Design and Construction of Ultra-Thin Continuously Reinforced Concrete (UTCRC) on N1 near Hugenote Tunnell

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Abstract: In 2009, the National Route 1 Section 1 between km 56.1 and km 61.5, located North East of Paarl in the Western Cape Province of South Africa, was rehabilitated and widened. As part of the rehabilitation and widening contract the downhill truck crawler lane was constructed as an experimental pavement section. This experimental pavement section was constructed with a 50 mm thick Ultra-Thin Continuously Reinforced Concrete Pavement (UTCRCP). Early in 2010 sections of the experimental UTCRCP started to fail and consequently necessitated repair. In October 2014 a service provider was appointed for the special maintenance of the truck crawler lane on the National Route 1 Section 1. The project called for the reinstatement of the failed experimental UTCRCP with a re-engineered UTCRCP and a Enrobé à Module Élevé (EME) asphalt base layer with an Ultra-Thin Friction Course (UTFC), at various locations along the southbound (downhill) truck crawler lane. The project objective was specifically formulated to enable a long term performance comparison of both the re-engineered UTCRCP and the EME with UTFC under repeated traffic loading. The focus of this paper is the documentation and assessment of the initial pavement (structural analysis) and material design process, the construction of the UTCRCP, with cognizance of the challenges experienced during construction as well as the initial performance comparison. EME will not be discussed in this paper.

1 Project Background

The route between Paarl and Worcester historically traversed through the Du Toits Kloof Pass. Inadequate capacity and poor road safety conditions necessitated the realignment of a portion of the National Route 1 Section 1 and the construction of a tunnel through the Klein Drakenstein Mountains.

The new route was officially opened to traffic in 1988. In 2009 the National Route 1 Section 1 between km 56.1 and km 61.5 was rehabilitated and widened. As part of the rehabilitation and widening contract, the downhill truck crawler lane was constructed as an experimental pavement section ([1], [2], [3]).

This experimental pavement section was constructed with a 50 mm thick Ultra-Thin Continuously Reinforced Concrete Pavement (UTCRCP). Early in 2010 sections of the experimental UTCRCP started to fail prematurely and consequently necessitated repair ([4]).

2 Project Objective

The project called for the reinstatement of the failed experimental UTCRCP with a re-engineered UTCRCP and an Enrobé à Module Élevé (EME) asphalt base layer with a Ultra-Thin Friction Course (UTFC), at various locations along the southbound (downhill) truck crawler lane.

The project objective was specifically formulated to enable a long term performance comparison of both the re-engineered UTCRCP and the EME with UTFC under repeated traffic loading.

Only the UTCRCP will be discussed in this paper, the EME is discussed in separate paper(s).

3 Introduction

The concept of UTCRCP was introduced in South Africa in 2007 ([2],[3]). The main reasons for the introduction of the UTCRC technology are that with more than 70% of the road network in South Africa being older than its 20-year design

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life, major investments into structural strengthening of pavements are required and that, due to severe budget constraints, new innovative pavement repair strategies need to be developed that will be more cost effective. The South African National road network is shown in Figure 1.

A number of experimental sections were constructed in South Africa, one of which is located on National Route 1, Section 1 (N1/1), near Cape Town. This experimental section was constructed on the truck crawler lane that traverses a steep downhill section of approximately 6.5 kilometre length between the Huguenot Tunnel West Portal and a toll plaza and is the subject of this paper.

Previous papers have reported on the construction of the experimental section on N1/1 during the summer of 2009/2010 ([1]) and the investigations into the premature failure of the experimental section on N1/1 during the summer of 2010/2011 ([4]).

Figure 1: The South African National Road Network

After extensive monitoring of the failed experimental section and subsequent analyses described in [1] a project was started in 2014 to repair the failed section. The failed section was replaced with different options of the UTCRCP concept, a conventional Continuously Reinforced Concrete Pavement (CRCP) section and a high-modulus asphalt section of EME. Construction commenced in March 2015 with a completion in December 2015.

This paper describes some of the work undertaken during the current project and includes performance to date of the experimental section, finite element analyses, proposed UTCRCP repairs and further research

4 As-built Pavement Structure

The pavement structure constructed during the 2009/2010 contract comprised of a 50 mm UTCRC layer, 30 mm finely graded Asphalt Concrete (AC) interlayer, 170 mm Bitumen Stabilised Material (BSM) upper subbase and 300 mm Cement Treated lower subbase; selected gravel layers. Detailed information regarding the materials, pavement structure and rehabilitation design are provided in [1].

The concrete used in the UTCRC layer was a high strength mix with 30 mm hooked steel fibres included, a compressive strength 90 MPa min to 120 MPa max, flexural strength not less than 10 MPa and energy absorption greater than 700 MPa, measured according to ASTM C1550-12a ([5]). The purpose of the AC interlayer was to provide a level surface constructed to tight tolerances so that the UTCRC layer could be constructed to tight tolerances and to ensure bond with the BSM subbase layer.

Bond between the UTCRC and lower three layers is very important as the design philosophy of the UTCRCP is to achieve a composite structure with good bond between the pavement layers, reducing traffic induced stresses in the UTCRC and thereby allowing the use of a very thin concrete layer. The UTCRC layer was constrained through three terminal end beams at each end and intermediate beams at a spacing of approximately 250 to 300 metres. The terminal beams were 500 mm deep, while the intermediate beams were 250 mm deep.

5 Pavement Performance

The pavement developed numerous defects since the end of construction in March 2010. The defects that have been observed to date include the following: buckling of UTCRC layer, blow-ups; transverse cracking, day joints opening and steel breaking, punch outs; debonding of UTCRC from AC interlayer, horizontal movement following blow-ups, spalling of concrete at day joints and transverse cracks, and vertical deformation of UTCRC layer.

A number of these defects may be attributed to thermal stresses developing in the UTCRC layer due to diurnal temperature cycles (refer to Figure 3). These include buckling and blowups, day joints opening and steel breaking, horizontal movement after blow-ups and the debonding of the UTCRC layer from the AC interlayer. Curling of the slab developed overnight at the free end of the UTCRC layer after a day's production, i.e. at the day joint between two days work, resulting in a short length of slab debonding from the AC interlayer.

Figure 2: View on N1/1 UTCRCP shortly after completion of construction in 2010

With the number of day joints the production rate varied between 50 and 95 meter per day over a construction length of approximately 4 500 metre and average width of 4 metre. It is fair to say that since no anchoring was constructed at the end of each day, overnight movements may have occurred due to shrinkage and temperature variations and this phenomenon may have had a significant influence on the debonding of the UTCRCP layer.

Curling and debonding also occurred at the longitudinal free edges. The subsequent failure of the joint seals along the edges provided a pathway for moisture to enter the

Figure 3: Defects mainly at construction joints along the National Route 1 truck crawler lane that can be attributed to thermal stresses developing in the UTCRCP layer due to diurnal temperature cycles (December 2010)

interface between the UTCRCP layer and the AC below. This also accelerated the debonding process.

In order to keep the lane serviceable, damaged sections of the UTCRCP were cut out and repaired with asphalt patches. However, movement of the slabs continued and day joints in particular opened up resulting in a loss of load transfer with subsequent fatigue failures and punching.

A total of 33 cores were drilled in the pavement and these provided very useful input into understanding the performance of the pavement, specifically with regard to debonding. Figure 4 summarises the results from the core survey, including the percentage of occurrence.

Figure 4: Results from core survey on the National Route 1 truck crawler lane west of the Viaduct

Cores taken from the UTCRP also showed that movement took place not only at the interface between AC and UTCRCP but also between AC and BSM or in the BSM. Shear failure took place at the weakest point in the pavement structure.

This expected debonding between the 50 mm UTCRC layer and the 30 mm finely graded Asphalt Concrete (AC) was later confirmed when the failed UTCRC sections were removed during the repair of the failed sections, between March 2015 and December 2015.

6 Initial Finite Element Analysis

As part of the monitoring and initial investigation into possible causes for failure, a Finite Element Analysis (FEA) was undertaken to model behaviour of the UTCRC layer under specific conditions (load cases) ([6]). The FEA focussed specifically on UTCRC behaviour due to thermal stresses, i.e. buckling and sensitivity of the UTCRC to the presence of honeycombing, which effectively reduces the slab thickness as well as its stiffness, the position of the steel mat, geometric imperfections in the UTCRC profile which leads to a reduction in the thickness of the UTCRC and the addition of longitudinal edge beams to the UTCRC slabs. This work is discussed in detail in ([4]).

Buckling of the slab manifests as bulges during high temperatures and disappears when temperatures drop. Therefore, the initial FEA focussed on this phenomenon specifically. The UTCRC slab was loaded by incrementally increasing the temperature, thereby developing stresses in the slab due to constrained thermal expansion.

Buckling was investigated as the UTCRC slab is considered to be very slender due to the large spacing between intermediate beams (restraints) ([7]). The results of the FEA indicated the following: the risk of buckling is very high where honeycomb concrete is present, increasing the thickness reduced the risk of buckling slightly, the addition of edge beams also proved to be very effective in reducing the risk of buckling.

An increase in slab thickness from 50 mm to 70 mm resulted in a slight increase in the buckling resistance of the UTCRC. It was therefore suggested that the slab thickness and the workability of the concrete be increased to assist in reducing the risk of honeycomb concrete. Increased workability is possible by an increase in water content with a slight risk of reducing strength, which could be mitigated by the increase in thickness of the slab.

Should it not be possible to completely eliminate the risk of honeycomb concrete, then the use of edge beams should be considered as these are very effective in minimising the risk of buckling. For this FEA the load case with 150 mm deep edge beams did not reach a point where buckling occurred. Therefore, it was concluded that the risk of buckling was eliminated through the use of the edge beams.

Figure 5: Complex Model used in FEA

Figure 5 shows the complex model with line AA indicating the line of symmetry of the model, which implies that the mirror image to the right of the Figure 5 need not be modelled. The blue area simulates the UTCRC slab, the greenish-grey the subbase, red the lower subbase and brown the in-situ subgrade.

The dark blue squares are the 20 kN single wheel loads, 150 mm apart, of a double wheel tandem axle with the axles 1350 mm apart. Dynamic loading, at 10 km/h, is applied 200 mm from the edge of the concrete with the subbase and other sub-layers extending 1.2 m beyond the edge. Plots of results in this paper have been taken from calculated pavement behaviour along line BB.

The following assumptions were made during compilation of the basic model for the FEA:

- Because of the speed of loading, linear elastic models are used.
- The reinforcement is modelled as independent elements from the concrete and is placed at mid depth of the concrete slab.
- Smaller closely spaced elements, are used to model the concrete at cracks. The crack itself has zero width from the reinforcement down to the bottom of the slab but the width increases, as observed on site, from the reinforcement to the top surface of the slab. Compression and the transfer of shear forces can therefore occur at the crack, but not tension.
- Bond is assumed between all the sub-layers for all the scenarios.
- In the modelling of the 50 mm UTCRC, no bond between the slab and the subbase is assumed since a substantial amount of horizontal movement has been detected on the existing 50 mm UTCRC thus resulting in a loss of bond.

Full bond is assumed between the subbase and the UTCRC slab for the other cases except close to the crack itself where partial contact, implying no bond, is assumed over a width of 100 mm on both sides of the crack.

Figure 7 shows the same moving load as indicated in Figure 6 but now crossing the crack. The stress is now higher but still close to the crack. Note that the high stress occurs close to the surface of the slab.

Figure 6: Tensile surface stress in a 50 mm UTCRC under a wheel moving at 10 km/ hour - load midway between cracks

Figure 8 shows the same moving load as indicated in Figure 6 and Figure 7 above but now the load has crossed the crack. The tensile stress, shown in red, is still higher close to the surface of the slab and lose to the crack but at a different position to the position shown in Figure 7, i.e. the position is now behind the wheel where it was in front of it previously.

Figure 7: Tensile surface stress in a 50 mm UTCRC under a wheel moving at 10 km/hour - load crossing the crack

Figure 9 shows the moving load at the position as indicated by the dark blue area on the surface of the 70 mm UTCRC (crack spacing of 400 mm). The stress patterns are the same as that for the 50 mm slab except that tensile stress is now developing below the load when surface tensile stress is at its highest, still in a similar position behind the wheel close to the crack.

Figure 8: Tensile surface stress in a 50 mm UTCRC under a wheel moving at 10 km/hour - load has crossed the crack

Figure 9: Tensile surface stress in a 70 mm UTCRC under a wheel moving at 10 km/ hour - the load has crossed the crack and tensile stress is developing at the bottom of the slab

7 Valuation of the FEA Results

Some of the results of the analyses are plotted in Figure 10. Also included in Figure 10 are results using both the Westergaard equations and a multi-layer analyses program, typically used in the analyses of flexible pavements. The intention of the results plotted in Figure 10 is to specifically show the trends in stress as a result of slab thickness and not the real values since slab dimensions, edge effects, slab support and other conditions are different for the different models.

It is important to note that except for the FEA modelling, where both top and bottom stresses are shown, the results of all the other methods that are plotted, are the maximum tensile stresses at the bottom of the slab. The following interesting observations can be made from Figure 10:

- The trend in maximum tensile stress is basically the

same for all models if the slab thickness is greater than 70 mm.

- The tensile stress tends to be less sensitive to thickness using the FE models compared to that of the other models; this may be as a result of a change in crack spacing in the FE models as the thickness increases.
- The trends in change of maximum tensile stress with change in slab thickness at the bottom and at the top of the slab is the same for the FEA modelling
- When the slab thickness is less than 70 mm, the multi-layer and the FEA modelling show the same trends. This trend is different from that rendered by the Westergaard equations for both interior as well as edge loading down to a slab thickness of 50 mm.
- The vertical compressive stress on the surface of the subbase, directly below the slab, increases by 89% when the slab thickness decreases from 100 mm to 50 mm and increases by 33% when the slab thickness decreases from 100 mm to 70 mm.

The maximum tensile stress is higher at the bottom of the slab than at the top surface of the slab. However, observations in the field have shown a number of surface cracks midway between transverse shrinkage cracks. Cracks which primarily affect the long term performance of the pavement are cracks that develop at the surface of the slab close to transverse construction joints or early shrinkage cracks, compare Figure 6 (50 mm slab) and Figure 9 (70 mm slab), leading to structural failures.

The development of surface cracks is further enhanced by the higher shrinkage at the surface of the slab and a bigger variation in surface temperatures resulting in curling, together with a loss of bond and even a void developing close to the shrinkage cracks. Cracks and transverse joints in the slab, which strictly speaking eventually becomes a hinge when the load transfer from the one to the adjoining slab is lost, implies a decrease in stiffness in that region which increases the deflection resulting in a loss of support (pumping and erosion) due to higher stress at the interface

between the slab and the subbase. This increases tensile stress at the top of the slab close to the crack/joint which leads to structural failures. A loss of bond between a thinner slab and the top of the subbase increases the risk of the thinner slab to be pushed around under traffic loading, and an increase in voids and a resulting increase in stress in the slab.

Based on the above observations and since the trends in relative maximum tensile stress for all the different models are very similar, the maximum tensile stress at the surface of the slab will be used in further deliberations, especially since the added tensile stress that develops as a result of higher shrinkage and lower temperatures at the surface of thinner pavements may have to be considered in future modelling. This approach is considered acceptable if it is kept in mind that the ratio maximum stress-at-the-bottom to stress-at-the-top under wheel loading is similar for the 50 mm, 70 mm and slightly higher for the 100 mm thicknesses of UTCRC. It is an accepted principle that the structural performance of a pavement is a function of the stress to strength ratio.

Applying these principles and interpreting the results obtained from the FEA with the use of the concrete pavement design program cncPAVE ([8]) lead to the following findings:

- The theoretically calculated stress in the 50 mm UTCRC using FEA, is relatively low, well within the limits normally applied and the failures observed cannot be explained by this calculated stress alone.
- The failures that eventually developed under loading can only have occurred if a total loss of bond and significant sized voids have developed between the slab and the subbase. Contributing factors include a big variation in slab strength together with a significant decrease in the effective thickness of the slab (concrete not well compacted and honey-combed) as well as a substantial decrease in the stiffness of the subbase, especially at its contact with the UTCRC slab.
- It can be assumed that curling of the slab, especially at

Figure 10: The relative maximum stresses in a concrete slab obtained using different methods of calculation

the construction joints and its free edges, has enhanced buckling, movement of the slab downhill and a loss of bond as well as the development of more voids between the slab and the subbase.

- Furthermore, curling at the edges of the slab together with opening up of the longitudinal joint between the UTCRC slab and the adjoining asphaltic second lane has allowed surface water to enter the structure which aggravated the weakening of the sub-layers and the loss of support of the slab.

8 Current Structural Analysis

The results of the initial FEA guided the design team in their proposals for the repair of the UTCRCP. The following design parameters were therefore incorporated in the cncPave analysis:

- The thickness of the UTCRCP was increased from 50 mm to 70 mm mainly to improve workability and limit the risk of honeycombs;
- Edge beams will be provided to manage the risk of buckling and to improve curling and resistance against edge loading;
- At construction (day) joints, the slab thickness was increased to improve load transfer capacity, using ties key joints; and
- Intermediate anchor beams will be provided at approximately 60 m intervals, coinciding with day joints.

Layer stiffnesses had to be determined for the pavement layers in the existing pavement structure. Back calculations were performed on the best performing section of the UTCRCP. The optimisation of the UTCRCP design was based on aiming to achieve a crack spacing of 0.5 m while also limiting the percentage shattering to 0.8% and the pumping to 5%.

Based on the optimisation strategy and design parameters, the cncPave analysis confirmed that the following pavement structure should suffice to accommodate the design traffic load for 30 years:

- 70 mm UTCRCP at 7.5 MPa flexural strength and 5.6 mm diameter reinforcing mesh at 67 mm square spacing. A spacing of 100 mm would have been preferred to achieve a preferred 0.5 m crack spacing but the mesh is provided in standard sizes;
- 30 mm AC medium with high (7%) binder content and 2% Voids in the mix;
- 140 mm insitu BSM (remove 50 mm UTCRCP, 45 mm AC Medium asphalt and 15 mm of existing BSM);
- 335 mm C3 cemented Quartzitic gravel sub-base; and
- 300 mm+ decomposed granite subgrade.

Edge beams need to be provided on both sides of the slab constructed monolithically with the slab. The beams are 200 mm wide and 150 mm deep i.e. 70 mm slab thickness plus an additional 80 mm. This additional edge beam having been attached to the UTCRCP in particular changes the complexity of the construction method and can

be regarded as counterproductive with reference to the original intension of a simple concrete overlay to store or improve the structural capacity of conventional pavements. It was therefore proposed to include an experimental pavement section where the 70 mm thick UTCRCP (with edge beams) is replaced with a 100 mm thick UTCRCP without edge beams.

However, it was deemed prudent to further analyse the UTCRCP structure in order to confirm the design proposals concluded from the cncPave analysis. For this, FEA was again used and a more complex model was developed while a dynamic wheel load was applied to the model (du Preez, 2015).

The input variables such as concrete strength and stiffness, steel diameter and spacing, crack spacing and crack width in the slab and the stiffness and thickness of sub-layers are derived either from conditions observed on site or obtained from calculations.

9 Proposed UTCRCP Repairs

The results of the assessment of the pavement performance, the cncPave analysis and the two FE analyses have been implemented in the design of the UTCRC repairs. The use of edge beams features strongly in this section and was discussed in detail in a previous publication (Bredenhann et al, 2014). Essentially, the edge beams eliminate the risk of buckling of the very slender UTCRCP slab.

The contract comprised a number of pavement types to replace the failed UTCRCP, namely two CRCP sections, an EME pavement section and two UTCRCP sections, one 70 mm thick and one 100 mm thick. Some design aspects of the UTCRCP sections are:

- Edge beams, 150 mm deep will be included in the 70 mm thick pavement section;
- The 100 mm thick pavement will be a flat slab, i.e. no edge beams;
- Day joints will be constructed as 250 mm deep intermediate beams as it is believed that this will reduce the risk of curling at day joints;
- A concrete mix with lower flexural strength (minimum 8 MPa) compared to that of 2009/2010 has been specified, which should improve workability of the mix, improving placement and compaction of the mix.

10 Construction Sequence

Due to the high expansiveness of the UTCRC, it is very important to plan the construction sequence of the layer. This was illustrated during this project where a section of the lane had to be skipped during construction and then filled in later. This filled in section was constrained on both sides by concrete that had already hardened and shrunk. During subsequent high temperatures in the summer, this section experienced localised buckling, which was addressed by inserting an expansion joint.

11 Conclusions

It can be concluded at this stage that a 100 mm UTCRC slab will out-perform both the previously constructed 50 mm as well as the proposed 70 mm UTCRC. Indications from the current FEA and the initial FEA are that the 70 mm UTCRC will show much improved performance, despite the fact that the maximum tensile stress is about the same as that in the 50 mm slab, for the following reasons:

A thicker slab with lower strength requirements will enhance workability, better compaction and less variation in strength and effective thickness (lower risk of honeycombing).

- Edge beams and thickening of the slab at construction joints will reduce curling at these sensitive positions and enhance bond between subbase and slab. This will reduce both the risks of uplift of the slab and voids (pumping) developing below the slab under traffic loading.
- Edge beams and thickening of the slab at construction joints will reduce the negative effect of traffic loading at edges of the pavement as well as load transfer at these joints.
- Edge beams will further reduce the risk of surface water entering the supporting layers and the consequential pumping and developing of voids with all its other negative effects.
- Thickening of the slab at construction joints will enhance anchoring of the slab and reduce the risk of slab movement as well as buckling under adverse environmental conditions.
- A thicker slab will reduce curling of the slab as well as the stress on the subbase thereby reducing the risk of pumping, stripping and rutting at the interface between slab and subbase which lead to the loss of bond and the formation of voids.

12 Further Research

The models used in the FEA for the current project will be refined and enhanced through an extensive research study. Some of the work will focus on cyclic load tests in order to better understand the behaviour of the material under repeated loading, as is encountered under traffic loading. The details and outcome of this study will be reported on in future publications.

It is expected that this further research will contribute

greatly to the body of knowledge that has already been developed for the UTCRC pavement type and that the understanding of the behaviour of very thin, high strength concrete pavements will be further enhanced.

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