roads (Kannemeyer, 2008; Du Plessis, 2011).

For low-volume road applications a technology known as Ultra Thin Reinforced Concrete Pavement (UTRCP) was originally developed by the CSIR and supported by the Gauteng Department of Roads and Transport (GDRT) (CSIR, 2011; Du Plessis et al. 2011). The research project is a partnership between The CSIR, The Concrete Institute (TCI) of South Africa and the University of Pretoria (UP). The innovation is intended as an efficient solution to providing a surfaced road solution in rural residential areas where traditionally the roads are unsurfaced and of poor quality.

UTRCP has matured to a stage where it is being implemented and used on a number of township roads (Groenewalt and Van Wijk, 2010; Jansen van Rensburg,

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2013). The design tools for the innovative UTCP systems are currently based on conventional concrete pavement design methodologies. It has been incorporated in cncPave concrete pavement design software of the South African Cement and Concrete Institute (Strauss et al. 2007).

The available design methods in cncPave for UTRCP can now be validated against the performance of actual trial sections. Also, the suitability of the CBR cover curve approach for the design of UTRCP as contained in the old Guidelines For The Construction of a 50 mm Thick Ultra-Thin Reinforced Concrete Pavement (CSIR, 2011) needs to be evaluated.

During the implementation of the UTCP, concerns were raised about a number of issues, including:

- Problems related to high shrinkage and thermal expansion stresses in the material. In both technologies "pop-ups" have occurred due to thermal expansion. Thermal- and shrinkage related stresses also cause excessive warping and curling of the UTCP.
- Uncertainties around the optimum thickness of the material and the function of the steel mesh in the structural performance.
- The structural capacity of the UTRCP system in the light of its use on higher order roads with higher traffic volumes.

Although UTCP technologies are being implemented in South Africa, designers are still faced with a number of uncertainties. There is a need for a mechanistic approach to the design of UTCP that is based on an improved understanding of the structural system and damage accumulation in the pavements. This is to reduce the risk of further premature failures that have occurred on some pilot UTCP projects.

Objectives

The overall objective of this project is to increase the understanding of the design and performance of UTCP. The main objective can be divided into a number of sub-objectives, which are addressed in this paper:

- perform mechanistic analysis of the UTRCP test sections and township roads;
- assess the suitability of the CBR cover curve design method for the design of UTRCP, and
- a critical review on the structural capacity of the UTRCP system.

Mechanistic analysis of UTRCP sections

Mechanistic analysis based on the deflection data recorded during the HVS testing and the evaluations of the in-service pavements are presented here. The stress condition in a hypothetical pavement structure constructed in accordance with CBR design curves in the current design guide for UTRCP issued by the CSIR (CSIR, 2011) is also assessed. The functional life of the pavement structures is predicted using the South African cncPave concrete pavement design software (Strauss et al. 2007).

Structural analysis of UTRCP sections in Mamelodi, Soshanguve and the R80 highway

The deflection measurements which were performed on UTRCP pavement sections in Mamelodi, Soshanguve and the HVS test section on the R80 highway. These deflection results were used as the benchmark for the analysis (Denneman and Du Plessis, 2012). The mean deflections of the Mamelodi, R80 and Soshanguve sections were 1.0 mm, 0.7 mm and 0.6 mm respectively (Denneman and Du Plessis, 2012).

Structural analysis of the pavement structures is performed using EverFE v2.24, a finite element method (FEM) software package for the analysis of rigid pavements, developed at the Universities of Maine and Washington (EverFe, 2013). FEM software was used because it allows accurate modelling of the pavement geometry and load conditions, including warping of the slab due to temperature differentials between the top and bottom of the slab.

Assumptions

It is rather unfortunate that little information on the engineering properties was gathered during the various trials and the construction of the township road sections. Engineering properties are therefore assumed based on published typical values for 30 MPa compressive strength concrete:

- Young's modulus is assumed at 30 GPa
- Poisson's ratio is assumed at 0.2
- The Modulus of Rupture (MOR) is assumed at 4 MPa
- The coefficient of thermal expansion is assumed at 12 x10-6/°C

MOR is an indication of the flexural strength (tensile strength in bending) of the concrete and is a specialized test that is required to determine this value. In the absence of the true MOR value, an accepted relationship is used (Portland Cement Association, 2013):

MOR = $k\sqrt{fc}$, where k = spring stiffness and Fc = 28-day compressive strength (MPa)

The pavement subgrade is modeled as a dense liquid (winkler spring) as originally developed by Westergaard (Westergaard, 1926), where k = pressure on the subgrade divided by the deflection (MPa/mm). A general value of 0.74 is used (Portland Cement Association, 2013). Thus, for a standard 30MPa concrete mix, the calculated MOR would be 4 MPa and for a 40 MPa mix, the MOR would be 4.6 MPa. Post mortem investigations at the HVS testing at the R80 after the completion of the HVS tests and analysis revealed average MOR value of 5.25MPa

Analysis and results of the Mamelodi pavement sections

The modulus of the subgrade was varied to match the deflections measured at the Mamelodi site. Rolling wheel deflections were recorded using the Road Surface Deflectometer (RSD) in conjunction with a calibrated 80kN back axle loaded truck (Denneman and Du Plessis, 2012). The pavement structure used in the analysis is shown in Table 1.

Table 1: Pavement layer characteristics of Mamelodi sections

Layer	Thickness	Modulus [MPa]	Poisson's Ratio
Concrete slab	50	30 000	0.2
Granular	150	70	0.35
Granular	150	60	0.35
Granular	150	50	0.35
Subgrade	∞	varied	N/A

Table 2 shows the deflection and calculated maximum tensile stress in the pavement at different subgrade stiffnesses from EverFE analysis. The average deflection measured with the RSD (under a standard 80 kN axle load) was 1.0 mm. The analysis indicates that the stress in the concrete at this deflection (and under a standard axle load) is in the order of 8 MPa; this is about twice the typical modulus of rupture for 30 MPa compressive strength concrete.

Table 2: Results FEM analysis Mamelodi multiple support layers

Subgrade Modulus [MPa]	Spring Stiffness (k) [MPa/mm]	Deflection [mm]	Maximum Tensile Stress [MPa]
50	0.258	0.659	7.62
40	0.206	0.696	7.68
20	0.103	0.859	7.90
10	0.052	1.13	8.17
5	0.026	1.58	8.46

UTRCP with strong single base layer

To assess whether the stresses in a UTRCP on a weak subgrade can be reduced by introducing a strong base layer, EverFE analysis were repeated replacing the granular layer of 70MPa with a high strength/quality 150mm thick base layer (South African G1 base classification) on varying support as shown in Table 3. A modulus of 300 MPa was assumed for the G1 as recommended in TRH4 (Committee of State Road Authorities, 1985).

Table 3: EverFE UTRCP material inputs for a strong base layer

Layer	Thickness	Modulus [MPa]	Poisson's Ratio
Concrete slab	50	30 000	0.2
Granular (G1)	150	300	0.35
Subgrade	∞	varied	N/A

The results of the analysis are shown in Table 4. The results indicate that even with a 150 mm G1 base layer, the subgrade has to be of relatively high quality to significantly reduce the stresses in the UTRCP. The subgrade modulus will have to be in excess of 100 MPa to reduce the tensile stress in the pavement to such an extent that it approaches the MOR value of the material.

Table 4: EverFE results strong base layer

Subgrade Modulus [MPa]	Spring Stiffness (k) [MPa/mm]	Deflection [mm]	Maximum Tensile Stress [MPa]
100	0.516	0.230	5.05
50	0.258	0.334	5.53
40	0.206	0.378	5.69
20	0.103	0.557	6.21
10	0.052	0.823	6.74
5	0.026	1.23	7.28

Stresses of the concrete under HVS experiment

The stresses of the concrete in the Mamelodi section is compared to the stress condition under the HVS tests at the R80. The first experiment that was analyzed was HVS test 460A4. Full details on the HVS experiments are contained in (Du Plessis et al. 2010).

The load condition was as follows:

- edge load, dual wheel, 20kN per wheel, Tire inflation pressure 680 kPa, and
- load patch for FEM analysis: 150 mm x 190 mm.

Table 5 shows the structure of the HVS experiment 460A4. The test was run on what was called a "strong support" condition in the experiment. The moduli of the layers supporting the slab were back-calculated from falling weight deflectometer results. The initial elastic deflections measured during the test at known positions were in the order of 0.15 mm (Du Plessis et al. 2010). As during the Mamelodi case, the modulus of the subgrade was varied to match the deflection (measured vs. calculated).

Table 5: Structure HVS experiment 460A4

Layer	Thickness	Modulus [MPa]	Poisson's Ratio
Concrete slab	50	30 000	0.2
Emulsion treated base	50	1400	0.35
Imported base and road bed	250	400	0.35
Subgrade	∞	145 (k=0.747 MPa/mm)	N/A

The maximum tensile stress calculated for the pavement is 2.94 MPa, the maximum deflection 0.15 mm (matching the deflections measured by the FWD), indicating that the stresses experienced by the pavement are much lower than the stresses in the pavement at Mamelodi UTRCP pavement sections.

Stress under different axle loads Mamelodi

The sections in Mamelodi carry light traffic (residential streets). To investigate the stress under different axle loads, the pavement is analyzed under a range of load conditions. The average pavement structure (yielding 1 mm displacement under RSD deflection measurements) is used for this analysis. The structure is shown in Table 6. The loading of the axle is varied. The results in terms of stress and displacement are shown in Table 7.

Table 6: Average Mamelodi structure

Layer	Thickness	Modulus [MPa]	Poisson's Ratio
Concrete slab	50	30 000	0.2
Granular	150	70	0.35
Granular	150	60	0.35
Granular	150	50	0.35
Subgrade	∞	15 (k=0.0775 MPa/mm)	N/A

Table 7: Results of EverFE: Stress and displacement under different loads

Axle Load [kN]	Max Displacement [mm]	Stress [MPa]
80	1.20	9.82
70	1.07	8.60
50	0.809	6.15

30	0.548	3.70
10	0.287	1.25

The results indicated that using a 30 kN axle load, the calculated stress in the concrete is 3.7 MPa which is below the expected MOR of the material but using a normal 80 kN axle load resulted in a calculated concrete stress of over 9 MPa, which is approximately double the MOR of the material.

Comparison of stresses in various UTRCP structures.

In the final analysis, the stresses in the UTRCP under the HVS testing (the R80 test sections) and the stresses in the Mamelodi and Soshanguve pavements under different axle loads are compared. First, the Soshanguve pavement structure is back-calculated based on RSD deflection data using the same approach as used for the Mamelodi structure in Section 4.1.2 (Average deflection of 0.6mm). The resulting structure to match the 0.6 mm deflection under the RSD is shown in Table 8.

Table 8: Back calculated pavement structure Soshanguve

Layer	Thickness	Modulus [MPa]	Poisson's Ratio
Concrete slab	50	30 000	0.2
Granular	150	150	0.35
Granular	150	100	0.35
Subgrade	∞	50 (k=0.258 MPa/mm)	N/A

Included in the final analysis, the influence of the temperature gradient in the concrete pavement is investigated. Thermal warping and curing are known to have a significant effect on the stress condition in the pavement. The HVS tests were performed during day time and most of the traffic movements on the urban roads in Mamelodi and Soshanguve are also expected to take place during the day. A positive temperature differential (surface hotter that the bottom) is, therefore, taken into account. From temperature logging during the HVS tests the difference between the top and bottom of the slab is approximately 4°C on average, with an average surface temperature of 40°C (Du Plessis et al. 2010). Stresses calculated for the HVS tests under the loading applied by the HVS equipment are compared to the stresses in the Mamelodi and Soshunguve sections under different axle loads.

The results in terms of maximum stress (σ) and deflection (μ) for the load cases including and excluding temperature differential are shown in Table 9 and are graphically displayed in Figure 1 (excluding the temperature induced stresses). The results indicate that the temperature differential in the slab leads to a significant increase in the maximum stress. The analysis further shows that where the axle loading on the pavement exceeds 40 kN, the stresses in the actual pavements constructed at Mamelodi and Soshanguve are higher than those calculated in the HVS experiments.

Table 9: Results comparative analysis

Structure	Load condition	Load [kN]	No Curling μ [mm]	No Curling σ [MPa]	With Curling μ [mm]	With Curling σ [MPa]
HVS 457A5	Dual wheel	40	0.19	4.7	0.3	6.6
HVS 460A4	Dual wheel	40	0.17	3.7	0.4	6.0
Mamelodi	Standard axle	80	1.3	9.5	1.7	10.4
Mamelodi	Standard axle	60	1.0	7.1	1.4	8.0
Mamelodi	Standard axle	40	0.7	4.7	1.1	5.6
Soshanguve	Standard axle	80	0.7	7.3	1.0	8.5
Soshanguve	Standard axle	60	0.5	5.6	0.9	6.6
Soshanguve	Standard axle	40	0.4	3.7	0.7	4.7

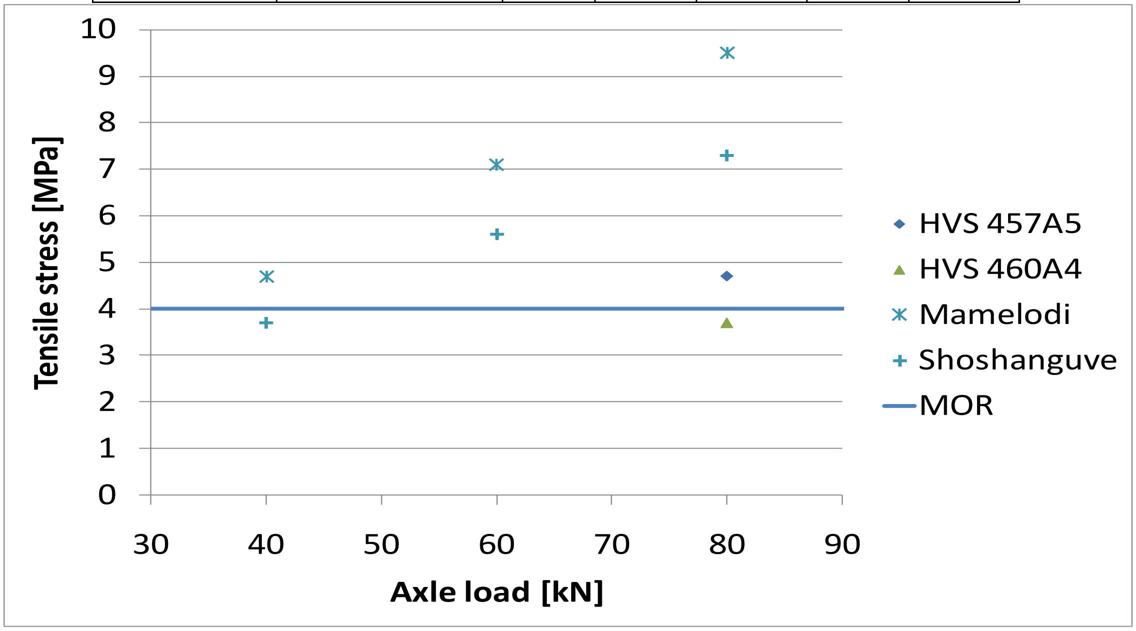

Figure 1: Comparison of stress situation under HVS testing and in Mamelodi and Soshanguve UTRCP at different axle loads

Analysis of stresses in pavement designed as per UTRCP guideline

In 2011 and prior to this analysis, the CSIR issued a document entitled "Guidelines for the Construction of a 50 mm Thick Ultra-Thin Reinforced Concrete Pavement (50 mm UTRCP)" (CSIR, 2011). The earlier version of the guideline document contains a CBR cover curve design approach for UTRCP pavements. In this section, the structural capacity of the pavement designs as proposed in the guideline document will be assessed using mechanistic analysis. The CBR based design curves for UTRCP are shown in Figure 2. In the old document (2011) The use of the 30 kN wheel load curve is recommended for urban streets, the 40 kN wheel load curve is recommended for urban bus routes, and the 60 kN wheel load curve is recommended for provincial type roads.

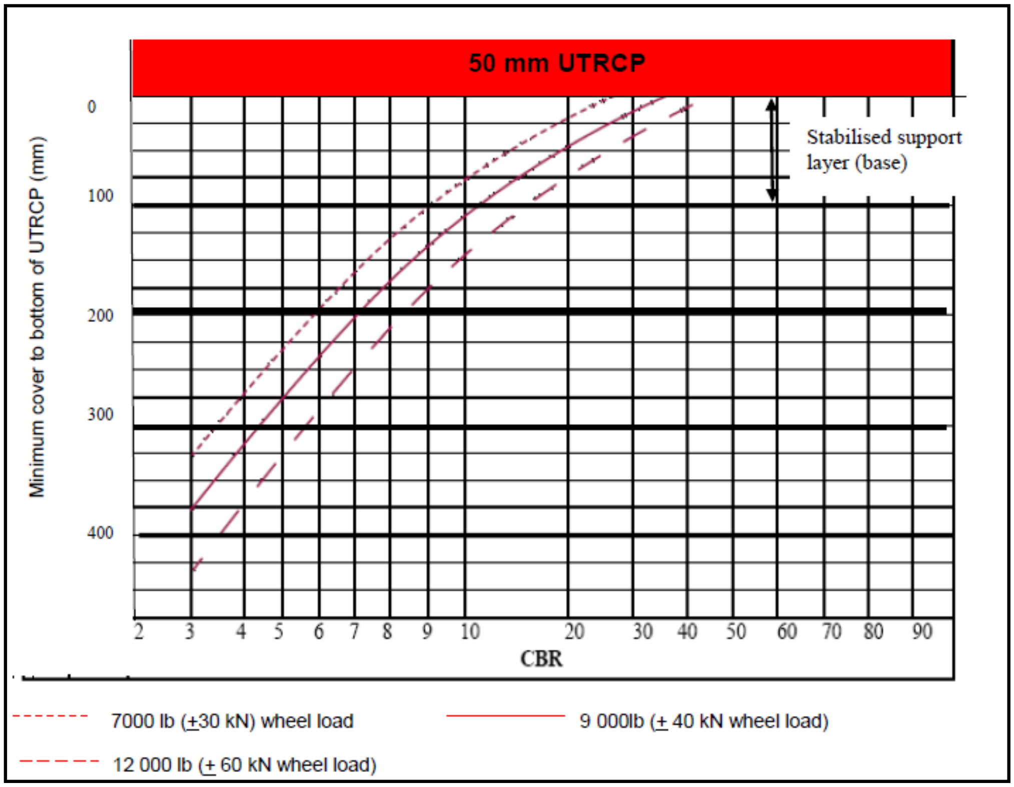

Figure 2: CBR design curves for UTRCP (CSIR, 2011)

To analyze the stresses in the UTRCP on top of a pavement structure with the indicated CBR values, the CBR values need to be converted to the insitu resilience modulus (Mr). Various conversion equations are available. For this analysis conversions offered by Heukelom and Klomp (Heukelom and Klomp, 1962) and the new US Mechanistic Empirical Pavement Design Guide (MEPDG) (NCHRP, 2004), shown as Equations 1 and 2, are used

$$M_r = 10.3 \times CBR \quad (1)$$

$$M_r = 17.6 \times CBR^{0.64} \quad (2)$$

The results of these conversions are shown in Figure 3. Note that there are significant differences between the stiffness values shown in these curves and the stiffness of the structure tested under the HVS. The HVS trial sections had a stronger support than what is recommended in the 2011 design guide. The back-calculated stiffness values for the support layers at the Mamelodi pilot section are similar to what would be required according to the design guide.

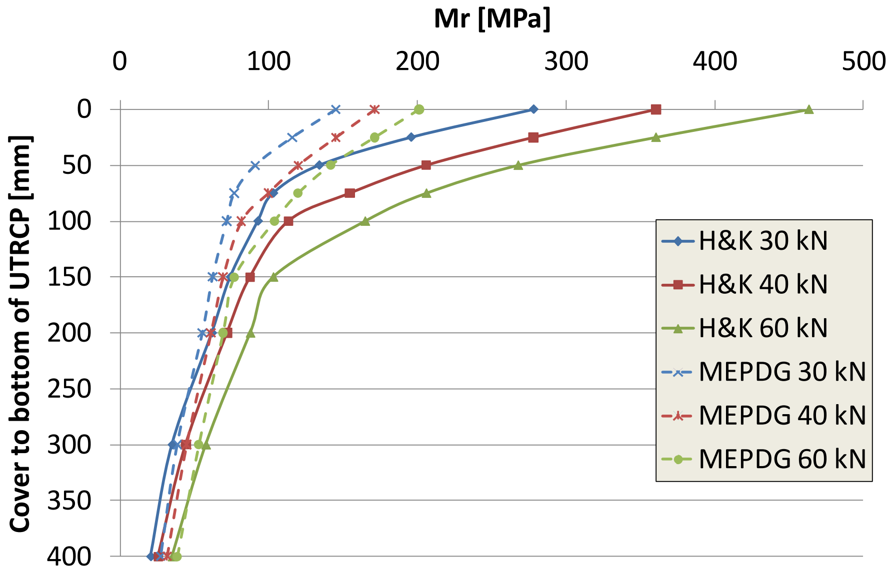

Figure 3: CBR curves converted to resilience modulus (Mr) values

Structural analysis of CBR cover curve pavements under dual wheel axle

The CBR cover curves were originally developed for theoretical single-wheel load situations. This analysis is performed using a standard axle configuration of a 80 kN dual-wheel axle load which is more typically used in modern pavement design. The pavement structures based on the CBR cover curves from the UTRCP guideline document for different road categories are shown in Table 10. The moduli of the different layers were converted from CBR to Mr using the conversion equations from Heukelom and Klomp (1962) and MEPDG (NCHRP, 2004), and are included in the table.

Table 10: CBR cover curve UTRCP pavement structures for different road categories

Layer	**Thickness [mm]**	**H&K**			**MEPDG**		
		Urban	**Urban bus**	**Provincial**	**Urban**	**Urban bus**	**Poisson's Ratio**
Concrete slab E [MPa]	50	30 000	30 000	30 000	30 000	30 000	0.2
Stabilized support layer E [MPa]	100	278	361	464	145	171	0.35
Granular E [MPa]	100	93	113	165	72	82	0.35
Granular	100	62	72	88	55	61	

E [MPa]							0.35
Subgrade k [MPa/mm]	∞	0.106	0.133	0.181	0.142	0.163	N/A

The pavement structures in Table 10 under a standard dual-wheel 80 kN axle load condition were analyzed using EverFE. The axle load was varied from 40 kN to 60 kN to 80 kN. The results of the analysis in terms of the maximum tensile stress in the UTRCP slab are shown in Figure 4. For comparison purposes, the stress condition under the HVS testing and the typical value of the MOR of 30 MPa concrete are also shown in the figure.

The results raised concerns about the suitability of the CBR design curves as contained in the original UTRCP design guide (CSIR, 2011). The results indicate that under a relatively low total axle load of 40 kN, the stresses in the different pavement structures are significantly higher than the MOR. Conventional design methods will predict a low number of load repetitions to failure as the stress/MOR ratio approaches unity. Of greater concern however, is that even for the design proposed for provincial roads, the stress may reach twice the MOR value under an axle load of 80 kN, which is considered a standard axle in South Africa.

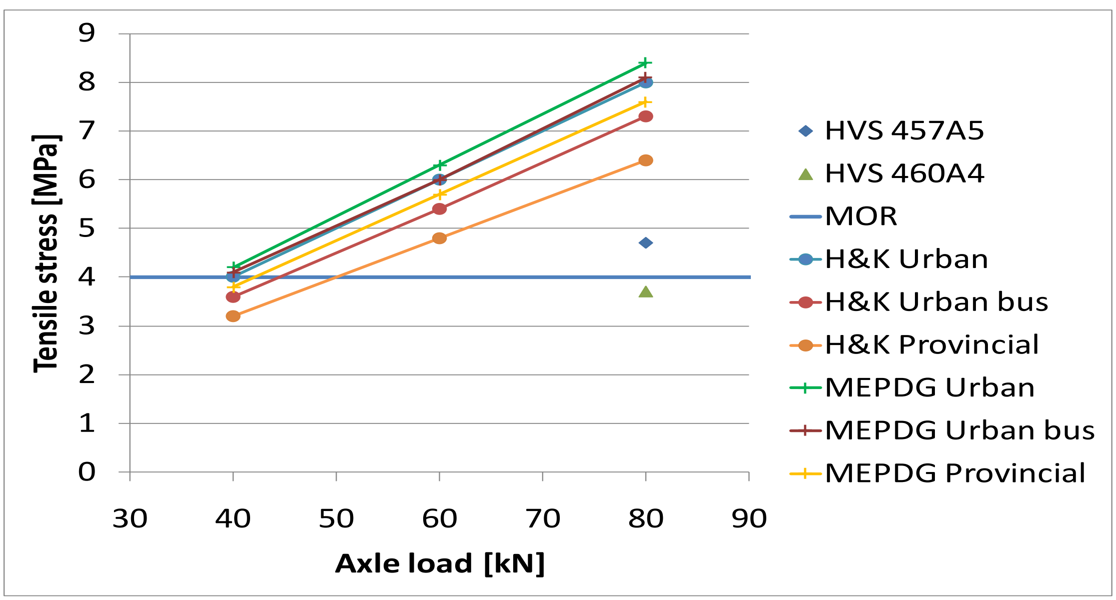

Figure 4: Stresses in UTRCP designed with CBR cover curves under different axle loads

cncPave analysis

Finally, the Mamelodi pavement was analyzed using cncPave v404 software (Strauss et al. 2007), which has a module for UTRCP. The standard load distribution contained in cncPave for urban roads is used.

cncPave is a computer simulation program whose purpose is to facilitate competent decision-making when designing concrete pavements. cncPave assumes that input values are uncertain. The approach is based on the evaluation of consequences. The consequences of a certain pavement design are expressed in terms of decision variables, viz.

- % shattered concrete surface (%SH),
- % pumping concrete surface (%PU),
- % faulting in the concrete pavement (%FA), (in case of plain and dowel concrete),
- Crack spacing (in case of reinforced concretes),
- International Roughness Index (IRI), and
- Life cost of the pavement, in SA Rand per square meter.

cncPave treats input variables and all output items as random variables and the program derives the probability distributions of the above decision variables by means of Monte-Carlo simulation. The average values of the decision variables can then be compared with certain decision criteria and the quality of design judged accordingly.

In addition, probabilities of the decision variables exceeding certain limits can be read off respective graphs. These probabilities can be used to establish the confidence intervals of decision variables.

Analysis was done for concrete with a MOR of 4.0. The pavement structure is modelled as per Table 1, with a 15 MPa subgrade to get to the average deflection of 1 mm if a 80 kN load would be placed on the pavement (see Section 3.1.2).

The failure mechanisms and decision criteria for the design of UTRCP using cncPave are shown in Table 11. The results from the analysis indicate that there is a 50% probability that the surface area with shattered concrete will be excessive after 7 years and 80% probability that shattering will be excessive after 10 years.

Table 11: cncPave decision criteria UTRCP

Decision Variable	Good	Acceptable	Excessive
% shattered concrete	below 0.2%	0.2% to 0.5%	over 0.5%
% pumping	below 2%	2% to 5%	over 5%
Crack spacing	0.3 m to 0.5 m	0.2 m to 0.7 m	below 0.2 m or over 0.7 m

Conclusions

As far as the structural analysis is concerned, the following conclusions are drawn:

Stresses in the concrete of the Mamelodi UTRCP sections are well above the modulus of rupture (MOR) under the influence of an 80 kN axle load. This means that, even with one pass of a 80kN axle load truck, micro-cracking under the slab will occur and, although not directly visible on the surface, conventional design methods would predict the Mamelodi pavement to fail under the first load repetition.

This analysis agreed to what was observed at the UTRCP streets in Mamelodi (Denneman and Du Plessis, 2012). Although a significant portion of the early failures were caused by construction related problems, early fatigue cracks were also observed within the first year of construction. Figures 5 and 6 show construction related and traffic related early failures observed at the Mamelodi UTRCP sections.

Figure 5: Construction related early failures at the Mamelodi site

Figure 6: Traffic related early failures at the Mamelodi site

It is realized that these UTRCP streets in a residential area will probably not be subjected to 80 kN axle loads and that the loads of normal cars and taxis are well below the MOR, but the pavement should be sufficiently strong to withstand at least a certain number of standard 80 kN axle loads. According to the design catalogue of UTG 3, the minimum amount of 80 kN axles designed for should be 200 000 during the 20-year design life (Committee of Urban Transport Authorities, 1988).

The stresses in the concrete in the R80 HVS sections are lower than those in the sections constructed in Mamelodi under the influence of the standard 80kN axle load. Because of the higher quality base material the R80 HVS sections have lower deflections which translate to lower tensile stresses in the concrete. Visual condition surveys of the sections on the R80 HVS test sections confirm this result.

Mechanistic analysis of structures as proposed in the original guideline for the construction of UTRCP (CSIR, 2011), shows that these would result in unacceptably high stresses in the concrete slab. There would be a high probability of early failure of these structures. It is therefore concluded that the CBR design guidelines as contained in the construction guide issued by CSIR are unsuitable for the design of UTRCP. It is therefore recommended that the guide be updated as a matter of urgency.

This investigation highlights the importance of using well-accepted mechanistic empirical design methods before the implementation of the technology. The structural capacity of the pavement depends on the strength of all the layers and a detailed investigation on the impact of using a different quality of base and subbase materials is required to ensure that the concrete is not stressed beyond its strength. The use of appropriate mechanistic-empirical design software such as cncPave and EverFE for the design UTRCP is recommended.

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