The design, construction and Heavy Vehicle Simulator testing results on Roller Compacted Concrete test sections at the CSIR Innovation Site and on a full-scale test road at Rayton

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Abstract

Although the use of Roller Compacted Concrete (RCC) is not new in South Africa, the use of it to construct roads is not that well known or studied. The Gauteng Provincial Department of Roads and Transport (GPDRT) in conjunction with CSIR Built Environment in South Africa and Cosal Consultants CC started a research program on the use of RCC technology for roads. Whereas RCC is normally constructed with a relatively low labor component using heavy mechanical equipment, one of the aims of this investigation was to evaluate the structural performance of RCC constructed with a relatively high labor component using hand-operated equipment. The evaluation was done using the Heavy Vehicle Simulator (HVS) of the GPDRT.

This paper briefly details two investigations. One HVS RCC test was conducted at the CSIR innovation site and the other on a full-scale test road at Rayton, Gauteng.

Through HVS testing it has been shown that this type of pavement performed well in the dry state, even when constructed on a substandard support system. Test results indicate that this type of pavement exceeded its predicted performance. The use of hand-labor for layer compaction is discouraged as this can lead to layer densities lower than acceptable standards, which result in poor performance. The importance of proper RCC mix design to mitigate the negative effects of shrinking and crack forming is highlighted in this study.

Keywords: Heavy Vehicle Simulator testing; Roller Compacted Concrete (RCC); Labor-based construction; Pavement Performance Evaluation

1.0 Background

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 labor-intensive construction techniques. In 2007, the Gauteng Provincial Department of Roads and Transport initiated its Expanded Public Works Program (EPWP). The goals and objectives of the EPWP are to alleviate unemployment, targeting especially women, the youth and the disabled (Gauteng Provincial Government. 2007). This goal will be achieved by creating work opportunities in the following four constructive ways:

- Increasing the labor intensity of government-funded infrastructure projects;
- Creating work opportunities in public environmental programs;
- Creating work opportunities in public social programs, and
- Utilizing general government expenditure on goods and services to provide the work experience component of small enterprise learnership/incubation programs.

In line with these objectives the EPWP embarked on a research program to improve the living standards of many rural communities by upgrading their residential streets to surfaced standards and to provide meaningful sustainable job opportunities by using labor-based pavement construction techniques. To address these needs, two suitable technologies were evaluated by the CSIR: Ultra-thin layer reinforced concrete pavement (UTRCP) (Du Plessis et al, 2011) and Roller Compacted Concrete (RCC).

This investigation deals with the evaluation of RCC using the HVS in full-scale field trails. Whereas RCC is normally constructed with a relatively low labor component and with heavy mechanical equipment, the one aim of this project was to evaluate the structural performance of RCC using a relatively high labor component and hand-operated equipment.

The investigation was conducted in phases. During the first phase a short full-scale test section was constructed at the Accelerated Pavement Testing (APT) facility of the CSIR in Pretoria. The second phase involved the construction and testing of a full-scale test pavement on an existing gravel road near Rayton, Gauteng (Route D1814). This paper details some of the interesting results and analyses of these tests.

2.0 Objectives

The primary objective of this project is to assess the performance of RCC under real field conditions through APT coupled with a laboratory-testing program. The outcomes of the project can be used to update the South African design method for rigid pavements developed by the Cement and Concrete Institute (C&CI) (Strauss et al, 2001) as also to develop a South African structural design guideline for the use of RCC in pavement construction.

More specific on the testing done with the HVS as reported in this paper, the objective focused on the success of using of high percentage of hand-labor during the construction of RCC. This was done through comparative evaluation of sections constructed by labor-based practices and full-scale mechanical equipment.

This study is aimed at building confidence in the use of RCC as a structural layer, with due cognizance being paid to pavement structure, construction, climate and traffic.

3.0 Description of Roller Compacted Concrete

RCC gets its name from the heavy vibratory steel drum and rubber-tired rollers used in compacting the material to its final form. RCC has similar strength properties and consists of the same basic ingredients as conventional concrete such as graded aggregates, cement and water, but with different mixture proportions (Harrington et al, 2010).

The biggest difference between RCC mixtures and conventional concrete mixtures is that RCC has a higher percentage of fine aggregates, which allows for tight packing, low void content and consolidation. Fresh RCC is stiffer than typical zero-slump conventional concrete. Its consistency is stiff enough to remain stable under vibratory rollers, yet wet enough to permit adequate mixing and distribution of paste without segregation. The use of RCC on roads can potentially offer multiple benefits compared with more conventional approaches.

RCC is typically placed with an asphalt-type paver equipped with a standard or high-density screed, followed by a combination of passes with rollers for compaction. Final compaction is generally achieved within one hour of mixing. Unlike conventional concrete pavements, RCC pavements are constructed without forms, dowels or reinforcing steel. Joint sawing is not required, but when sawing is specified, transverse joints are spaced further apart than with conventional concrete pavements. The low water-cement ratio of RCC results in less shrinkage crack development than ordinary PCC mixes.

RCC mixtures should be dry enough to support the weight of a vibratory roller after placement, yet wet enough to ensure adequate hydration and even distribution of the paste. Compaction is the process by which the aggregate particles in the RCC mixture are forced closer together, reducing the amount of air voids in the mixture and increasing the density of the layer. The increased density makes the pavement suitable in load-bearing applications. Rolling must occur before cement hydration begins to harden the paste between the aggregate particles. Achieving proper density during the rolling process helps to prevent non-uniform consolidation and isolated weak areas. Depending on the specific mixture and construction equipment used, external mechanical compaction by rollers may result in a 5 to 20 per cent reduction in volume (Portland Cement Association, 2004). Minimizing the air-void content in the RCC mixture is crucial to the durability of RCC. Excess air voids allow the penetration of air and water. Non-entrained air weakens the mixture, while excessive water can cause materials-related distresses in the aggregates, low field densities and insufficient early strength gain.

3.1 Possible Benefits

The use of RCC on roads can potentially offer multiple benefits by comparison with more conventional approaches. The primary benefit of RCC is that it can be constructed faster and more cost-effectively than conventional concrete. Other beneficial characteristics of RCC include the following (Portland Cement Association, 2004):

- The lower paste content in RCC results in less concrete shrinkage and reduced cracking from shrinkage-related stresses;
- RCC can be designed to have high flexural, compressive and shear strengths, which allow it to support heavy, repetitive loads without failure such as in heavy industrial, mining and military applications and to withstand highly concentrated loads and impacts;
- With its low permeability, RCC provides excellent durability and resistance to chemical attack, even under freeze-thaw conditions;
- RCC provides chemical and rut resistance in industrial areas where point loading from trailer dollies is a concern;
- Occasional light vehicles, such as cars and light trucks, can travel at low speeds on RCC pavements soon after completion without causing damage;
- Construction of RCC at ambient temperatures is suitable for labor-based construction and, hence, is ideally suited for Gauteng’s EPWP;
- Apart from the basic road-building equipment (grader, roller compactor, water cart), only simple, inexpensive construction equipment is required;
- The existing subgrade and alignment can be used;
- RCC can be used as an overlay on existing roads where there is no limitation on vertical alignment;
- A significant percentage of the cement is replaced in the mix by fly-ash, a waste product from coal-fired power stations;
- RCC surfaces require less lighting energy at night than bituminous surfaces because of the reflectivity of this type of surface;
- Repairs of potholes and utility cuts are simple using the same material, and
- Water demand is lower than that of conventional concrete, which is beneficial to the environment.

4.0 Methodology

The general methodology that was followed for the laboratory and field evaluations of the RCC mixes was as follows:

During the first phase of the project two full-scale trial sections with a total length of approximately 65 m and a width of 3.6 m were constructed at the CSIR’s innovation site. For the construction of the first section a normal 10-ton vibratory roller was used for compaction. The second section was constructed using hand-labor where compaction was done using hand-operated Bomag rollers, even for the compaction of the RCC layer (Du Plessis et al, 2012). During the second phase, RCC construction was done at Rayton (Route D1814) where normal 10-ton rollers were used for the compaction of all the layers (Du Plessis et al, 2013).

The RCC was subjected to a range of loading conditions and moisture regimes while being tested with the HVS in channelized, bi-direction trafficking mode in the center of the slab (interior loading).

5.0 Pavement Construction

The RCC test section at the CSIR innovation site was designed for local and provincial low-volume roads. The test pavements were designed for a South African Category B pavement, ES3 traffic class, which is classified as inter-urban collectors, and rural roads with a total cumulative traffic design of between one and three million equivalent standard 80 kN axles (E80s) over a structural design period of 20 years. The composition of an ES3 traffic class is: a maximum of 20% heavy vehicles per day over the 20-year design period. This relates to approximately 340 heavy vehicles per day and at an average of 1.2 E80s per heavy vehicle (50% laden and 50% unladen) (Committee of State Road Authorities, 1985). The designs for both sites (at the CSIR and Rayton) were supplied by Cosal Consultants CC. The South African pavement materials design manual classifies granular layers from the highest (G1) to the lowest (G9) quality and cementitious materials from the strongest (C1) to the weakest (C4). (Committee of State Road Authorities, 1985).

The design specifications for the RCC test section at the CSIR innovation site were:

- Subgrade: Min. CBR of 25 at 95% Mod AASHTO, PI<12, Max swell 1%;
- Subbase: 150 mm thick in-situ material compacted to 93% Mod AASHTO;
- Base: 150 mm thick G5 quality imported material stabilized with 3% cement (of which 20% was replaced with fly-ash), compacted to 95% Mod AASHTO (to conform with C4 specifications), and
- RCC: 150 mm thick layer mix design according to consultant’s specification.

The subgrade was ripped and re-compacted. After compaction, the in-situ material had an average California Bearing Ratio (CBR) of 58 and a field density of 1 788 kg/m^3 (94% Mod. AASHTO), which was above the specified South African limit of a minimum CBR of 25 at 95% Mod AASHTO.

The density of the subbase was measured with a nuclear density gauge after compaction. The subbase was only compacted to 90.7% Mod AASHTO, 2.3% short of the target density of 93% Mod AASHTO.

For the base material, the in-situ material was used (instead of the specified G5 material) and stabilized with 2.4% cement and 0.6% fly-ash. Laboratory results indicated that after stabilization, the base material had an unconfined compressive strength (UCS) of 244 kPa. This is lower than the acceptable standard for a South African C4 type stabilized base with a specified minimum UCS of 750 kPa. The field compaction was 92.3% Mod AASHTO, which was also lower than the specified minimum limit of 95% (Du Plessis et al, 2012).

The RCC layer was constructed with river sand and 9.5 mm crushed quartzite stone. The mix design consisted of a cement:sand:stone ratio of 1:2:3. As in the case of the stabilized base, 20% of the cement content was replaced by fly-ash. A CEM III A type (32.5 N) cement was specified. Apart from the fly-ash, no other type of additive or air entrainment agent was used.

The design specifications for the RCC test section at the Rayton site were (Du Plessis et al, 2013):

- 150 mm RCC;
- 150 mm C4 base material (G5 parent material) compacted to 97% Mod AASHTO;
- 150 mm G5 upper select subbase compacted to 95% Mod AASHTO;
- 150 mm lower select subbase compacted to 93% Mod AASHTO, and
- 125 mm G7 fill compacted to 90% Mod AASHTO.

The subgrade investigation revealed that the top 150 mm should be reworked and compacted to at least G9 material quality in order to satisfy the design requirements for a ES1 to ES10 pavement design (between 300 000 and 10 million equivalent 80 kN standard axles).

The RCC mix design as supplied by Cosal Consultants CC was:

CEM II 32.5 N:	12.2%
Fly-ash:	5.2%

- Sand: 45.4%
- 13 mm stone: 37.2%
- Water/Cement ratio: 0.53

The as-built pavement conformed to the design specifications with small variations. The concrete was supplied by a ready-mix supplier and no information on the true field mix was made available for evaluation.

6.0 HVS Results

Due to space limitations only the most significant HVS results are reported. The results of three HVS tests conducted on three different sections are summarized: the section constructed with mechanical equipment, the section constructed using hand-labor, and the full-scale section on Route D1814 at Rayton.

6.1 HVS test 467A5 RCC placed with mechanical equipment

The section was tested in a dry state, ambient temperature and a standard half-axle load of 40 kN for one million repetitions after which it was increased to 60 kN until failure. The 8 m long HVS test pad on the 65 m section was selected so that the HVS testing wheel ran over a shrinkage crack, as this was considered to be the weakest area in that test section (Du Plessis et al, 2012). The pavement failed after 1.1 million repetitions, which equates to 7 million E80s using the accepted exponential damage factor of 4.2. This surpasses the design life of the pavement which is between 1 and 3 million E80s. Structural failure occurred in the form of mainly transverse cracks and was concentrated around the shrinkage crack.

6.1.1 Elastic deflection response

Figure 1 shows both the surface deflections captured by the joint deflection measuring devices (JDMDs) and multi-depth deflectometers (MDD). MDD 12 and JDMD 1 and 2 were placed in close proximity of the shrinkage crack. Both instruments (JDMD and MDD) recorded increasing deflections downwards (although presented differently in the figure for the ease of distinguishing between JDMD and MDD recorded results). MDDs were installed at the surface and in the base (200 mm deep) and in the subbase (400 mm deep). The variations in the elastic deflections (Figure 1) are mainly due to daily temperature variations and the increased load for 40 kN to 60 kN after a million repetitions. The sudden drop in deflection at approximately 1.6 million repetitions is the result of aggressive additional crack formation around the instrumented shrinkage crack towards the end of the test. MDD data indicated that most of the deflections originated between the surface and the base (200 mm from the surface).

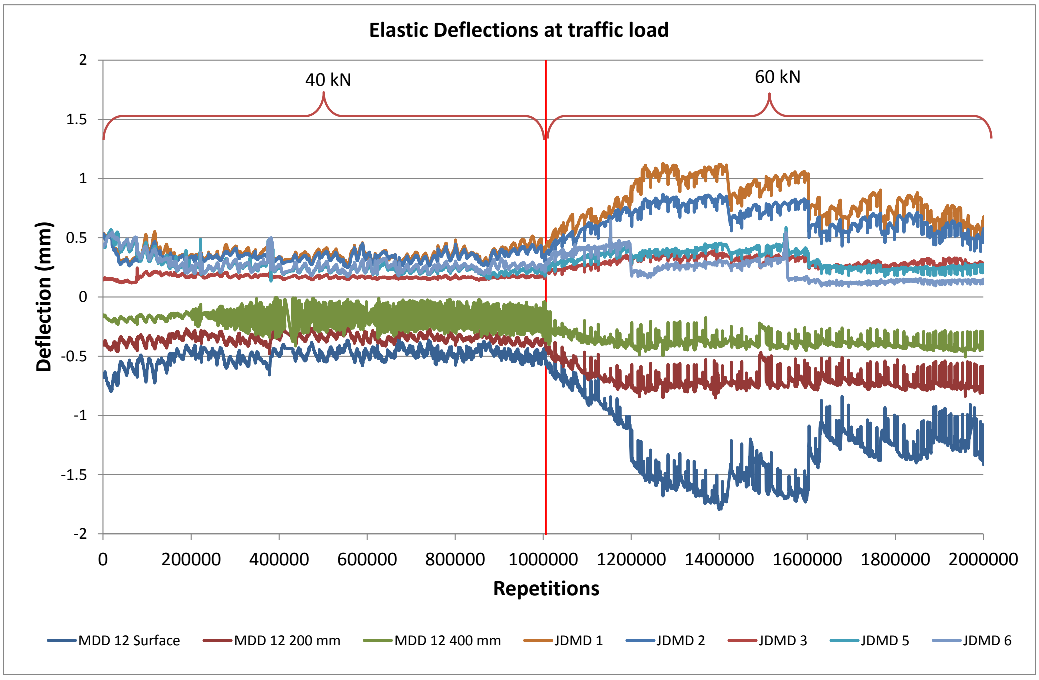

Figure 1. Elastic deflections recorded with JDMDs and MDDs on the normally constructed section

It is obvious that a significant degree of separation between the bottom of the concrete and the top of the base occurred during the 60 kN cycle. MDD deflections on the surface were higher than 1.7 mm in comparison with base deflections where the maximums were lower than 0.8 mm. Interesting to note that the permanent deformation on the rest of the area away from the shrinkage crack was low (JDMD 3,5 and 6).

6.1.2 Load-transfer efficiency

Load-transfer efficiency (LTE) across the shrinkage crack was recorded and are shown in Figure 2. LTE indicates the efficiency of how loading is transferred and carried by the concrete on either side of the crack. It is defined as the relationship between deflection of the unloaded slab (Δ_U) and the deflection of the loaded slab (Δ_L), or: LTE (%) = Δ_U/Δ_L x 100. An LTE of 100% is consistent with full-load transfer, and an LTE of 0% indicates zero load transfer (slabs fully separated by the formation of a crack of significant crack width).

By considering the above, it is possible to quantify the effectiveness of the load transferred through pavement deflection across a crack or a joint. The LTE was relatively high (above 90%) during the first 600 000 repetitions which dropped to below 40% after the load was increased to 60 kN. This drop in LTE (from over 90% to below 40%) signifies a significant loss in aggregate interlock across the shrinkage crack after the application of approximately 1.2 million load applications. The big variations in the data are due to day-night variations in LTE values due to slab expansion (daytime) and contraction (nighttime).

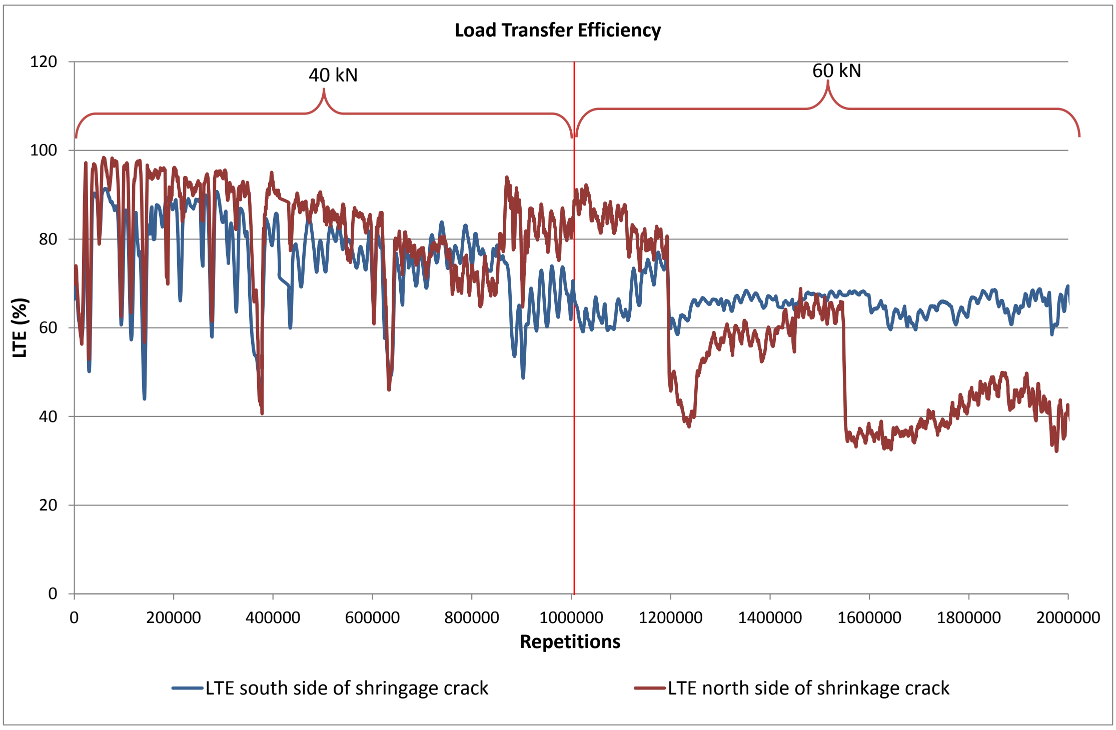

Figure 2. Load-transfer efficiency and relative movement results at test 467A5

6.1.3 Permanent deformation

Concrete pavements do not traditionally fail in rutting, but due to the weak substructure, the granular layers experienced a significant amount of permanent deformation that was observed at the surface after significant crack formation around the original shrinkage crack. The permanent deformation recorded by both JDMDs and MDDs is illustrated in Figure 3. Similar to the deflection figure (Figure 1), both instruments recorded increasing deformation downwards (although presented differently in the figure). Surface deformation of over 18 mm was recorded at the end of the test in the vicinity of the shrinkage crack (JDMD 1 and 2). This caused the slab to crack up to such an extent that no further testing was possible. Interesting to note that the permanent deformation on the rest of the area away from the shrinkage crack was low (JDMD 3,5 and 6).

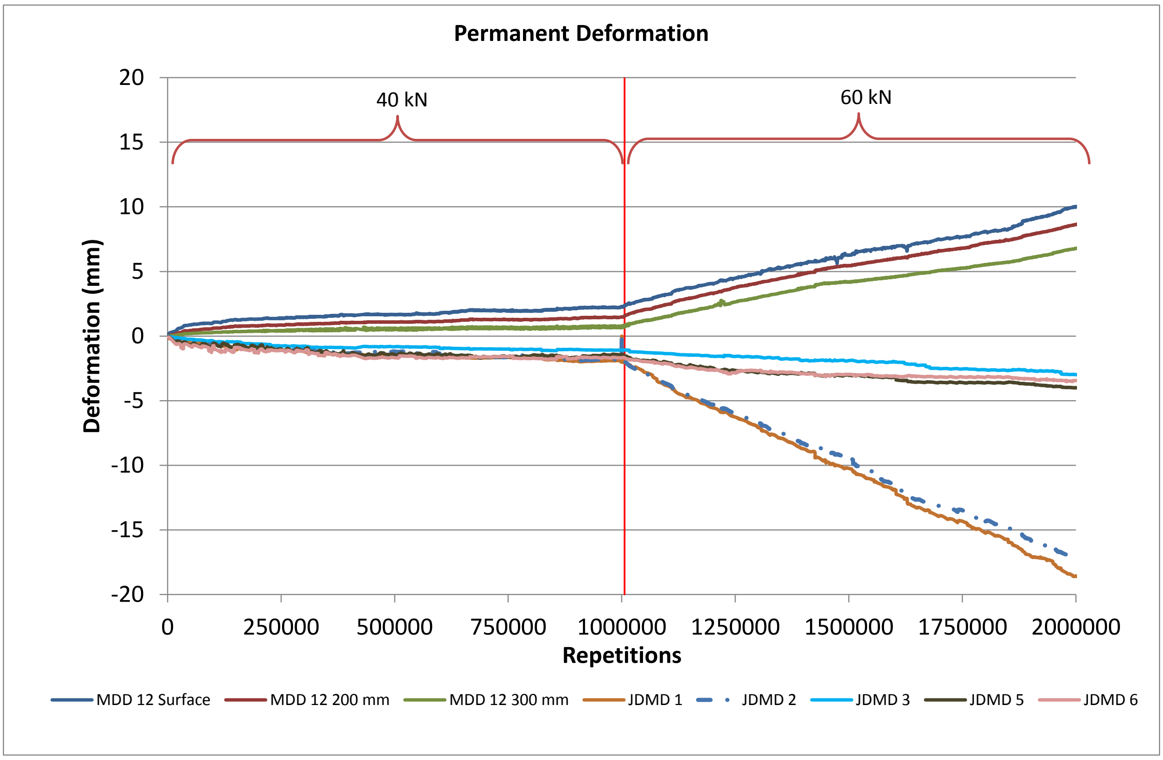

Figure 3. Permanent deformation recorded at test 467A5

6.2 HVS test 469A5 hand-constructed RCC section

Test 469A5 was the first test conducted on the labor-intensive constructed section. Testing was done in both the dry and wet states to simulate the effects of dry and wet periods. The dry/wet cycles were based on five days of trafficking under dry conditions, followed by two days of trafficking under wet conditions. This cycle was then being repeated until failure (Du Plessis et al, 2012). Water was introduced in this fashion to simulate the natural random occurrence of rain. Water was introduced from 227 500 repetitions onwards. Testing was completed after 609 036 repetitions when the section was considered to have failed. The section lasted for three wet cycles and failed within 37 000 dry repetitions after completion of the third wet cycle. A significant degree of pumping was observed during the wet cycles which caused cavities under the concrete that resulted in high surface deflections, excessive block cracking and severe surface deformation. This caused the early failure of this test section.

Reasons for the poor performance include:

- The subbase layer was not compacted properly as detailed in Section 5;
- The base layer (C4) was not constructed at optimum moisture content. Although the laboratory mix design suggested that the optimum moisture content should be 6.9%, the field mix moisture content was on average between 3.08% and 3.3%. This low water content negatively influenced the ability of the cement in the granular material to hydrate properly and lower material strengths were achieved than theoretically possible. The cemented material had an average UCS value of 245 kPa at field moisture contents. This value is significantly lower than the minimum prescribed value of 750 kPa for a C4 type cemented base material (Committee of State Road Authorities, 1985), and
- RCC layer: The average field thickness of the concrete layer was 145 mm instead of the prescribed 150 mm and the maximum 28-day strength of the field mix was 15.63 MPa (field-cored samples). This is less than that expected from CEM III 32.5 cement. A possible reason for the lower strength may be insufficient compaction of the RCC. Samples cored from the section showed big voids in the RCC field mix. A picture showing the failure is presented in Figure 4

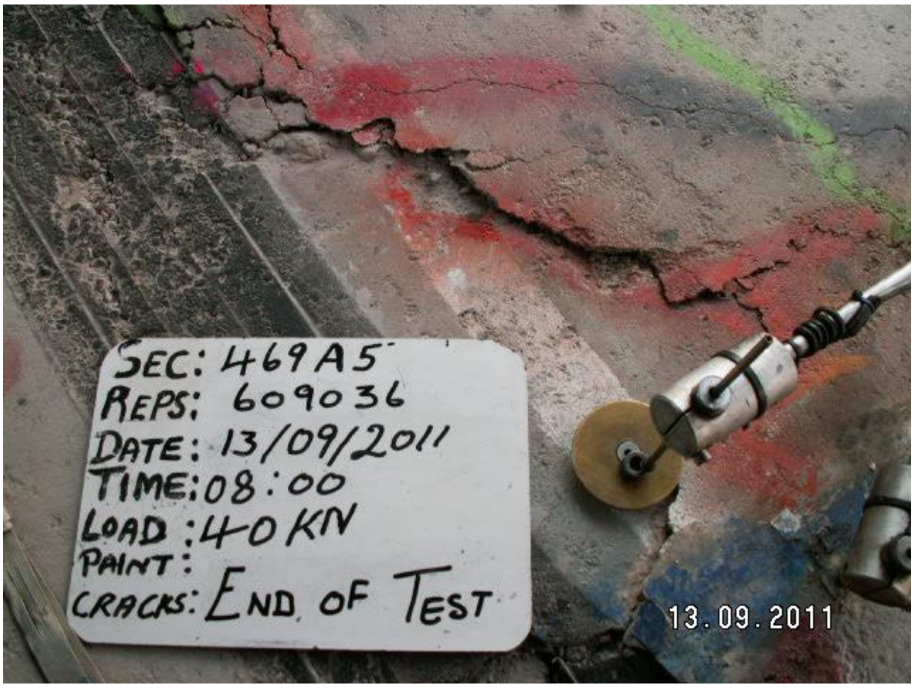

Figure 4. Failure after 609 036 repetitions on the hand-constructed RCC layer

6.3 *HVS test 470A5 RCC constructed at Rayton*

The shrinkage crack pattern of the full- scale field test section constructed on Route D1814 (at Rayton) is shown in Figure 5 and includes the HVS test pad with respect to the 100 m test section (Du Plessis et al, 2013).

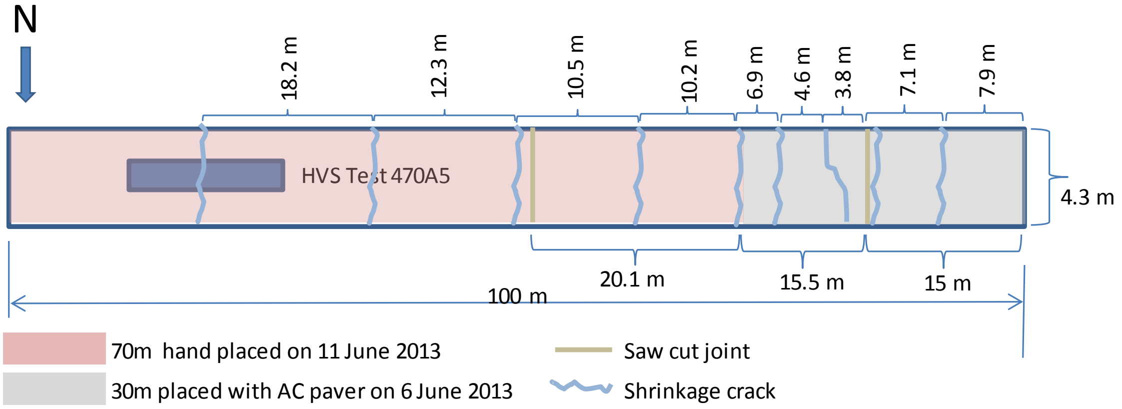

Figure 5. HVS test pad placed across a shrinkage crack

The HVS was positioned over the first shrinkage crack which appeared within 10 days of construction approximately 19 m from the eastern end of the 100 m RCC test section. It should be noted that the first 30 m (the grey area on the right-hand side in the figure) was constructed with the aid of an asphalt paver, the remaining 70 m being placed 5 days later using hand labor and a 10-ton vibrating compaction roller. Ready-mix concrete was used for the whole 100 m section. Although not accurately measured, the section constructed with the asphalt paver had smaller crack widths (and more cracks per length of road) than those developed during the hand-placed section (less cracks but with increased crack widths).

The first 1.207 million repetitions were done in the dry state using a 40 kN load (simulating an 80 kN standard axle load). Due to budget and time constrains testing was stopped after 2.5 million bi-directional repetitions. Because of the slow rate of deterioration, the load was increased to 60 kN (simulating a 50% overload) from 1.207 million repetitions onwards. In addition to this, water was introduced to the surface from 1.76 million repetitions onwards. Water was introduced in the same manner as the previous RCC test (five dry days followed by two wet days, then repeat). Using the 4.2 exponential power damage law, a total of 8.3 million standard 80 kN axle loads had been applied without any signs of visual damage. This exceeds the requirements of an ES3 design class (between 1 million and 3 million E80s).

The surface and in-depth deflections as measured by the MDDs are shown in Figure 6. The surface deflections are unrealistically high (over 1.7 mm) in the vicinity of the shrinkage crack and the surface deflections away from the crack (not shown in the figure) are low (less than 0.1 mm). The conclusion drawn from this is that a significant amount of permanent transverse slab warping occurred at the shrinkage crack, which caused a cavity and the concrete separated from the base. This conclusion is substantiated by the in-depth deflections as recorded by the MDD modules placed in the base (170 mm) and subbase (330 mm): The deflection module placed at the top of the base (at 170 mm in depth) recorded deflections less than 0.1 mm in comparison with the surface deflections (over 1.6 mm). It is obvious that the area surrounding the crack was structurally in a poor state in comparison with the rest of the testing area.

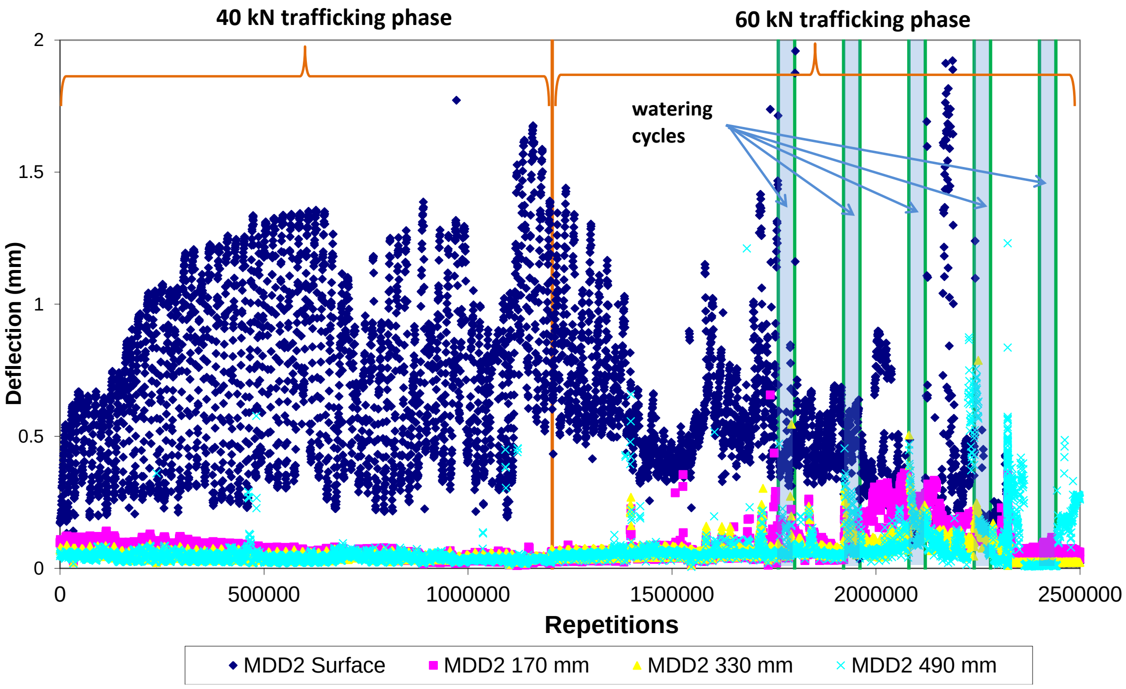

Figure 6. MDD surface and in-depth deflections at the facility of the shrinkage crack

LTE was also investigated at the crack (Figure 7). The figure shows the deflection bowls captured by various JDMD instruments placed opposite each other, across the shrinkage crack, during the hottest part of the day (pm) and during the coldest part at night (am). After 580 000 repetitions a significant drop in the load transfer can be seen, especially at night when a negative temperature differential (surface cooler than the bottom of the concrete) caused a significant degree of slab curing. The deflections were virtually zero during the day due to slab expansion and downward curling effects.

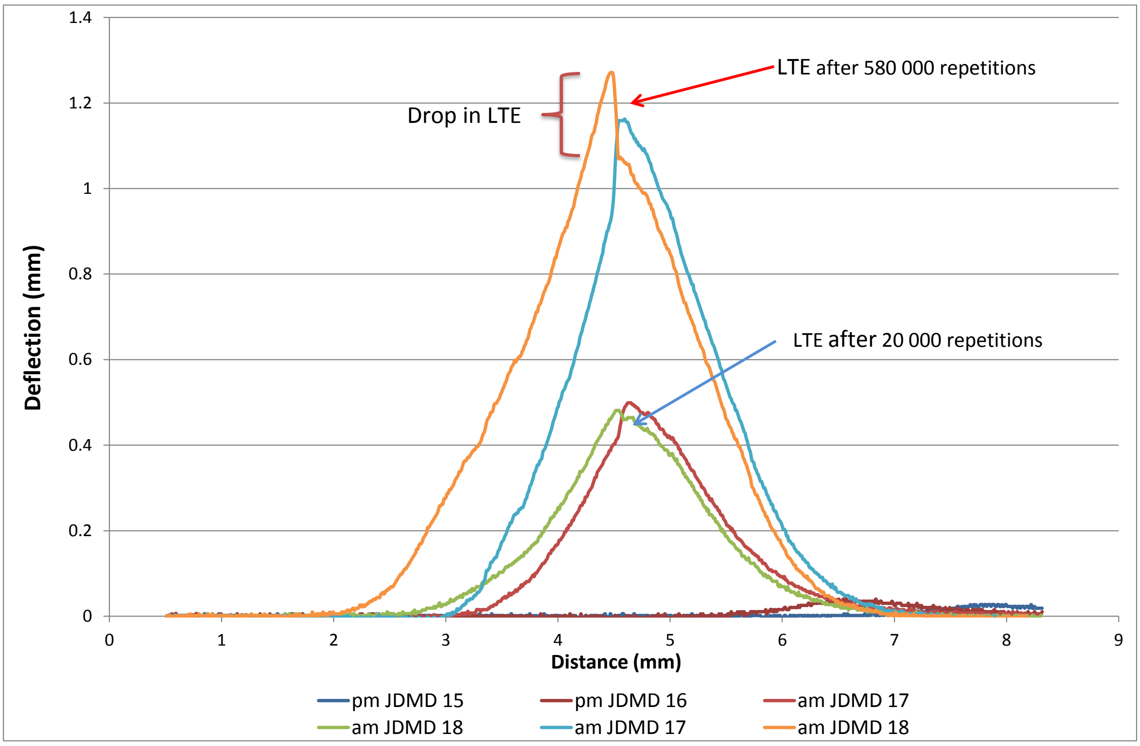

Figure 7. Deflection bowls showing the drop in load-transfer efficiency across a shrinkage crack

7.0 Conclusions and Recommendations

This paper summarizes the most significant results and findings of three HVS tests done on RCC pavement structures in South Africa. Although the sections have lasted their design life, the differences in the behavior at shrinkage cracks in comparison with uncracked areas are of concern. The importance of proper design of all the pavement layers is highlighted in this study. Deviations from the design specifications can lead to costly early failures. To meet the performance requirements, the RCC layer should be placed on top of a well-designed base course material which should not be water-sensitive (should water enter the pavement though surface cracks). Long-life pavement performance of concrete type structures is governed, inter alia, by the following four important guiding principles:

1. The concrete should be designed in such a way that any uncontrolled shrinkage cracks are sufficiently small to ensure that good aggregate interlock is maintained and that the ingress of water into the lower layers is prevented;
2. The surface deflections should be as low as possible to prevent hydraulic action which causes pumping of the support material under the influence of traffic and water;
3. The loss of material as a result of pumping should be minimized through (1), as well as through proper design of the base layer in order to ensure that the base layer has sufficient resistance against water erosion, and
4. It should be realized that temperature plays an important role in the performance of concrete pavements and that any concrete mix should be designed to withstand the build-up of stresses resulting from changes in temperature and temperature gradients within the concrete.

The negative impact of using hand-labor on the structural life of RCC is illustrated in this study. Due to the low water-cement ratio and the granular structure of RCC mixes, good compaction can only be achieved when heavy full-scale vibrating rollers are used (as opposed to light-weight hand-operated compacters). A significant drop in structural life was observed during the HVS test compacted by hand- operated equipment. During a post-mortem investigation, cores taken from the hand-compacted section revealed cavities and voids inside the concrete. This obviously caused a significant reduction in the bearing strength of the concrete layer.

The hand-placed (but compacted by a 10-ton roller) section at Rayton proved to be a greater success but care should be taken during the mix design and construction to ensure that shrinkage cracking is well controlled, both in terms of crack spacing and crack widths.

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