

Initial Results of APT evaluation of Roller-compacted Concrete Performance in South Africa

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Abstract

In conjunction with the Gauteng Department of Roads and Transport and Cosal Consultants CC in South Africa, the CSIR Built Environment is evaluating the applicability of Roller-compacted Concrete (RCC) as an option for the upgrading and rehabilitation of low-volume residential and provincial roads. RCC is normally constructed with a relatively low labor component and with heavy mechanical equipment, the main aim of this investigation has been to evaluate the structural performance of RCC constructed with a relatively high labor component using hand-operated equipment. In order to determine the structural capacity of the RCC, full-scale Heavy Vehicle Simulator (HVS) tests were conducted in conjunction with Finite Element modeling of its behavior. This paper summarizes the provisional results from the first Accelerated Pavement Test (APT) carried out on the control section constructed in the regular fashion with normal, heavy construction equipment. Subsequent testing will include the evaluation of the labor-intensive constructed sections. With APT testing it has been proven that this type of pavement has performed exceptionally well in the dry state, even when constructed on a substandard support system. Initial indications are that the performance of this type of pavement has exceeded its predicted performance.

Introduction

The upgrading of unsurfaced residential roads has become a priority for many metropolitan areas in South Africa. Coupled with this is the need to construct roads using labor-intensive construction techniques. In 2007, the Gauteng Department of Roads initiated its Expanded Public Works Program (EPWP). The goals and objectives of the EPWP are to alleviate unemployment, targeting women, the youth and the disabled in particular (1,2). 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 in order 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 evaluate the success of using Roller-compacted Concrete (RCC). Although RCC is usually constructed with a relatively low labor component and with heavy mechanical equipment, the main aim of this project has been to evaluate the structural performance of RCC using a relatively high labor component and hand-operated equipment.

A short full-scale test section was constructed at the Accelerated Pavement Testing (APT) facility of the Council of Scientific and Industrial Research (CSIR) in Pretoria, South Africa. The experiment was conducted in two phases. In phase I a portion of the test section was constructed with normal, heavy mechanical equipment

(with a relatively low labor component), called the Control Section. Phase II consisted of the construction and testing of a section using a high labor component and hand tools. This paper is limited to the phase I study, as the phase II study has not been completed yet.

The primary objective of this project is to assess the performance RCC under real field conditions through APT coupled with a laboratory-testing program. Comparative testing of the sections constructed by the two techniques will assist in the evaluation of labor-based RCC construction practices.

This study is aimed at building confidence in the use of Roller-compacted Concrete as a structural layer, with due cognizance being paid to pavement structure, construction, climate and traffic, by providing practitioners with reliable design information to enable them to make informed decisions.

Roller-compacted Concrete

RCC derives its name from the heavy vibratory steel drum and rubber-tired rollers used to compact it into 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 has different mixture proportions (3).

The most noticeable difference between RCC mixtures and conventional concrete mixtures is that RCC has a higher percentage of fine aggregates, which results in a low void content mix, tight packing and good 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 by comparison 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.

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 paste. Proper proportioning is essential for ensuring that the mix has sufficient paste to coat the aggregate particles and fill the voids of the compacted mix. Coating of the aggregate particles must be achieved in order to obtain a strong and durable pavement and to ensure load transfer through aggregate interlock at joints (3).

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 which hardens 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 percent reduction in volume. 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. The strength of RCC decreases with reduced density as shown in Figure 1 (4).

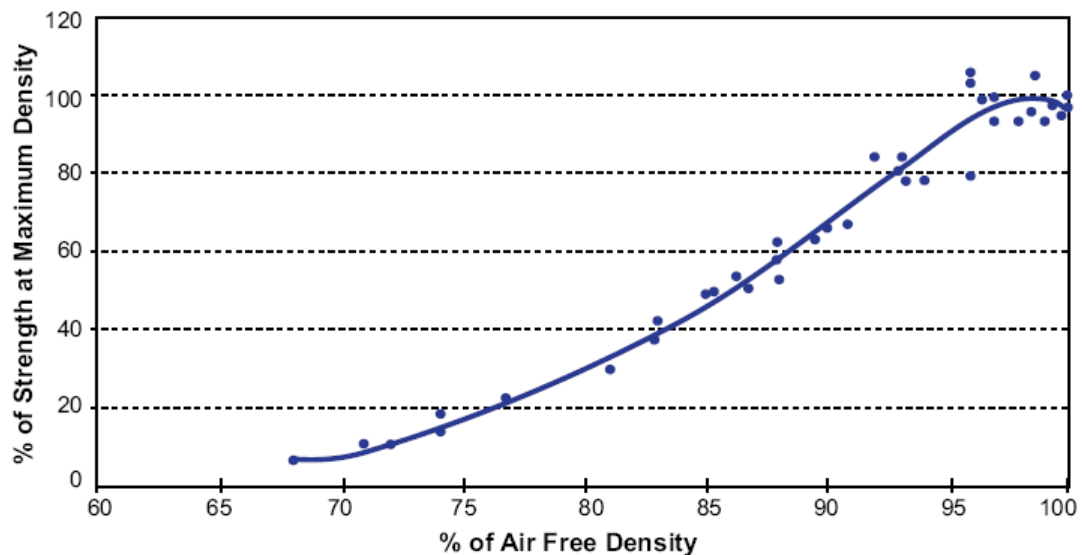


Figure 1: Strength versus density for various RCC mixes (after Schrader 1992)

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 (3):

- The lower paste content in RCC results in reduced 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 therefore, it 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 as a result of the reflectivity of this type of surface.
- Repairs of potholes and utility cuts are simple using the same material.
- Water demand is lower than that of conventional concrete, which is beneficial to the environment.

If the technology is proven sound, RCC can have:

- Lower life-cycle cost for comparable performance;
- Lower maintenance costs, and
- Better performance in difficult areas where heavy loads and stop-start traffic are common, such as container terminals and parking areas.

Methodology Followed in this study

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

- Two full-scale trial sections with a total length of approximately 65 m and a width of 3.6 m were constructed. All structural design material input parameters from laboratory testing, as well as flexural strength, fatigue life and durability, were determined;
- Accelerated Pavement Testing, during which the RCC was subjected to a range of loading conditions and moisture regimes under the HVS in channelized, bi-direction trafficking mode to assess the influence of the input parameters on the bearing capacity of the material (see Figure 2), and
- Analysis of laboratory and field data.

Although RCC is continuously cast and compacted, it is important to realize that, at the end of each working day, a construction joint will have to be made to finish the day's work. Formwork used to ensure correct compaction will be removed the next day for the continuation of slab casting. The structural integrity of this construction joint will also be evaluated through HVS testing.



Figure 2: The Heavy Vehicle Simulator

Pavement Construction

The RCC test section was designed for local and provincial low-volume roads with design traffic of 1 to 3 million standard 80 kN axle loads (E80s). The South African Mechanistic Pavement Design Method was used for the structural design of the pavement, together with inputs from the Falling Weight Deflectometer (FWD), Dynamic Cone Penetrometer (DCP), test pits, soil sampling and the laboratory material test results of all the materials used. The design specifications for the RCC test section 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 in situ material stabilized with 3% cement (of which 20% was replaced with fly ash), compacted to 95% Mod AASHTO, 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 CBR of 58 and a field density of $1\,788\text{ kg/m}^3$ (94% Mod. AASHTO), which was above the specified limit (minimum CBR of 25 at 95% Mod AASHTO) (Figure 3).



Figure 3: Subgrade preparation and compaction

The density of the subbase was measured with the Troxler nuclear density gauge after the subbase was compacted. It was determined that the subbase was only compacted to 90.7% MOD AASHTO, 2.3% short of the target density of 93% Mod AASHTO (see Figure 4).



Figure 4: Subbase construction

The construction of the base material is shown in Figures 5a and 5b. The in situ material was stabilized with 2.4% cement and 0.6% fly ash. Laboratory results shown 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%.

A Tractor-Loader-Backactor (TLB) and 10-ton vibrating roller-compactor were used to mix the stabilizer into the in situ material for the base and RCC layer construction (Figure 5c and 5d).

The RCC layer was constructed with river sand and 9.5 mm crushed quartzite stone. The mix design consisted of 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 32,5 N cement was specified. Apart from the fly ash, no other type of additive or air-entrainment agent was used.

The sand, stone, cement and fly ash were mixed according to the mix design and distributed over the base. It was compacted with the 10 ton compactor while water was added. The water: cement ratio was 0.36. The section was cured under plastic sheeting for 10 days. The final RCC surface can be seen in Figure 5e.

Post construction evaluation of the thicknesses of the constructed layers revealed that the average thicknesses were: subbase = 175 mm, base = 92 mm and RCC layer = 95 mm. Four shrinkage cracks appeared over the length of phase I of construction (the section constructed with heavy mechanical equipment). The total section length was 42 m and shrinkage cracks appeared at 8.5 m, 13.4 m, 19.2 m and 32.2 m from the start of the RCC constructed pavement section. The crack widths before trafficking were measured to be lower than 0.2 mm (30 days after construction).



Figure 5a: Mixing cement and fly ash with in situ material



Figure 5b: Compacting base with roller-compactor



Figure 5c: Mixing RCC materials



Figure 5d: Distribution of RCC materials



Figure 5e: RCC layer after construction of phase I (mechanical equipment)

HVS Test Layout

The HVS test pad (see Figure 6) was placed over the area on which the first shrinkage crack had appeared (8.5m from the start of the constructed RCC section). Instrumentation was concentrated around the shrinkage crack to enable the determination of cumulative damage in terms of deflections, load transfer efficiency (LTE), joint faulting, crack growth and deformations. The shrinkage crack can be seen in Figure 7. Although the entire test pad was instrumented, the results presented in this paper are focused on the damage which accumulated around the original shrinkage crack. multi-depth deflectometers (MDDs), thermocouples, joint deflection measuring devices (JDMDs) and a laser profilometer were used to measure the response of the RCC under HVS loading. HVS loading was done in the dry state without the application of water, with interior loading and channelized trafficking.

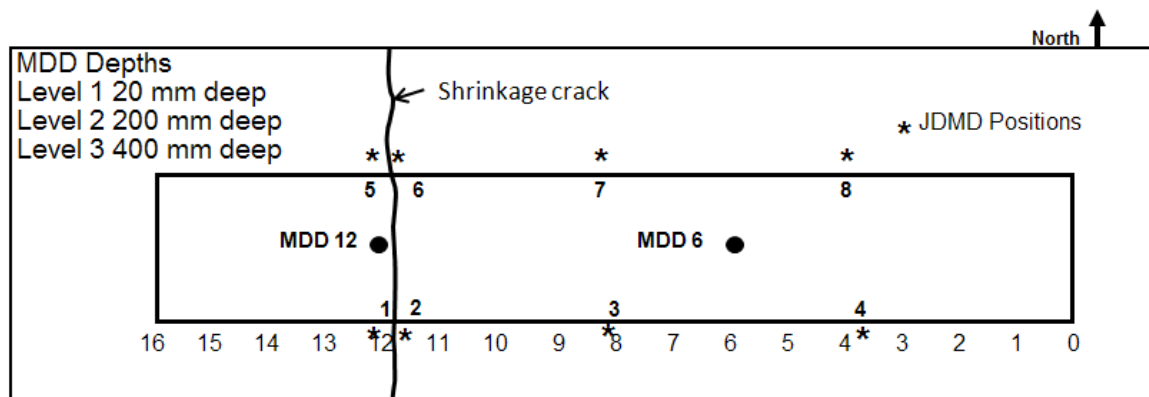


Figure 6: Test section layout



Figure 7: Shrinkage crack at point 12 prior to trafficking

HVS Results

As only one test (phase I) is complete by the submission date of this paper, only provisional results are presented here. The section was tested in a dry state under a standard half-axle load of 40 kN for one million repetitions. Because of time and budgetary restraints and the slow rate of deterioration, the load was increased to 60 kN from 1 million load repetitions onwards. Using the well-accepted damage factor of 4.2, the number of standard 80 kN axle load (E80) repetitions is equivalent to 5.5 for each 60 kN load repetition. The result of this increase in load level is clearly visible in the elastic response (Figure 8). Although testing was continued, structurally the pavement was considered failed after 1.8 million repetitions, which equates to 5.4 million E80s. This surpasses the design life of the pavement which is between 1 and 3 million E80s.

Elastic Deflection Response

The variation in the elastic deflection (Figure 8) is mainly due to daily temperature variations and the increasing load from 40 kN to 60 kN after 1 million repetitions. The sudden drop in deflection at approximately 1.6 million repetitions is the result of additional crack formation around the instrumented shrinkage crack at point 12 (see Figure 11). The figure shows the data from JDMD 1 and 2 (placed across the shrinkage crack) and MDD12 at 3 levels: the surface, at a depth of 200 mm (in the base) and 400 mm (in the subbase). The MDD data is presented on a negative scale in the figure to differentiate between the JDMD data, although both instruments recorded deflections positively downwards.

The measured deflections are high and are mainly due to the increase in the load level, as well as the characteristics of the material, such as the concrete strength and the underlying base and subbase being weaker than expected. After the load was lifted to 60 kN, the peak surface deflections increased to over 1 mm. MDD surface deflections are higher than JDMD data mainly because the instrument records data close to the load (between the HVS wheels), whereas the JDMD deflections are recorded further away from the loaded wheel. The MDD data shows that most of the early deflections originated from the base and deeper layers (surface deflections similar to deflections at 200 mm) but during the 60 kN phase most of the deflections originated between the top and the base at 200 mm inside the pavement.

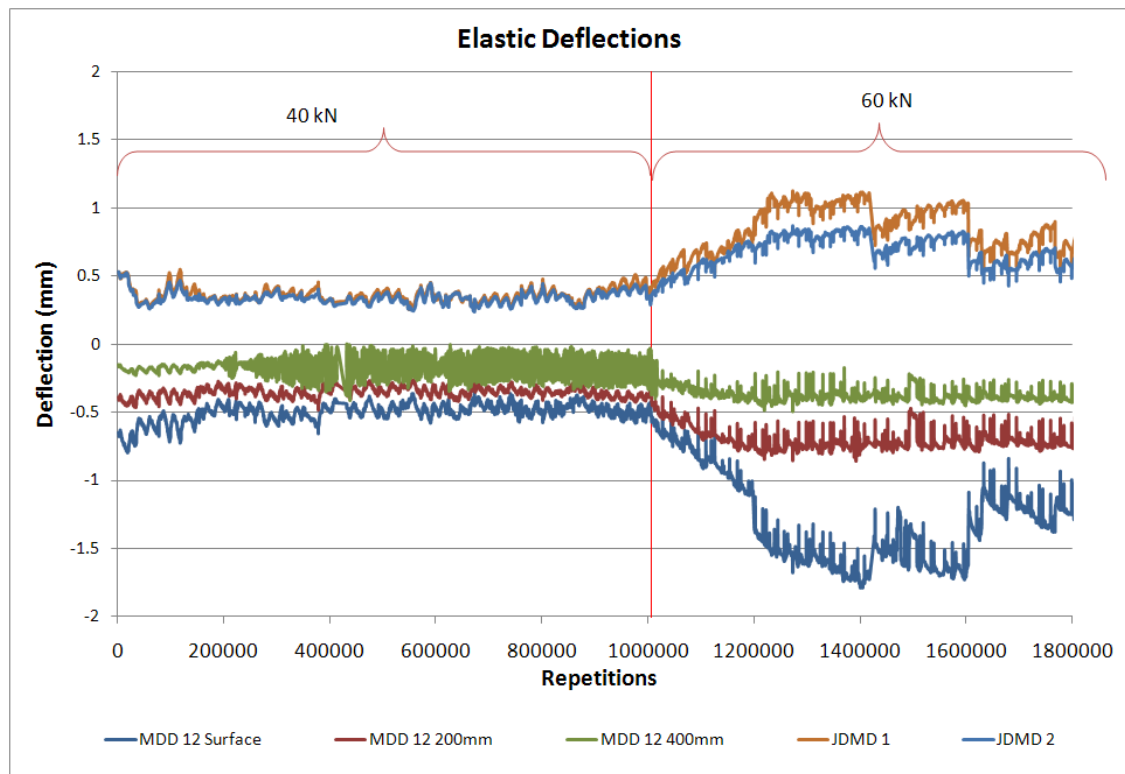


Figure 8: Elastic deflection data

Load-transfer Efficiency and Relative Movement

Relative movements (RM) and load-transfer efficiency (LTE) across the shrinkage crack at point 12 are shown in Figure 9. LTE indicates the efficiency with which the load is transferred across a 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:

$$\text{LTE (\%)} = \Delta_U / \Delta_L \times 100$$

An LTE of 100% is consistent with full load-transfer, and an LTE of 0% indicates zero load transfer.

Relative movement is the movement of the loaded slab (Δ_L) relative to the movement of the unloaded slab (Δ_U), or:

$$\text{RM (mm)} = \Delta_L - \Delta_U$$

An RM of 0 mm indicates that both the loaded and unloaded slabs had the same reaction to the applied load and correspond to an LTE of 100%.

By considering the above two parameters, it is possible to quantify the effectiveness of load transfer through pavement deflection at a crack or a joint. RM measures the absolute difference in movement (deflections) across the joint/crack, whereas LTE measures the relative difference in deflections of the unload and loaded sides of a crack/joint.

The LTE was relatively high (above 80%) during the first 800 000 repetitions, with a maximum RM of approximately 0.2 mm. The LTE dropped to just below 70% after the load was increased to 60 kN, after which it remained fairly constant. The RM ranged between 0.25 mm and 0.4 mm. This drop in LTE signifies a significant

loss in aggregate interlock across the shrinkage crack after the application of approximately 1.2 million load applications.

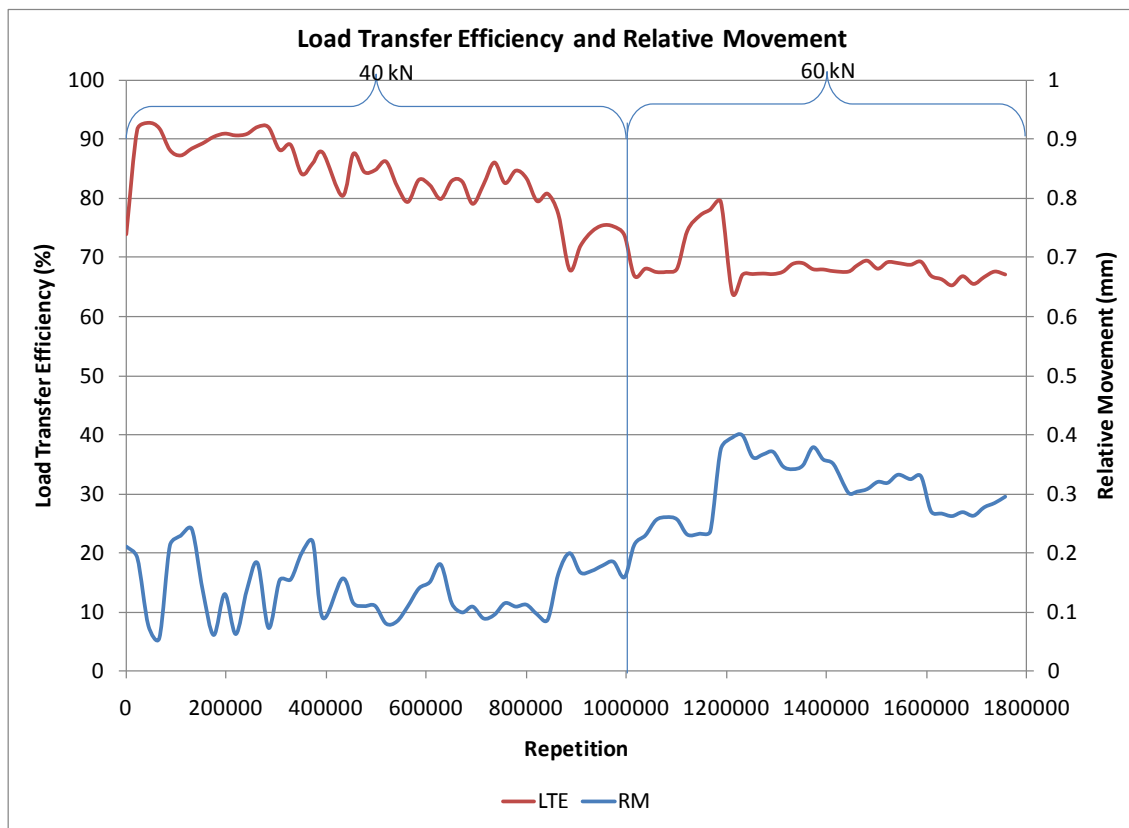


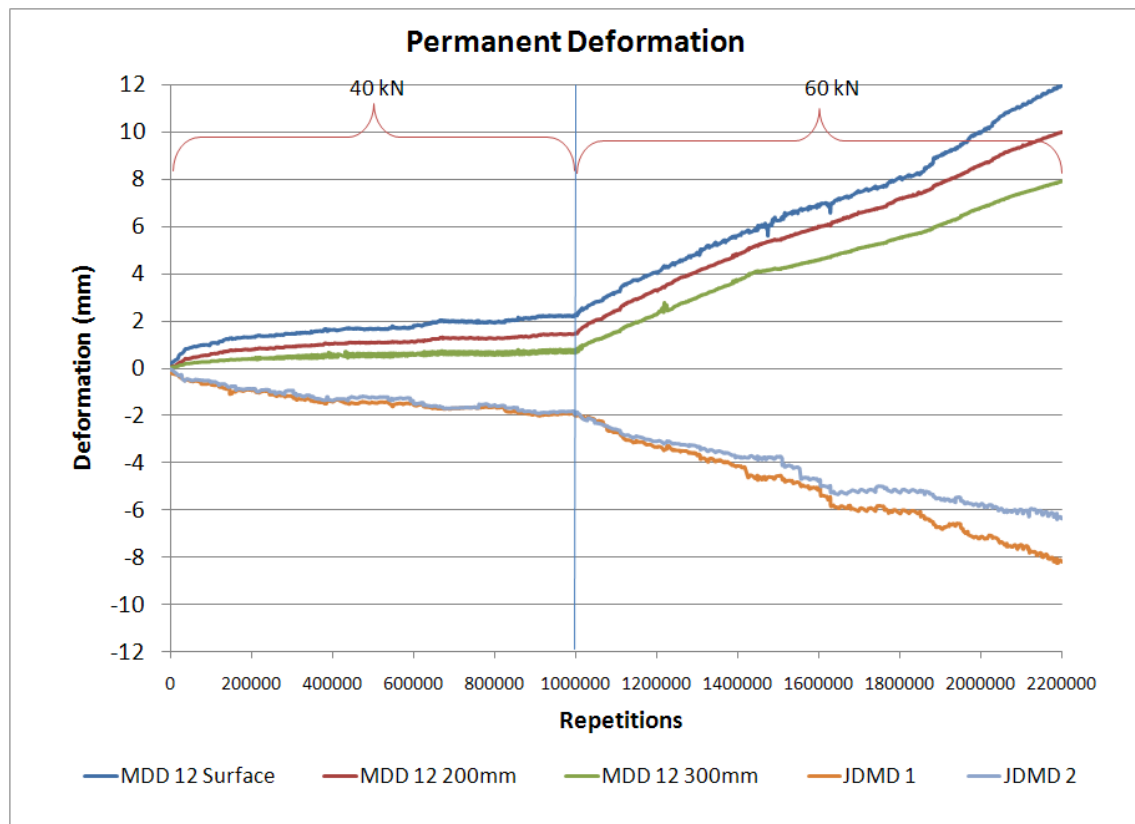
Figure 9: Load Transfer Efficiency and Relative Movement

Permanent Deformation

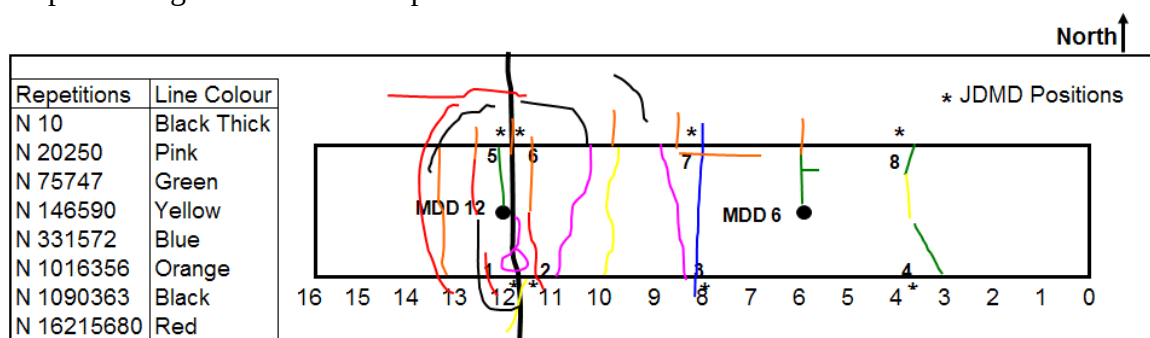
The permanent deformation recorded by both JDMDs and MDD12 is illustrated in Figure 10. Similar to the deflection figure (Figure 8), the JDMD data is presented on a negative scale in the figure to differentiate between the MDD data, although both instruments recorded permanent deformations positively downwards. Concrete pavements do not fail in rutting traditionally, but due to the weak substructure the layers experienced a significant degree of permanent deformations. Similar to the deflection response, the permanent deformation had a significant increase after the load was increased from 40 kN to 60 kN. The average rates of deformation per 100 000 repetitions are shown in Table 1. The initial high rate of 0.84 mm/100 000 repetitions is termed the “imbedding phase”. This imbedding phase is indicative of all APT tests, after which the pavement enters a stable phase of linear increase in deformation, as shown in Figure 10. Total surface deformation of over 12 mm was recorded at the end of the test, which is mainly due to substructure deformation as MDD 200 mm and 400 mm recorded deformations of 10 mm and 8 mm towards the end of the test.

Table 1: Average rate of deformation per 100 000 repetitions

	JDMD 1	JDMD 2
Imbedding phase (mm/100 000 reps)	0.838	0.953
40 kN phase (mm/100 000 reps)	0.198	0.193
60 kN phase (mm/100 000 reps)	0.657	0.519

**Figure 10: Permanent deformation data****Crack Formation**

The crack formation caused by the repetitive HVS loading is shown Figure 11. Cracks formed in quick succession during the imbedding phase (0 - 100 000 repetitions). Although very visible, these crack widths were small (smaller than 0.2 mm). Therefore, they are not considered to be structural cracks. A few additional cracks developed during the stable 40 kN phase.

**Figure 11: Crack formation**

After the 60 kN loading phase (from one million repetitions onwards) structural cracking appeared with crack widths bigger than 0.3 mm (as indicated by the orange, black and red cracks in Figure 12). These cracks encircled the original shrinkage crack at point 12 (Figure 12).



Figure 12: Circular crack pattern after 1.6 million repetitions

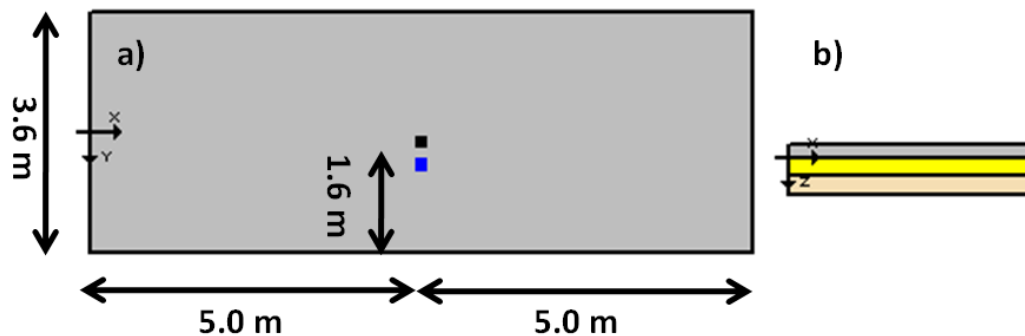
Finite Element Modeling

The RCC test section under HVS loading was modeled using EverFE 2.24 (6) finite element software. The properties of the pavement layers as used in the analysis are shown in Table 2. Laboratory tests showed that the concrete had a compressive strength of 25 MPa. Based on this information a typical Young's modulus value of 28 000 MPa was selected for the material. The spring stiffness (k) of the subgrade was varied until the response of the structure in terms of vertical displacement under HVS corresponded with the measurements of the JDMDs taken at the site.

Table 2: Layer properties

Layer	Thickness [mm]	Modulus [MPa]	Poisson's ratio
Slab	100	28 000	0.2
Stabilized base	150	800	0.35
Subbase	150	150	0.35
Subgrade	∞	30 ($k = 0.154$ MPa/mm)	

The pavement model and position of the HVS loads are shown schematically in Figure 13. To simulate the situation during the RCC HVS test, the 40 kN dual-wheel load was placed at a distance of 1.6 m from the edge of the slab. The tire contact areas were modeled as 200 mm x 200 mm patches at a center-to-center spacing of 350 mm.

**Figure 13: EverFE Model shown in plan- and cross-section view**

During the test, the temperature was recorded at the top, center and bottom of the slab. The tested part of the slab was constantly in the shade. As such, only negative temperature differentials between the top and bottom of the slab were recorded in the tested area. The bottom of the slab was on average 5.3°C warmer than the top during the hours of testing. The temperature differential is accounting for in the EverFE analysis, assuming a coefficient of thermal expansion of $11 \times 10^{-6}/^{\circ}\text{C}$.

The EverFE analysis shown above indicates that the maximum tensile stress (σ_d) at the bottom of the slab under the HVS was 2.2 MPa on average. The maximum compressive stress at the top of the slab was 1.6 MPa.

For concrete pavements, the number of repetitions to failure is typically predicted using a ratio between σ_d , determined from linear elastic analysis, and the modulus of rupture (MOR) of the material (3). MOR data for the RCC material was not available, but for 25 MPa compressive strength concrete, the MOR can be expected to be around 3.7 MPa. Based on this assumption, the stress/strength ratio in the pavement during the HVS test was around 0.59. Figure 14 shows the result from the HVS test plotted against the fatigue damage relation for JPCP in the new American Mechanistic Empirical Pavement Design Guide (MEPDG) (7).

It is not possible to assess whether the NCHRP 1-37 damage relationship is valid for the technology under study, based on a single data point, especially since the actual MOR for the tested material is not known. Further work is required to develop reliable damage models for the use of RCC in South Africa.

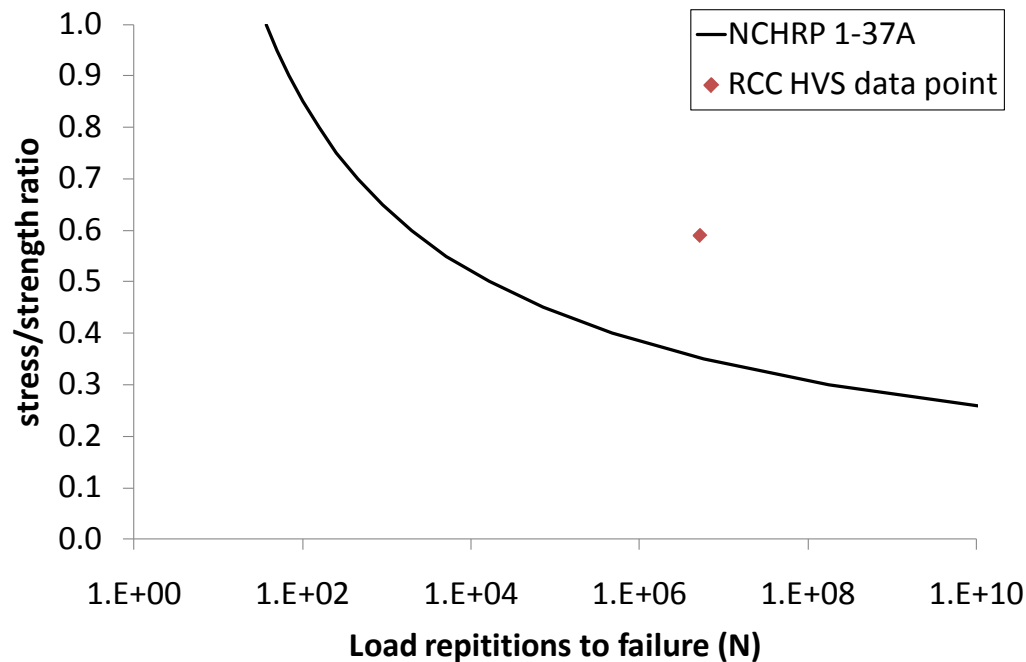


Figure 14: RCC data point relative to fatigue life prediction curve from MEPDG

Conclusions

This paper summarizes the initial findings of the first uncompleted HVS test conducted on a full-scale roller-compacted concrete test section constructed by means of normal mechanical methods. It reports on typical pavement performance measures, such as deflections, crack growth, load-transfer efficiency, permanent deformation and joint faulting.

The initial results are very promising. Although the RCC layer was constructed on a substandard substructure and with RCC strengths below what is expected from a CEM III cement mix, it showed good performance in the dry state. Although the pavement has experienced a significant amount of cracking, high surface elastic deflections and low LTE, it lasted over 5 million equivalent 80 kN axle-load applications higher than the original design life of 1 to 3 million.

Normally permanent deformation (rutting) is not a failure mechanism in concrete pavements, but it is reported in this study due to the significance of the substandard granular layer works under the concrete. As mentioned in the construction section, both the base, subbase and RCC layers did not meet their respective specified design material specifications. A total of over 12 mm of deformation was recorded on the surface, most of which originated from the granular layers below the concrete. Test-pit analysis investigations will be done after the completion of the HVS testing to verify the extent and degree of layer deformation of all the layers under the RCC.

The important factor, which was not evaluated in this study, is the effect of water. This test was conducted during the dry months when no rain fell during the testing period. It is anticipated that the rate of deterioration will increase under the influence of water, especially when structural cracks are visible on the surface, which will allow for the ingress of water to the base.

Follow-up testing will include evaluating a labor-intensive constructed section, as well as determining water sensitivity of this type of pavement construction.

Acknowledgements

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References

- 1) Department of Infrastructure Development. (2007). Gauteng Province, South Africa. Development. Web page:
<http://www.did.gpg.gov.za/Pages/GEPWPBackground.aspx>.
- 2) Publication of the Gautrans Provincial Government (2007). *Framework for Monitoring and Evaluation of the Expanded Public Works Programme*, June 2007.
- 3) Harrington, D., Abdo, F., Adaska, W. and Hazaree, C. (2010). *Guide for Roller-compacted concrete pavements*. National Concrete Pavement Technology Center, Iowa State University, 2010
- 4) Water resources. (2004). *Roller-compacted Concrete Density: Principles and Practices*. Skokie, Illinois: Portland Cement Association.
- 5) Schrader, E.K. (1992). *Roller-compacted concrete for dams: State of the art*. International Conference on Advances in Concrete Technology, Athens, Greece, 1992.
- 6) University of Maine and University of Washington. (2011). EverFE v2.24, <http://www.civil.umaine.edu/everfe/>
- 7) NCHRP, 2004. Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, NCHRP1-37, <http://www.trb.org/mepdg/guide.htm>