The Roodekrans Trial Sections: The Role of Structural Support under Very Thin Jointed and CRC Pavements subjected to Heavy Traffic.

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Abstract

The Roodekrans trial sections were constructed to evaluate the effect of aggregate interlock, dowels, continuous reinforcement and various supporting layers on the relative performance of very thin concrete pavements. The sections were constructed on the exit road from a quarry and have successfully sustained 400 000 equivalent 80 kN axle loads to date. The concrete pavement thickness varied from 50mm to 140mm and the base support consisted of either a natural or stabilized gravel layer 100mm thick, or in some cases, thin asphalt between the stabilized base and slab. After 2 years of heavy truck traffic, a panel of 30 experienced road-engineers visually evaluated performance and found the role played by the support conditions to be crucial for the performance of the road.

This paper summarizes the design and construction of the 10 sections and discusses their performance with specific reference to the role that the support conditions played in the good performance achieved. The findings of the reviewers are first discussed to obtain a viewpoint on the performance of the sections, followed by an analytical evaluation of the sections to arrive at some mechanistic explanations for the good performance of the sections.

The data obtained from these sections have been used in upgrading the mechanistically based design program, cncPave, that has been developed in South Africa.

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Introduction

The Roodekrans thin concrete pavement experiment originated to address the lack of local (South African) information on the performance of relatively thin concrete pavements. In a joint initiative between the Cement & Concrete Institute (C&CI), the Council for Scientific and Industrial Research (CSIR), the University of Pretoria (UP) and Consulting Engineers, BKS, a number of test sections were constructed at the exit from a quarry west of Johannesburg. The main objective of the test sections at Roodekrans was to obtain information on the performance of relatively thin concrete pavement sections under real traffic. This information was required for the calibration of the thin concrete component of the concrete road design package cncPave (ref, 2004).

The site is approximately 164 m long, 3.6 m wide and slopes upwards from the exit of the quarry to the end of the section. Short sections of thin concrete pavement, 3.6 m wide, were placed on top of a newly constructed embankment on an access road to a quarry. The test sections aimed:

- To establish the performance transfer function for thin sections;
- To compare the performance of different thicknesses of pavement;
- To establish the life expectancy of the concrete around dowels;
- To establish the change in the load transfer capacity of aggregate with time and loading, and
- To compare the performance of differing support conditions under thin concrete slabs.

Details of the design of the various sections are as follows (the abbreviations in brackets are used in the figures in this paper to identify the specific sections):

- 75 mm jointed steel fibre reinforced concrete (SFRC) with 30 kg/m³ steel fibre with varying joint spacings (3 m slabs – 6 m section) supported by 140 mm foam concrete subbase and 125 mm stabilized gravel subbase [75 mm SFRC, foam (1); 75 mm SFRC, stab(2)];
- 75 mm SFRC with 30 kg/m³ steel fibre with a 200 mm x 200 mm x 4 mm steel mesh (no joints – 13,5 m slab) supported by 25 mm emulsion treated base (ETB) over 125 mm stabilized gravel subbase [75 mm SFRC, ETB (3)];
- 50 mm and 75 mm continuously reinforced concrete pavement (CRCP) placed on top of a thin bituminous emulsion stabilized natural gravel inter-layer on a 100 mm cement stabilized natural gravel base (no joints – 13,5 m slab) [50 mm CRCP, ETB (4); 75 mm CRCP, ETB (5)];
- 100 mm CRCP (no joints – 13,5 m slab) and 100 mm butt-jointed jointed concrete pavement (JCP) (joints at 2 m and 3 m intervals - 15 m section) on top of the 100 mm cement stabilized natural gravel base [100 mm CRCP, stab (6); 100 mm JCP stab (7)];
- 100 mm butt-jointed JCP (joints at 2 m and 3 m intervals - 15 m section) on top of a thin hot mixed asphalt inter-layer on the stabilized base [100 mm JCP, AC, stab (8)], and
- 140 mm JCP sections with butt and aggregate interlock joints as well as a 140 mm butt jointed doweled JCP, all on a natural gravel base (joints at 2 m, 3 m and 4 m intervals - 18 m section) [140 mm JCP butt (9); 140 mm JCP aggregate (10); 140 mm JCP, dowel (11)].

All the sections were constructed on a relatively stiff embankment with an in situ average falling weight deflectometer (FWD) deflection of 1.5 mm before the base was constructed. It is the role that this support played in the performance of the concrete surfacings that is the focus of this paper. The sections were constructed in February 2002 and opened for traffic in March 2002. A general view of the road is shown in Figure 1.

Traffic and condition

In order to quantify failure of low-volume concrete roads within a short space of time, all the sections were designed to carry 40 000 to 60 000 equivalent 80 kN axle loads using the design technology available at the time.

The experimental sections have carried 400 000 equivalent 80 kN axle loads over a period of approximately 33 months. Traffic consisted of only heavy vehicles, with an average of 4 E80s per vehicle and 1.4 E80s per axle. Regardless of this, there was very little apparent structural damage despite the fact that joints had not been sealed and visually noticeable movements, with some displacement of base material, had occurred at joints. The only cracks that had occurred were mid-slab cracks in some panels of the JCP and DJCP sections with joint spacing exceeding 5.0 m, and corner breaks on 3 out of the 50 joints. However, longitudinal cracks are starting to appear on the surface in the vicinity of the wheel paths especially in the 75 mm CRCP. The 50 mm and 100 mm CRCP seem to be in a better condition when compared with the 75 mm CRCP section.

Figure 1. General view of the experimental sections.

Monitoring program

The sections have been monitored since the start of construction by means of an extensive program of measurement. The measurements include in situ material properties, dynamic cone penetrometer (DCP) measurements, photographs, as-built data (density, concrete properties, moisture contents, etc), weather data, deflections (FWD and deflectograph), slab movements, concrete temperature, road profile and trafficking measurements (traffic counts and weights). To date, only a small portion of this data has been analyzed.

Design and Construction

The reasoning behind the thin concrete was based on the philosophy that, if it was possible to have a foundation which would not deflect if loaded with a wheel load that could not crush concrete, then the construction of a thin concrete pavement on such a foundation would be possible without fatigue failure developing (Bergh et al, 2005).

Material Properties and Pavement Behaviour

The various material properties for the test sections are summarized in Table 1. The subgrade and subbase consisted of weathered granite (Bergh, 2004). The stabilized gravel subbase was high quality natural gravel (CBR > 25 at 93 per cent modified AASHTO density) with 2 per cent cement and compacted to an average of 100,7 per cent Modified AASHTO density. The in situ material was compacted to a minimum of 93 per cent Modified AASHTO density. From the above information, it can be concluded that the concrete layers have been placed on stable layers of subbase and subgrade.

The ETB consisted of subbase material stabilized with 1,5 per cent anionic stable grade 60 per cent emulsion, 1 per cent lime (only where the PI exceeded 8) and 1 per cent cement. The emulsion treated material was used to allow the use of 100 mm steel shuttering and to make up the difference in thicknesses of the 100 mm, 75 mm and 50 mm concrete layers. The asphalt (where applicable on Section 8) was continuously graded (12 mm maximum size aggregate) hot mix asphalt with 60/70 penetration grade bitumen.

The concrete was a standard 19 mm stone mix with a specified 30 MPa cube strength after 28 days. Concrete was provided by a ready-mix plant and joints (where applicable) were not sealed. The steel fibres (Sections 1, 2 and 3) were introduced into the mixer truck on site and were hook-ended RC-80/60-BN steel fibres. The reinforcing for all the CRCP sections was a 200 x 200 x 5.6 mm mesh (Bergh, 2004; Steyn, 2004). The concrete was cured for four weeks with a curing compound and plastic sheeting before opening the experimental road to fully laden trucks leaving the quarry.

Table 1. Summary of selected in place material properties for the various test sections.

LAYER	MATERIAL PROPERTY	Layer Thickness and Material type						
		75 mm SFRC, foam; stab	**75 mm SFRC, ETB**	**50 mm; 75 mm CRCP, ETB**	**100 mm CRCP, ETB**	**100 mm JCP, stab**	**100 mm JCP, AC**	**140 mm JCP; dowel**
Concrete	Compressive strength 28 days [MPa]	22.5 to 28	28	31 to 42	32 to 39.5	32 to 37	34 to 37	34 to 37
Base / Subbase	Average UCS [kPa]	1 950						
	PI	Non Plastic						
	Average Stiffness [MPa]	750						
Subgrade	Average CBR [%]	75						
	PI	6						
	Grading Modulus	2.5						
	Density [kg/m^3]	2 143						
	Average Stiffness [MPa]	180						
	Classification	A1 - a(0) and A2 - 4(0)						

A summary of the deflection response data for the various sections is shown in Table 2. The data indicates the typical maximum surface deflection as detected using a FWD. No clear trend was visible for these deflection values over the period that it was monitored, indicating no clear trend in pavement deterioration that affected the elastic deflection of the pavement structure.

Table 2. Summarized deflection response data for the various test sections.

RESPONSE PARAMETER	**75 mm SFRC, foam; stab**	**75 mm SFRC, ETB**	**50 mm; 75 mm CRCP, ETB**	**100 mm CRCP, ETB**	**100 mm JCP, stab**	**100 mm JCP, AC**	**140 mm JCP; dowel**
Average surface deflection range (FWD) [mm]	0.52 to 0.61	0.75	0.55 to 0.63	0.48	0.50	0.59	0.51 to 0.69

Performance

The performance of the thin concrete sections is defined in terms of their ability to carry the applied traffic during their life. A survey was conducted (after approximately 30 months of trafficking) by engineers from client, academic, contractor and research backgrounds who were invited to evaluate the condition of the pavement. These evaluations focused on both the client/designer and road user perception of the condition of the pavement. Further, reviewers were requested to evaluate the facility being used as a highway, street or hard standing (apron). Reviewers assessed the pavement in terms of the percentage area perceived to be in a failed condition. The summarized results of this survey to evaluate the sections as a street are shown in Figure 2.

The information in Figure 2 indicates that, of all the sections, the 75 mm SFRC on foam section (indicated as 1 in Figure 2) had the largest area perceived to be in a failed condition (58 per cent) when the facility was evaluated as a street, from a professional viewpoint. When the same section was evaluated from a street user viewpoint, it was also perceived to have been in the worst condition (43 per cent) of all the sections. On the other end of the scale, the 100 mm CRCP section (indicated as 6 in Figure 2) was perceived (from a professional viewpoint) to be the best performing section with only 9 per cent of the surface area perceived to have failed. Generally, the worst two sections (indicated as 1 and 7 in Figure 2) and the best two sections (indicated as 6 and 3 in Figure 2) received the same ranking for both the ‘professional/client’ and the ‘road user’ perspectives.

The condition of the pavement should be judged considering the actual traffic together with the intended application of this type of thin concrete road. The thinnest sections are intended mainly for township and lightly-trafficked access roads, where the traffic loading on these test sections would be equal to over 30 years of normal traffic.

Figure 3 shows some of the surface conditions encountered during the review. It is clear from the figure that the unsealed preformed joints show severe spalling and that the longer panels of the slabs placed directly on top of stabilized layers had cracked. Note also the sound condition of shorter panels in the background. The reviewers observed that:

- Slab support was deemed crucial for the performance of the sections under traffic;
- The best performance was obtained from sections with ETB or asphalt below the slab;
- Slab curling increased the risk of failure, especially at slabs with longer joint spacing that were on top of a stabilized layer;
- The successful placement and the alignment of dowels were crucial if mid-slab cracking was to be avoided, and
- Reinforced very thin slabs (< 75 mm) performed as well as thicker non-reinforced slabs (> 100 mm) on the stiff bases.

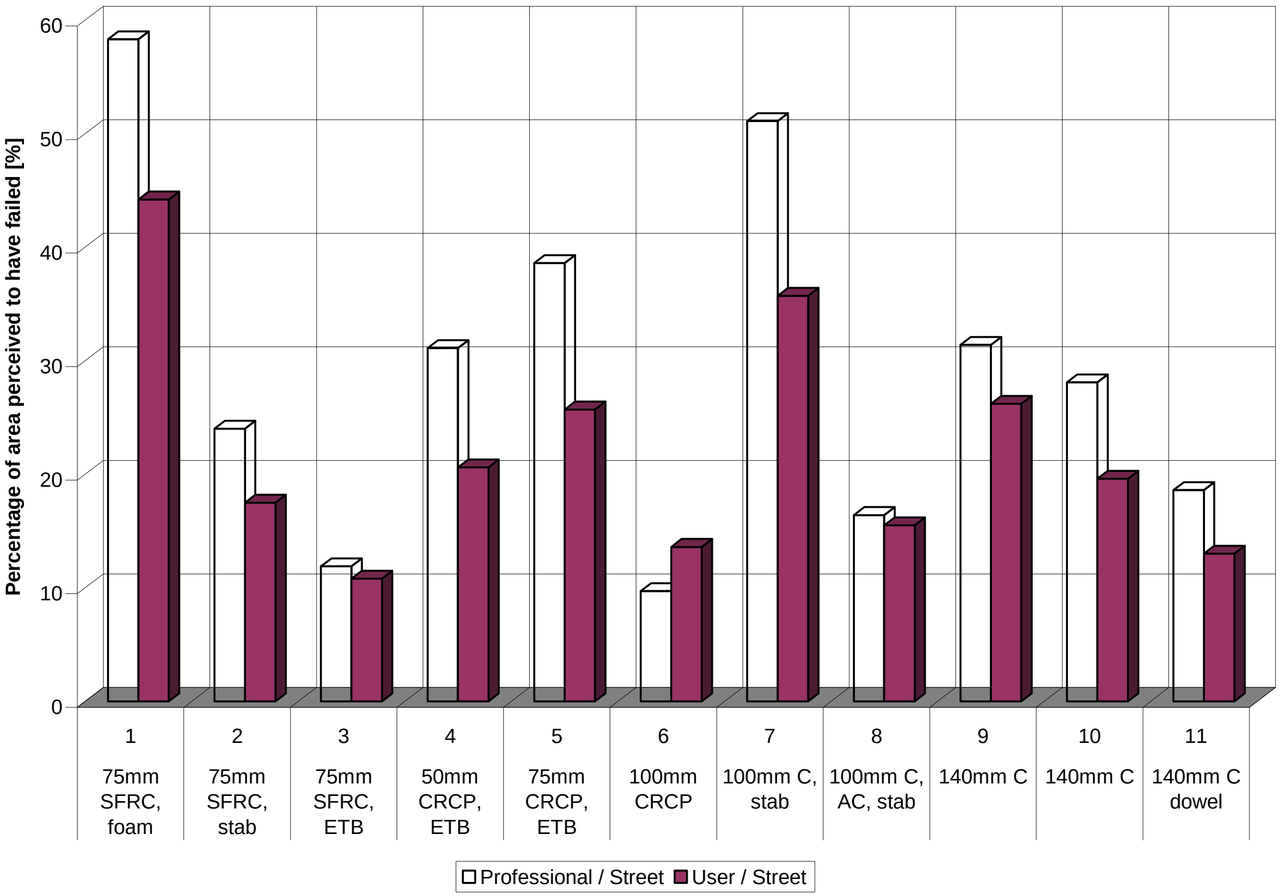

Figure 2. Summary of reviewers' perception of the area of pavement failed when evaluated as both professionals and users – evaluated as a street.

Significance of support for performance

It would not be correct to conclude from the performance of the sections in question that thin concrete sections can be used for any application with the expectation that equally good performance will follow. While the reality has shown that the thin concrete sections could carry a reasonable amount of traffic without suffering undue failures (especially for low volume streets and rural roads), it is important to develop an understanding of the reasons for this performance.

It was indicated earlier in this paper that it is postulated that one of the main reasons for the thin concrete sections performing so well under the traffic, is the relatively strong support provided by the subgrade and subbase layers. This was one of the fundamental design features of the sections. The contribution of the support from the subgrade to the performance of the sections is thus evaluated mechanistically to illustrate this phenomenon.

Mechanistic evaluation

The review and condition survey indicated that the 50 mm CRCP layer appeared to perform better than the 75 mm CRCP. This phenomenon was evaluated by Strauss and Perrie (2004). They investigated the effect of a critical thickness for thin concrete pavements. Finite element modelling was employed in their analysis in order to obtain information on the relative effect of parameters such as slab thickness, slab support stiffness (and others) on the development of stress. They concluded that, based on modelling and field observations, a critical thickness at which the stress at the top of a slab, and thus potential for surface cracking is a maximum, does occur. This is illustrated in Figure 4 and indicates that performance is dependent on the following conditions:

- The base having a relatively high stiffness. This is the case with bases cemented or stabilized using either portland cement or asphaltic materials. The higher the stiffness, the greater this critical thickness;
- Bond between the base and the slab. Increased bond increases this critical slab thickness, and
- The shrinkage gradient through the slab. An increase in the gradient increases the critical thickness.

Figure 3. Typical cracks encountered on longer panels during the review of the sections. Note the good condition of shorter panels in the background.

In order to further explore the effect of the support conditions on the behaviour of the concrete layers, the stresses and strains that develop in the concrete layers with varying degrees of support were calculated using a multi-layered approach (mePADS, 2004). In these calculations, four cases with concrete layer thicknesses of 50 mm, 75 mm, 100 mm and 140 mm (similar to those used in the Roodekrans experiment) were used. A simple pavement structure consisting of three layers was used. These consisted of a concrete surfacing, a stabilized base and the subgrade. The structural parameters of all the layers were kept constant for the various calculations (concrete stiffness = 28 GPa, base thickness of 125 mm with a stiffness of 1 000 MPa), with only the stiffness of the subgrade support layer that was varied between 140 MPa and 70 MPa.

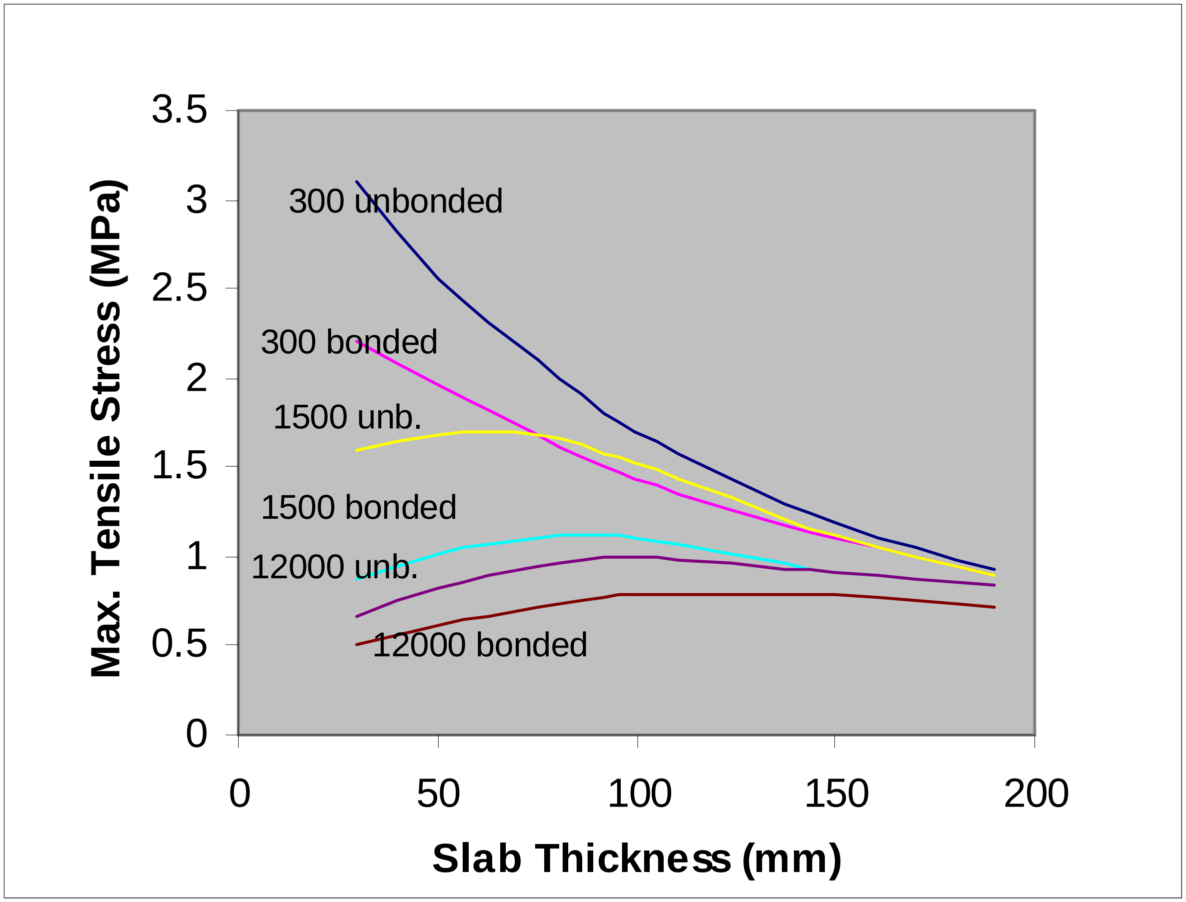

Figure 4. Maximum tensile stress at the surface of a slab and close to the joint as a function of slab thickness, support stiffness and bond between base and slab (Strauss and Perrie 2004).

The 140 MPa case was taken as the reference stiffness, with two additional subgrade stiffness values of 112 MPa (80 per cent of the default stiffness) and 70 MPa (50 per cent of the default stiffness) respectively. A simple circular load of 20 kN with a contact stress of 700 kPa was used for the analysis. The objective of the mechanistic analysis was to determine the way in which these three subgrade stiffnesses affected the stresses and strains developed in the concrete layer – and thus the behaviour of the concrete in the pavement structure.

The focus of the strain analysis was on the tensile strain at the bottom of the concrete surfacing layer, as this should provide an indication of the strains that may cause crack development in the concrete under traffic loading. The tensile strain at the bottom of the concrete surfacing is thus expressed (for the three different subgrade support cases) as a percentage of the same tensile strain calculated for the reference case with a 140 MPa subgrade support.

The results of the analysis for the strains are summarized in Figure 5 and illustrates two interesting phenomena. The first is that as the subgrade support decreases for the same pavement structure, the tensile strain at the bottom of the concrete layer increases, causing the potential for cracking and failure of the concrete surfacing to increase. This phenomenon is supported by the general understanding of the way in which a pavement works mechanistically.

The second interesting phenomenon is the observation that the 75 mm concrete surfacing appears to be affected the most critically by the decrease in subgrade support stiffness. It is followed by the 50 mm, 100 mm and 140 mm concrete surfacing layers. In Figure 6 this phenomenon is illustrated further.

The focus of the stress analysis is on the stresses developed at the top and the bottom of the concrete surfacing. The same analysis as for the strains (comparing stresses developed at the two lower subgrade stiffness levels with the higher reference stiffness case) was performed for the stresses. The results of these analyses are shown in Figures 6 and 7.

In Figure 6 the principal (tensile) stresses developed at the top of the concrete are shown. The increasing trend in stress with decreasing subgrade stiffness (support) is again illustrated. Further, it is interesting to note that the effect of the subgrade support stiffness on both the 50 mm and the 75 mm concrete surfaces is equal. This again supports the critical thickness hypothesis, postulated by Strauss and Perrie and shown with the strain trends in Figure 5.

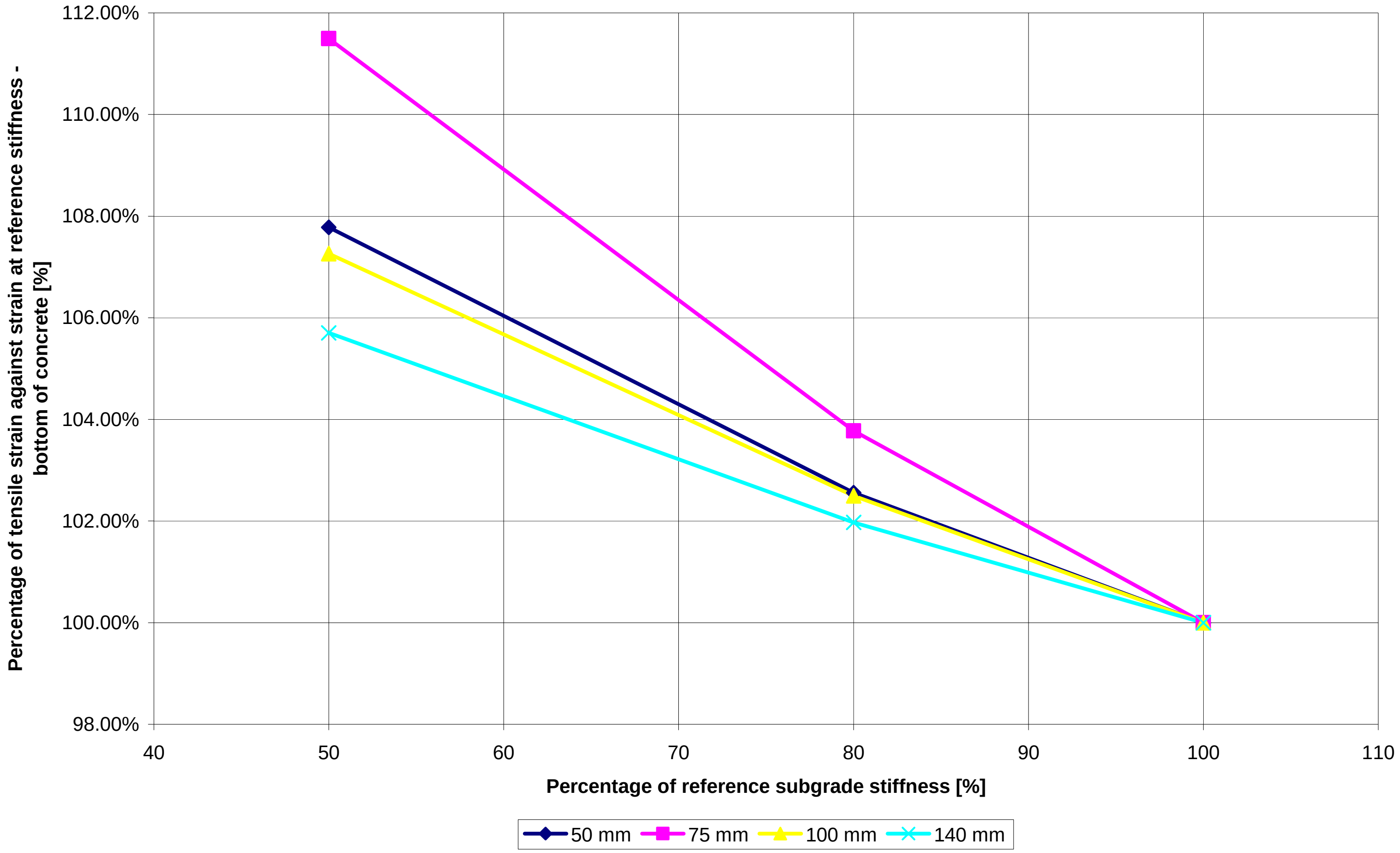

Figure 5. Tensile strain at bottom of concrete surfacings at three subgrade support stiffness levels, as a percentage of the tensile strain calculated at the reference subgrade support stiffness.

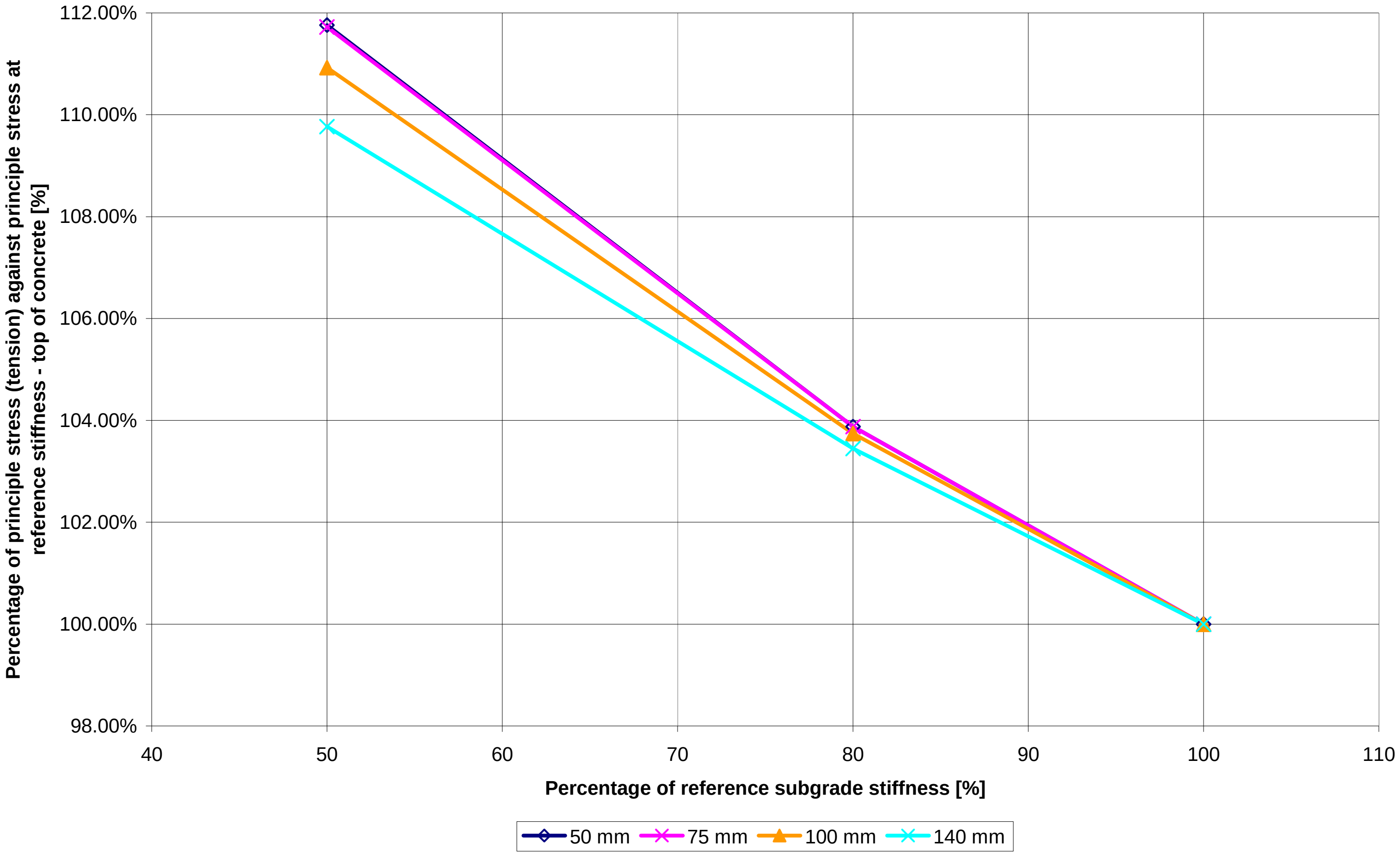

Figure 6. Principal (tensile) stress at top of concrete surfacings at three subgrade support stiffness levels, as a percentage of the principle (tensile) stress calculated at the reference subgrade support stiffness.

Figure 7 focuses on the principal (tensile) stresses at the bottom of the concrete layer. Similar trends are observed with reference to both the decreasing stiffness and increasing stress trends and the critical thickness hypothesis. The critical thickness effect is more pronounced (similar to the strains – Figure 5) for the principal stresses at the bottom of the concrete.

In support of the more pronounced effect of the subgrade stiffness to the stresses and strains developed in the concrete, it is apparent from Figures 5, 6 and 7 that the slope of the trend for each of the thicknesses is steeper for the critical 75 mm concrete thickness than for the 50 mm concrete thickness. The trend continues with the slope for the 140 mm concrete thickness being the lowest of the four. This supports the hypothesis that the effect of the subgrade stiffness is more pronounced for thinner (or more critical i.e. 75 mm concrete) concrete thicknesses when evaluating thin concrete pavements.

The maximum calculated principal stresses at the top and the bottom of the concrete layers were 1.4 MPa (compressive at top of slab), 1.8 MPa (tensile at top of slab) and 1.8 MPa (tensile at bottom of slab) respectively. These stresses were lower than the respective compressive strengths (22.5 to 42 MPa – Table 1) and tensile strength (4 MPa) of the concrete – explaining the relatively good performance of the concrete sections under the applied traffic.

Practical Conclusions

The significance of this research to practitioners is as follows:

- The project has demonstrated that relatively thin concrete surfacings can be used as part of a balanced pavement structure (one with adequate support to the concrete) for the construction of roads with traffic ranging up to at least 400 000 E80s (and even beyond this point, as the current condition of the sections are still functionally very acceptable);
- The existence of a critical thickness, generally in the order of 75 mm but dependent on support stiffness and bond, was demonstrated through the analysis of the stresses and strains in the concrete. This information will assist designers to analyze and select appropriate thicknesses for thin concrete sections, and not only a practical thickness (that may be the critical thickness for the structure),
- The experimental sections were constructed by hand (not covered in this paper) and the use of labour on construction projects where heavy plant is not readily available (i.e. developing countries) to construct roads capable of carrying heavily loaded vehicles, has thus been demonstrated.

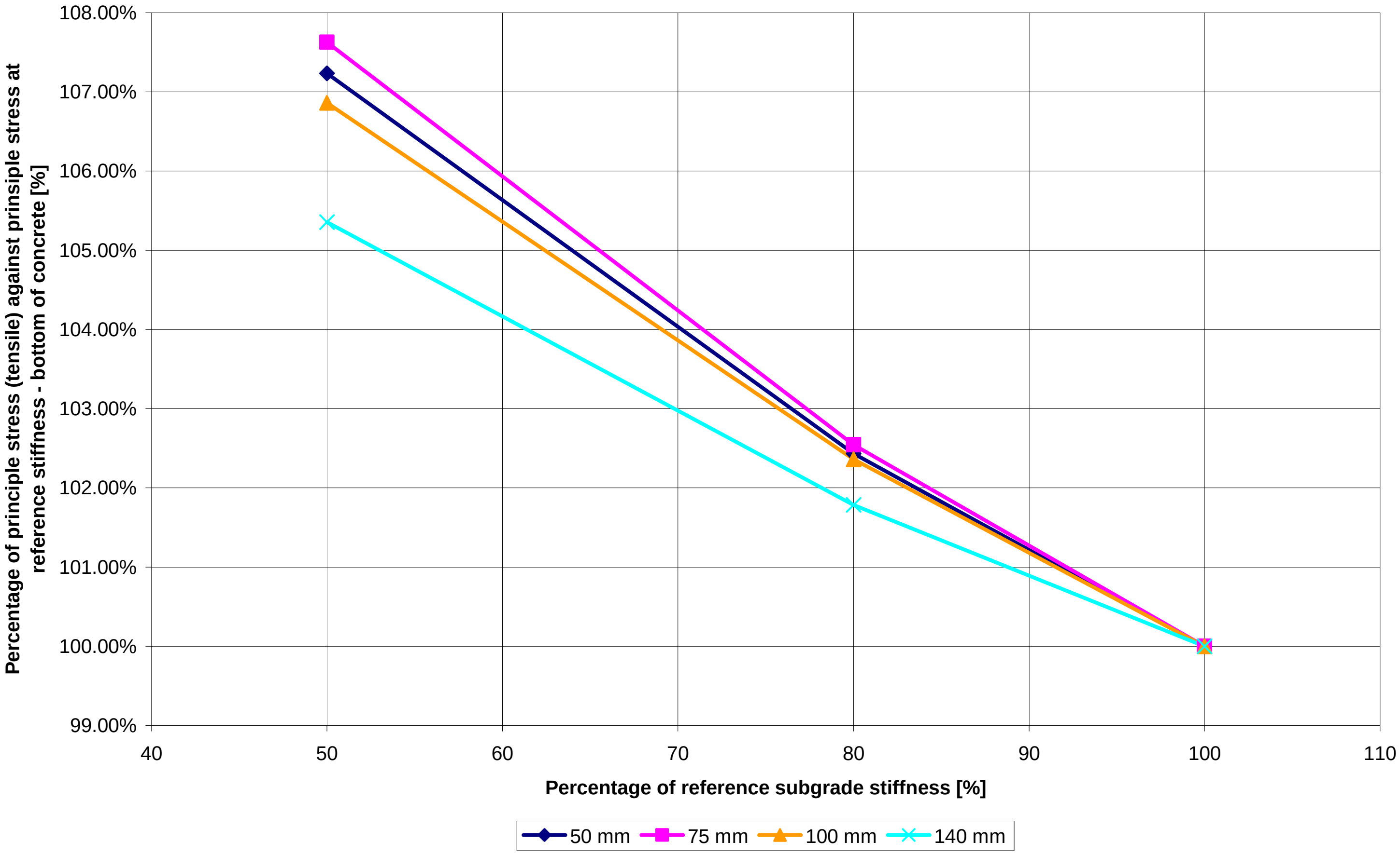

Figure 7. Principal (tensile) stress at bottom of concrete surfacings at three subgrade support stiffness levels, as a percentage of the principle tensile stress calculated at the reference subgrade support stiffness.

Conclusions

The following conclusions are drawn based on the information discussed in this paper:

- The thin concrete layers are only part of a pavement structure that contributes to the performance of the concrete. The support system also plays an important role;
- Relatively thin concrete surfacings can be used effectively to carry heavily loaded vehicles, if the concrete is supported adequately in the pavement;
- A critical thickness appears to exist for the concrete layer above and below which the effect of the support stiffness is less critical than at the critical level (75 mm in the case evaluated);
- Both the compressive and tensile stresses developed in the concrete for the conditions evaluated are lower than the compressive and tensile strengths of the material used, explaining the relatively good performance of the sections observed in the field.

Acknowledgement

The authors would like to thank the organizations that sponsored the project for their support over a number of years. These include C&CI, CSIR-Transportek, the University of Pretoria and BKS. The permission of each of these organizations to publish the findings is acknowledged.

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