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Evaluation of Elastic Modulus of Crushed Stone Base Layers for Compaction Control

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Abstract

Construction of high-quality crushed stone layers is referred to as "an art and one that is not profusely found today". Conventional acceptance control procedures only confirm densification of the layer and other fundamental material properties with no direct measurement of strength. As a result of this there appears to be a missing link between design requirements and acceptance control. Slushing is required during the construction process to lock up the aggregate, ensuring stability and a good distribution of the fines through the layer. This study endeavours to confirm whether there is a significant difference in the Elastic Modulus of crushed stone layers before and after the slushing process and to investigate cost-effective and appropriate means of controlling this. Preliminary results suggest that poor workmanship can be clearly identified and an increase in Elastic Modulus can be confirmed following the right construction methods and procedures.

Keywords: Crushed Stone Bases, Slushing, Elastic Modulus, LWD, Sustainable Infrastructure.

1. Introduction

Crushed stone base was first used in South Africa in the 1950's and was then known and produced as a single crusher-run material. Crushed stone is produced from continuous gradings with excess fines, which are expelled during the construction process, after compaction. During the development phase of crushed stone layers some observant Engineers in the 1950's noticed after a sudden downpour towards the end of the compaction process, that the crushed stone layer would expel some fines, which is now known as the slushing process. Slushing of a crushed stone layer is done to maximise density and interlock the aggregate within the layer to allow the layer to perform at its peak with regards to compressive and shear strength.

Kleyn (2012: 114) notes that constructing a crushed stone base layer is a very exacting process and specifications must be stringently applied if it is to perform as intended and be a cost-effective solution. Kleyn (2012: 113) further notes that it is possible to construct a crushed stone base layer that complies with density requirements before the slushing process has been dealt with.

Accepting such a layer during construction, however, will result in a layer being unable to withstand the required traffic loading to the same degree and which will eventually fail prematurely. It is therefore imperative to confirm that the construction process for crushed stone base layers has been dealt with in its entirety and this should be done quantitatively.

2. Research approach

Establishing whether there is a difference in the Elastic Modulus of crushed stone base layers, before and after the slushing process at the same moisture content, will allow construction supervision personnel to identify whether the construction processes of a completed crushed stone base layer have been fully dealt with. This will prevent possible premature failure of crushed stone base layers related to insufficient or incomplete construction processes with economic advantages as it will prevent costly remedial measures.

Non-destructive tests were conducted on completed crushed stone base layers of currently running road construction sites within Namibia. Completed layers of crushed stone bases were subjected to testing by means of the Light Weight Deflectometer (LWD) to analyse the development of the layer's Elastic Modulus. To analyse the development of the layer's ability to resist deformation, testing was done before slushing (after compaction) and after slushing.

The layer is normally at or close to Optimum Moisture Content (OMC) after compaction and before slushing. The moisture content at this stage was confirmed by the nuclear method to serve as an indication. Testing to confirm the Elastic Modulus was done at this point using an LWD. During the slushing process more water is added, and the layer is generally at a moisture content higher than the optimum as this is required to re-arrange the aggregate particles in the layer to their optimal positions during slushing. Testing to confirm the Elastic Modulus was done after slushing using an LWD. The moisture content at this stage was also confirmed by the nuclear method for comparison with the moisture content before slushing.

3. Testing and analysis of results

One of the projects available to the author, for the purpose of this research, was the upgrading of Main Road 36 (MR36) and Main Road 44 (MR44) in the Erongo region on Namibia's Atlantic West Coast. These sections of road form part of the inland road between Walvis Bay and Swakopmund that has been upgraded to dual carriageway standard. It is part of the Trunk and Main Road network along the coast. The route between Swakopmund and Walvis Bay serves several groups of road users. These include long distance heavy vehicles to and from the Walvis Bay harbour, daily commuters and seasonal recreational local traffic to the beaches and sand dunes between Swakopmund and Walvis Bay. Development in the mining and tourism industry has led to an increase in heavy and light traffic movement with an average of over 5500 vehicles per day travelling between the two towns. There are two routes between the two towns, Trunk Road 2 Section 1 (TR2/1) also referred to as the road in front of the dunes and Main Road 44 (MR44) at the back of the dunes. The purpose of upgrading MR44 to dual carriageway is to bypass the town of Swakopmund for traffic that is destined for Walvis Bay and in particular the heavies that need to reach the harbour. The expected Annual Average

Daily Traffic (AADT) will be in the order of 1500 with 64.2% heavy vehicles as per traffic counts for the year 2015. For a structural design period of 20 years and an average of four E80's per heavy vehicle, this will result in an estimated 28.7 million cumulative standard axle repetitions.

The other project available to the author, for the purpose of this research, was the upgrading of Trunk Road 9 Section 1 (TR9/1) between Windhoek and Hosea Kutako International Airport in the Khomas region of Namibia. This road forms part of a long-term objective to ensure a north-south and an east-west system that is linked to ensure high transport mobility, which is necessary for efficient transportation in and around Windhoek, while providing a link to all major trunk roads for traffic from and to the City. The high traffic volumes on Trunk Road 9 Section 1 (TR9/1) between Windhoek and Hosea Kutako International and especially the portion in and around the city have resulted in the existing pavement requiring a much-needed upgrade and rehabilitation to alleviate stress on the pavement as well as increase the level of service. The existing single carriageway freeway was constructed in the 1980's and the second of the dual carriageways is currently under construction and part of a case study available to the author. The project is intended to increase mobility and allow traffic that is moving east-west to bypass the city to other destinations. The expected Annual Average Daily Traffic (AADT) ranges from 4500 to 6500 with 10% heavy vehicles for the different sections and phases of TR9/1 as per traffic data for the year 2015. For a structural design period of 20 years and an average of four E80s per heavy vehicle, this will result in an estimated 45 to 50 million cumulative standard axle repetitions for the different sections and phases of TR9/1.

Testing proceeded on available sections of G1 crushed stone base on the projects mentioned. Testing of the available sections commenced as soon as a portion of base layer had been processed, shaped, and compacted (i.e. before slushing). The sections were subject to testing at 40m intervals of which each position was tested at 2m from the left-hand and right-hand side and dependent on the width, also a test in the middle. Generally, the arrangement applied to three tests every 40m on freeway sections of which the width was 12.4m.

There are several aspects that need to be complied with to ensure that a crushed stone layer functions as intended and can carry the required loads. These aspects include pavement composition, construction, maintenance, and rehabilitation. According to Kleyn (2012: 110) a properly constructed crushed stone layer can be used in a pavement designed to carry up to 50 million standard axle repetitions. It is exceptionally water resistant and the only material that increases its resistance to accommodate an increase in loading over time. However, Kleyn (2012:110) notes that the material must be produced to very tight specifications and a meticulous construction process to be able to achieve this.

The following observations with regard to the construction processes followed during the construction of the base on the MR44 project were observed. It was clear that not enough effort and time was spent during the processing of the layer, including watering and mixing of the crushed stone material, before placing and shaping (the initial compaction process). Ideally, the moisture content of the layer should be at optimum or very close to it, to ensure that the required density of the crushed stone layer is achieved. Low moisture contents during this process might delay the initiation of the slushing process and the full effect thereof might not be achieved. When slushing commenced, more water was applied as a saturated base is required to gain full benefit from the slushing process. During the slushing process the construction team applied two steel drum rollers with a water bowser. The rollers were not in vibration mode during this process, i.e., they were used in static mode. The construction team had a set number of passes during the slushing process, irrespective of the fact that the slush should become clearer until mainly water is expelled from the layer. It was clear that the slushing process was not complete, and more effort should have been applied to ensure that there was proper interlock of the aggregate particles within the crushed stone layer. Apart from these observations, the site supervision personnel noted the variability of the surface of the layer during the visual inspections and that the required “mosaic” had not been achieved. Remarks such as not uniformly mixed, segregation, weak spots and uneven surface were noted on the inspection forms as reasons for not accepting the work.

As is the case and noted for the MR44 project, the construction team on the TR9/1 project also did not spend enough time and effort during the processing, the addition of water and mixing of the layer before compacting. After placing and compacting the layer there was a significant delay before the slushing process commenced. The construction team delayed the onset of the slushing process by three to four days. By this time the layer had dried out considerably and a lot more moisture needed to be added to apply the slushing process to its full effect and re-arrange the particles within the layer as required. The construction team also employed a peculiar method in the slushing process. The water bowser was not used on the road in tandem with the steel wheel roller but sprayed water onto the layer from a parked position next to the works. A set number of passes was applied by the rollers irrespective of whether the slushing process was complete or not. Slushing did not continue, as required by Kleyn (2012: 116), until the slush that is expelled from the layer clears up and is mainly water. Given the long delay and onset of the slushing process, it was observed that the layer only just started to expel fines during the slushing process when the construction team ceased the operation. Also noted during the slushing process was that the rollers applied excessive vibration and it could be noticed that there was de-densification of the layer in the process.

In total the author tested 255 positions on the MR44 project, that is a combination of tests done before slushing, during slushing and after slushing, and 320 positions on the TR9/1 project, which is also a combination of tests done during the different stages of construction, to establish whether there was an increase in the elastic modulus before and after slushing of the G1 crushed stone base. It was found that there was, but that correct reporting of the values depends on many variables such as the fundamental material properties and the moisture content at the time of testing. From the observations noted during construction of the crushed stone layers, on both projects, there were deviations from the suggested methods of construction for crushed stone layers as described by Kleyn. It is therefore not clear that the full effect of the slushing process to increase the elastic modulus had been captured and accessed due to the incorrect construction methods. However, the LWD was able to identify and note that there were complications. In some cases, results from the LWD device indicated a decrease in the elastic modulus after slushing. In other positions, low E values were recorded where moisture contents were higher. Variability of the layer, which was noted from visual inspections by the site supervisory personnel, was confirmed by the LWD device.

Figure 1 summarises all the testing done before and after slushing on the MR44 road between Swakopmund and Walvis Bay. Results before slushing noted an average modulus of 101MPa with a coefficient of variation (CV) of 24%. Results after slushing reported an average modulus of 139MPa with a CV of 24%, confirming the variation amongst the results before and after slushing to be in the same order. The difference in moisture content, before and after slushing, on average was 0.8 percentage points.

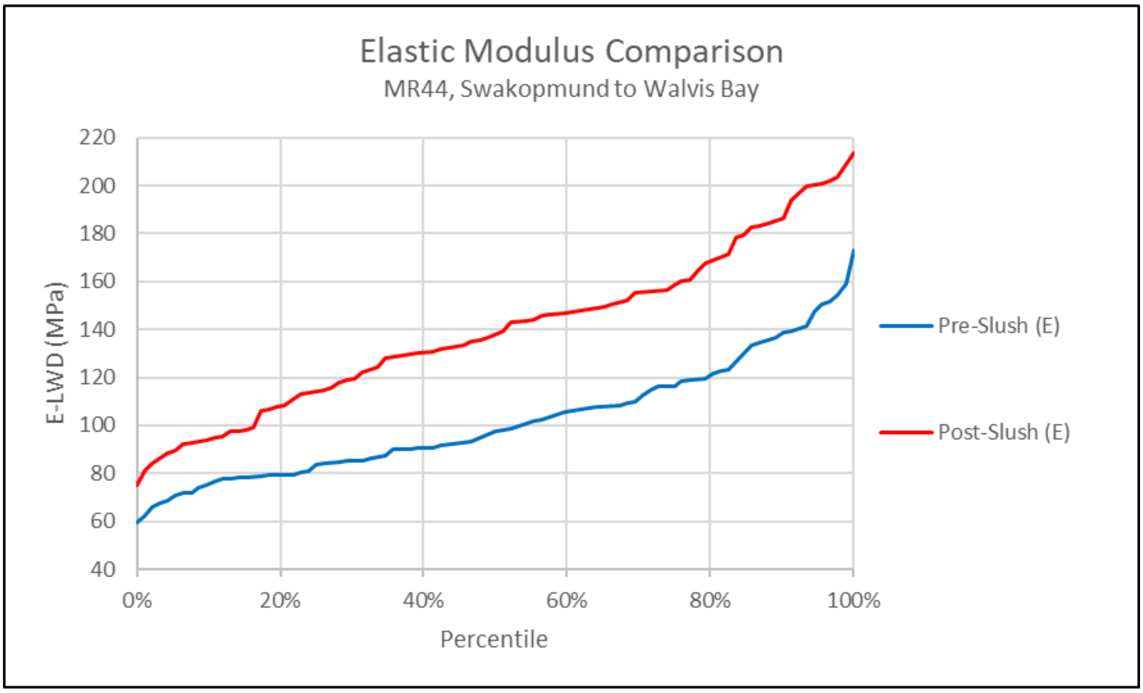

Figure 1 – Summary of LWD Results, MR44

Figure 1 shows a steady increase in the elastic modulus of the base layer after the slushing process, irrespective of the fact that irregular/incorrect construction processes were followed. The South African Pavement Engineering Manual (Chapter 10: 74) shows ranges of the resilient properties of granular layers with different support conditions. The ranges applicable to a G1 crushed stone layer in service, with a granular support, range from 150MPa to 600MPa. The lower value is equivalent to the 95th percentile before slushing but the 70th percentile after slushing. The wide range in practice is noted in the South African Pavement Engineering Manual (Chapter 10: 74) and indicated to exist for the same material as it is dependent on the in situ state.

Figure 2 summarises all the testing done on the TR9/1 road between Windhoek and the Hosea Kutako International Airport. Results before slushing showed an average modulus of 81MPa with a CV of 36%. Results after slushing reported an average modulus of 116MPa with a CV of 30%, confirming the variation amongst the results before and after slushing to be of a similar order, but indicating that slushing improved the consistency of the product slightly although the average moduli were generally lower than the other project.

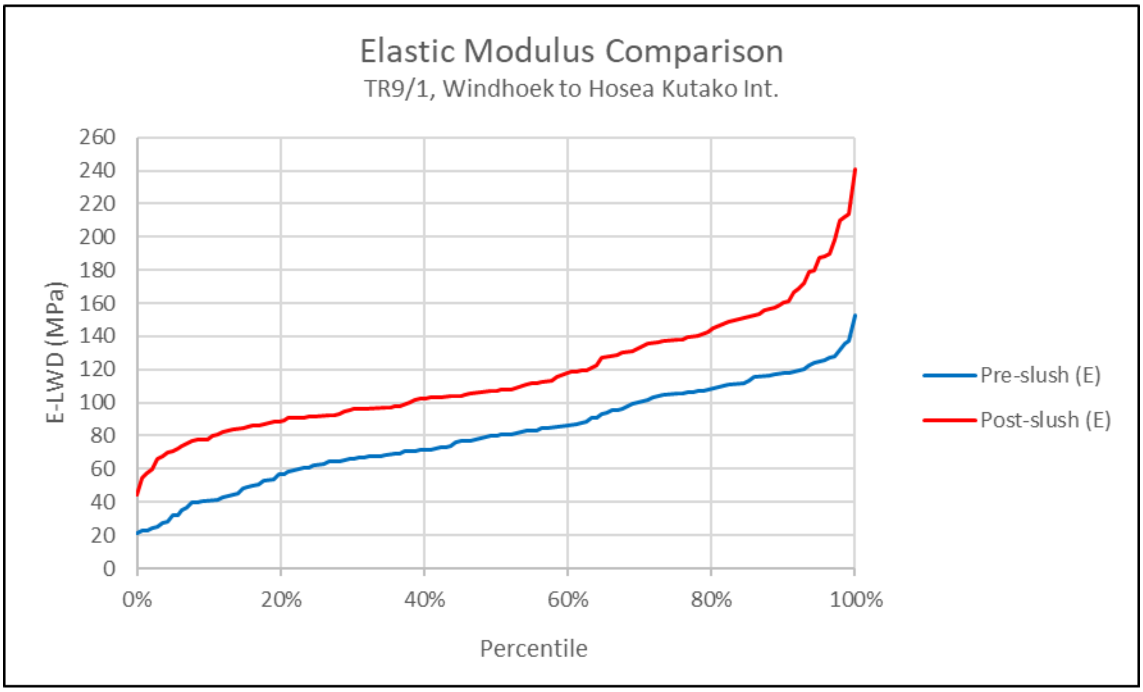

Figure 2 – Summary of LWD Results, TR9/1

Figure 2 shows an increase in the elastic modulus after slushing of the crushed stone base layer, irrespective of the fact that the layer was not constructed to the recommendations of Kleyn. The difference in moisture content, before and after slushing, on average was only 0.7 percentage points. With reference to the lower value of the suggested range as noted in the South African Pavement Engineering Manual (Chapter 10: 74), the lower value is equivalent to the 100th percentile before slushing but the 80th percentile after slushing.

It should be noted that the moisture content and material properties that affect the in service elastic modulus, differ from those at the time of construction, generally performing in a drier condition as shown by Emery (1981). This would result in an effective modulus higher than measured after slushing. The risk of premature failure may increase as a result of early trafficking before the layer has reached equilibrium moisture conditions.

Some of the sections on TR9/1 were tested again, a year after construction. Figure 3 indicates that the modulus has slightly increased on these sections. On these particular sections the average after slushing was 114MPa with a CV of 26%. The average for the modulus after 1 year was 125MPa with a CV of 22%. Emery (1992: 6-2) notes that the modulus is a function of moisture state and of material type. He mentions that there is a large increase in modulus as a material dries out and this increase is proportionally greater for materials of lower quality under pavement loading conditions, hence the insignificant increase in the modulus of the G1 crushed stone base.

The elastic modulus recorded on these sections is not what is anticipated nor within the required ranges as suggested by Theyse, De Beer and Rust (1996: 10) for use in mechanistic analyses of pavements. It might be that the values used for the South African Mechanistic Pavement Design Method have been overestimated and should be confirmed in the laboratory or by field measurements as suggested by Theyse, De Beer and Rust (1996).

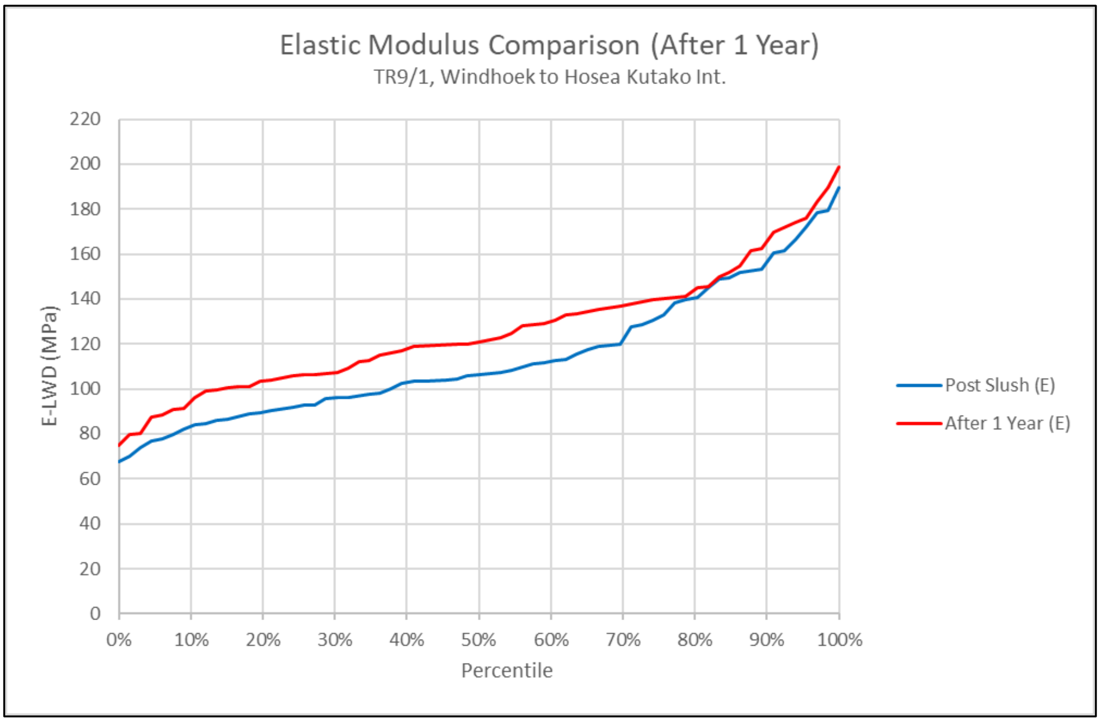

Figure 3 – LWD result comparison after 1 year, TR9/1

4. Conclusion

One of the reasons that crushed stone base layers fail prematurely is an incorrect and incomplete approach during the construction of these layers. Measuring the density of the layer will not always identify deficiencies in the arrangement/packing of particles within the layer and is a poor indication of the stiffness achieved. It is therefore imperative to measure the strength or stiffness (as opposed to only the density) of these layers during construction to confirm whether the right processes and procedures have been followed and the specified material properties have actually been developed during construction.

Many researchers note the missing link in controlling only densities of crushed stone layers and not confirming the actual strength achieved during construction. The LWD presents an acceptable alternative to density measurements that can confirm the modulus of the constructed layer. Apart from the stringent specifications that the crushed stone material must comply with, there are many other variables that may affect the measurements from the LWD device. These need to be carefully considered, managed, and maintained during a process to establish target values from the measurements of the LWD and through the proposed implementation of the quality assurance process.

From Figures 1 and 2 it is clear that there was an increase in the elastic modulus of the G1 crushed stone base layer after slushing. Despite the irregular/inadequate construction processes on both projects, however, there appears still to be a benefit from the slushing process, whether it was done as specified by Kleyn or not. When compared with the typical ranges of resilient properties for this type of layer, the average E-values obtained from testing on both projects fall short of the suggested range, minimum 150MPa. Stiffness is an indication of the layers ability to spread load and if it is too low and below the recommended minimum as indicated by the South African Pavement Engineering Manual (Chapter 10: 74), it is likely to have inadequate load spreading capabilities. This target should, however, be refined to ensure that the layer is evaluated taking into consideration the moisture content and material properties that affect the elastic modulus results, which operate in practice under different moisture and stress conditions (i.e. generally drier as shown by Emery (1981). Results obtained from testing should be reviewed and the higher end of the results extracted. Limits should be established taking into consideration the suggested ranges given by the South African Pavement Engineering Manual (Chapter 10: 74) to establish a target value for the elastic modulus. It should also be borne in mind that the road may be trafficked before the moisture content has reached an equilibrium condition, exacerbating the potential for premature failure.

To review a possible increase in the elastic modulus of the layer the test procedure was followed after the material was mixed, placed and compacted. Since testing with an LWD is not time consuming a considerable amount of test work can be done in a short period of time. Testing for this study was done at 40m intervals and dependent on the width of the layer at two or three positions across. Moisture readings were recorded at this stage to confirm the moisture content in the layer. After slushing of the layer, the same process was followed. It is important to do as much testing as possible to build up enough data to enable the user to statistically analyse the data and draw a conclusion based on the recommendation to establish judgement limits.

The elastic modulus recorded with the assistance of the Light Weight Deflectometer (LWD) for this study does not compare favourably with those ranges suggested by the South African Mechanistic Pavement Design Method (Theyse, De Beer and Rust (1996:10)). As suggested by the authors these values serve as a guideline, however, it is recommended that these values be confirmed by field measurements using the Falling Weight Deflectometer or other means.

It is therefore recommended that work continue on crushed stone layers using the Light Weight Deflectometer (LWD) to establish a link between the design and acceptance control procedures.

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