REDUCING PERCENTAGE OVERSIZE AGGREGATE IN GRAVEL WEARING COURSE MATERIALS BY LINEAR CRUSHING

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1. Introduction

The most frequently occurring defect on the Western Cape Government's (WCG) Department of Transport and Public Works (Department) proclaimed provincial gravel road network is stoniness fixed. Stoniness fixed consists of oversized aggregate (material retained on the 37.5 mm sieve) embedded in the existing wearing course layer [1] which reduces riding quality while also creating maintenance problems. In order to address this defect, the Department investigated the use of a linear crusher. After various studies and limited field trials, the Department purchased a linear crusher for further testing in the field. This paper investigates the effectiveness of reworking the existing wearing course layer by way of a tractor driven linear crusher to reduce the percentage oversize material and consequently improve riding quality and maintainability.

The type of crusher and tractor acquired, and various field trials conducted with the crusher are described in detail in the paper. The contents of the paper are as follows:

i. The need for reducing stoniness fixed
ii. The need for a linear crusher
iii. Selection of linear crusher and tractor
iv. Selection of trial sections
v. Work method
vi. Analysis of data from the trial sections
vii. Time and cost study
viii. Performance of trial section over time
ix. Conclusions and recommendations.

Keywords: stoniness fixed, gravel roads, linear crusher and innovation.

2. The need for reducing stoniness fixed

The Department's unpaved road network comprises of approximately 25 000 km, of which around 10 000 km are actively managed and maintained. It can be seen from **Figure 1** that up to 65 percent of the unpaved road network is in severe and warning stages with respect to stoniness fixed. The second most critical defect is potholes with ten percent of the unpaved road network in the severe and warning stages. Examples of unpaved roads with stoniness fixed defects are shown in **Figure 2**.

The oversized aggregate embedded in the existing wearing course layer and in-situ layer create maintenance problems and reduce the riding quality of the road. The Department identified that there was potential in crushing the embedded stones in that it could improve the maintainability of existing wearing course layers with stoniness fixed defects and it could potentially generate a wearing course from suitable in-situ material with stoniness fixed present.

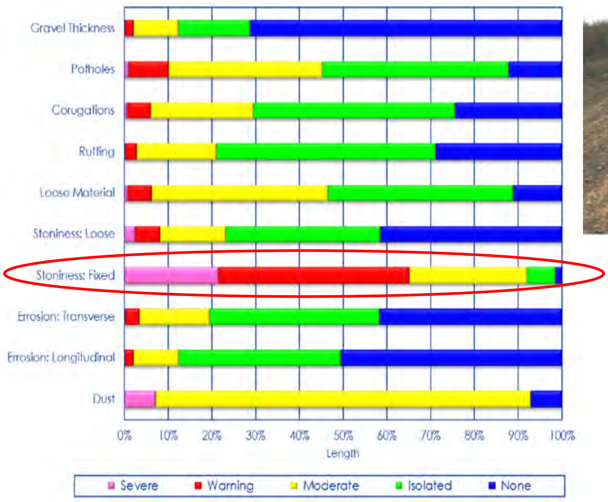


Figure 1: Defects on the Department's unpaved road network

Figure 2: Unpaved roads with stoniness fixed defects [3]

Blading the oversize material that has previously been bladed off the road back onto the road and crushing this material with the oversize material embedded in the wearing course will also assist in providing a wearing course with an improved particle grading and therefore bearing capacity.

3. The need for a linear crusher

The Department has traditionally utilised grid rollers as the method for breaking down in-situ wearing course material. The traditional work method comprised of:

i. Ripping the existing layer,
ii. windrowing the material to the roadside,
iii. using a grader to cut out small windrows of material, which are then broken-down by grid rollers,
iv. windrowing the broken-down material to the opposite side of the road,
v. mixing and adding moisture to broken down material,
vi. placing and compacting of broken-down material.

This method of working is effective and efficient in certain circumstances but was found to be lacking at times. The number of grid roller passes required to break down the material has a major impact on the productivity and cost of the grid roller method. It was found that harder materials (requiring more than eight grid roller passes) could be broken down more efficiently and effectively using a mobile crusher [2]. The breaking down of harder material using grid rollers also requires a well compacted and hard roadbed, that often must be reconstructed during and after the breakdown process.

The use of a mobile crusher was also investigated but not pursued further as it would require the in-situ material to be transported to the crushing site and back. This process also required legal approvals and authorisations.

The use of a linear crusher, that would be able to break down hard wearing course material on the road was seen as a possible cost-effective and efficient solution that would supplement current work methods.

4. Selection of linear crusher and tractor

Various types of linear crushers were investigated, evaluated and tested. It was found that the linear crushers used for agricultural applications were generally not suitable for the Department's application and that larger and stronger crushers are required. However, linear crushers that are pushed into the ground hydraulically were considered an over application for the Department's needs. The Directorate Mechanical Services of the Department did a detailed study on 24 types of crusher and tractor combinations that could be suitable for the application the Department envisaged. The parameters evaluated as well as the allocations assigned to each parameter for the crusher and tractor combination selected are shown in **Figure 3**. A FAE STC200 linear crusher and a John Deere 8245R tractor as shown in **Figure 4** were acquired after the detailed analyses of available types and models**.**

MAKE	FAE
MODEL	STC200
MASS [kg]	2830
WIDTH [mm]	2490
WORKING WIDTH [m]	2,06
SPEED [km/hr]	0,5
NUMBER OF HAMMERS	42
WORKING DEPTH [mm]	200
PRODUCTION [m^3/hr]	103
AGGREGATE SIZE [mm]	0 - 25
DRIVE	PTO
ROTOR SPEED [RPM]	800
ROTOR DIAMETER [mm]	750
TRAVEL SPEED [km/hr]	0.2-0.8
PTO SPEED [RPM]	1000
POWER [kW]	150
LIFE OF FW PARTS [hr]	400

LIFE OF SW PARTS [hr]	1000
LIFE OF MACHINE [hr]	7500
REPLACE FW PARTS [hr]	4
REPLACE SW PARTS [hr]	8
COST OF FW PARTS [R]	120000
COST OF SW PARTS [R]	380000
PRICE OF MACHINE [R mil]	1,5
PRICE OF TRACTOR [R mil]	3
TRANSPORT COST [R mil]	0,28
TOTAL PRICE [R mil]	4,78
LEAD TIME [Months]	3,5
WARRANTY [Year/hr]	2
AVAILABILITY [R/month]	12500
USAGE [hr/month]	100
FUEL [R/hr]	493
MAINTENANCE COST[R/hr]	1181
TOTAL COST [R/hr]	1799
COST [R/Road km] 3*P	10793

Figure 3: Crusher and tractor parameters evaluated by the Department's Directorate Mechanical Services in 2018

Figure 4: FAE STC 200 linear crusher (left) and John Deere 8245R tractor (right).

5. Selection of trial sections

Four trial section sites were selected near Oudtshoorn to test the selected tractor and crusher combination. The trial sections were set at 250m long and between 6m to 7.5m wide. The materials present at the four selected sites consisted of quartzite, greywacke, dorbank and shale wearing course as these are the materials generally used in the area as wearing course. The typical appearances of the wearing course materials present on the test sections are shown in **Figure 5**. The Dorbank trial section was not completed as the material was too hard to rip with the modified rippers of the CAT D7H dozer. The trials were conducted in the period June to July 2019.

Figure 5: Material types on the four trial sections. Quartzite (top left), Greywacke (top right), Dorbank (bottom left), Shale (bottom right)

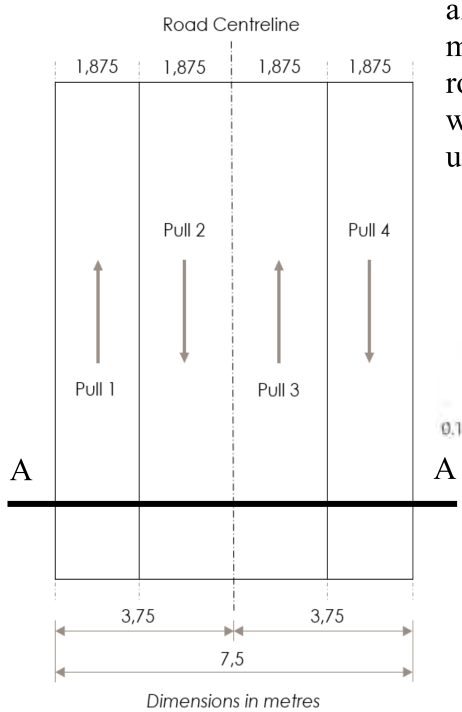
6. Work method

The work method is a result of several trials that were done to determine the most effective work method with the available equipment. The work method followed with the trial sections is as described in the paragraphs below:

i. Survey poles are set out at a 2.5m offset from the road shoulder (to ensure construction equipment does not disturb them) demarcating the beginning and end of the section and every 50m along the 250m length trial section (refer to **Figure 6**). Existing levels of the trial section surface were taken and recorded.

ii. The CAT D7H dozer takes position at the start of the section and starts ripping on the LHS of the road. A steel plate was fitted to the teeth of the rippers to limit the ripping depth to 150mm. The dozer takes three passes to cover the whole width (6m -7.5m) of the road.

iii. The grader blades loose wearing course material containing a high percentage of oversize material previously bladed off the road from the side drain and shoulder back onto the road surface on the side where ripping was done by the dozer. This material then forms part of the crushing operation. Some sections still had a thin layer of wearing course material from previous re-gravel operations on the road surface, which also forms part of the crushing process. Uncrushed material is sampled on the LHS and RHS of the half width road every 50m as marked by the survey poles. When working on one side of the road surface, the other side is used for traffic accommodation.



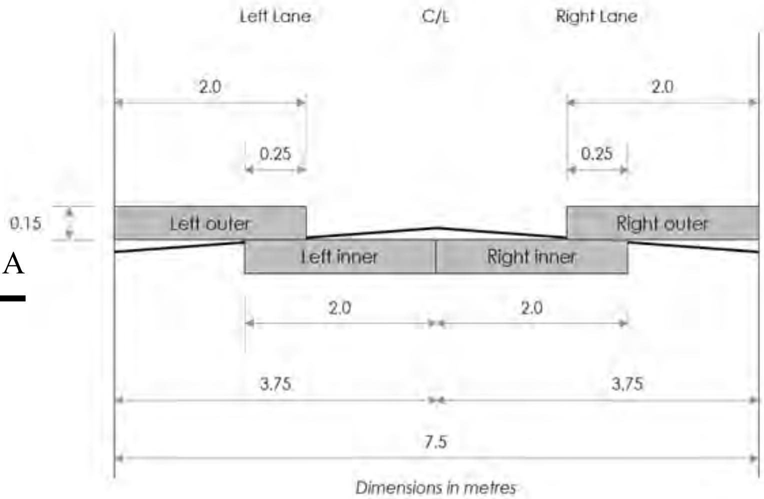


Figure 6: Layout of crushing process for typical 7.5m wide section(left). Cross section A-A illustrating the overlap of pulls (right)

iv. Behind the grader, the linear crusher approaches and starts with crushing the material (Pull 1 left outer in **Figure 6**). The linear crusher works at an optimal rate of ±700m/h. This speed can be adjusted for different applications but should remain close to the optimal rate.

v. After the first pull of the linear crusher, the dozer starts ripping along the centreline of the section. The crusher starts Pull 2 (left inner in **Figure 6**), against the centreline of the section. The initial plan was to do each pull with the linear crusher directly on the edge of the previous pull. This was found to be problematic on the first trial section with some material spilling over on the side of the finished pull, leaving a small windrow of uncrushed material in the completed pull. A decision was made to overlap the previous pull by a small margin to resolve the spilling over of uncrushed material. This overlap margin is adjusted when a change in road width occurs.

vi. Crushed material is sampled on the LHS and RHS of the half width road every 50m as marked by the survey poles. Crushing depth of the linear crusher pulls was determined by using the “dip” method between survey poles.

vii. The grader windrows the crushed material to the LHS shoulder of the road surface, creating a new temporary path along the windrow for traffic accommodation with crushing commencing on the RHS of the section. A watercart is used for dust control along the traffic accommodation route.

viii. The dozer does its third and final pull and the linear crusher then starts Pull 3 (right inner in **Figure 6**) on the RHS of the section.

ix. The grader blades loose wearing course material from the RHS side drain and shoulder onto the road for the linear crusher to finish the crushing process with its fourth and final pull on the section. As before, samples are taken of uncrushed and crushed material and crushing depth determined for the LHS and RHS of the half width road section. Organic material from the side drains should be removed by hand.

x. Finally, all crushed material is windrowed to the LHS using the grader. Wet mixing to optimum moisture content of the crushed material with the grader and watercart(s) commences. Traffic accommodation is done per standard re-gravel operation.

xi. The grader then commences with the placing of the crushed material for the new wearing course. When placement is finished, compaction is done with the vibratory smooth steel drum roller (±12 ton) to achieve compaction, followed by a pneumatic roller (±27 ton) to finish off the layer.

xii. Grading and Atterberg Limit tests were done on the samples taken in each pull at every 50m before and after crushing.

Figure 7: Trial section construction sequence: Setting out (top left); Ripping the in-situ material (top right); Blading oversized material onto the roadbed (bottom left); Crushing of in-situ material (bottom right).

Dust control during the crushing process is done by wetting the surface of the section planned for processing the next day, before departing from site at the end of the day. The moisture penetrates the road surface overnight resulting in a slightly moistened layer when crushing commences the following day. This assists in reducing the dust generated by the crushing process significantly.

It is not recommended to soak loose material with water right before crushing. Material that is too wet can form a grinding paste within the linear crusher chamber, which in turn will damage the equipment.

7. Analysis of data from the trial sections

The material properties before and after crushing were evaluated in terms of the Technical Recommendations for Highways 20 [3] materials performance classification graph. The graph is shown in **Figure 8.** The following further specifications pertain to the materials performance classification graph (the graph):

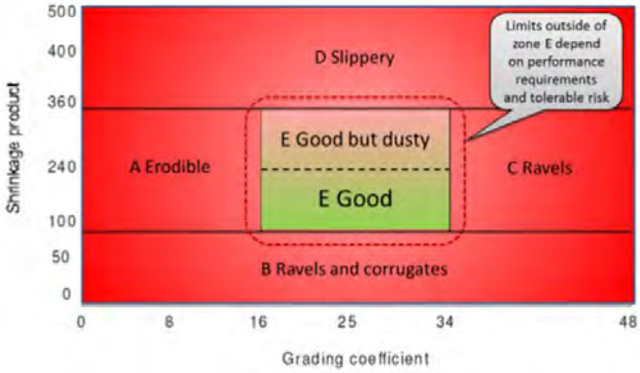


Figure 8: TRH 20 Material performance classification

- Grading coefficient: (%passing 28mm - %passing 2mm) x (%passing 5mm/100)
- Shrinkage Product: Linear shrinkage x %passing 0.425mm
- Oversize Index: % retained on 37.5mm ≤ 5%
- CBR: ≥ 15% at 95% maximum dry density.

The severity of the stoniness fixed defect is a function of the Oversize Index. Compliance with the Oversize Index specification will result in gravel roads with minimal stoniness fixed defects. It follows that reducing the percentage retained on the 37.5 mm sieve to below 5% (Oversize Index) will decrease the degree and extent of the stoniness fixed defect on gravel roads.
The before and after crushing graphs for the greywacke trial section are shown in **Figure 9** and **Figure 10** respectively. The red dot shows the average result of the samples tested. The trial sections for the quartzite and shale materials show similar trends.

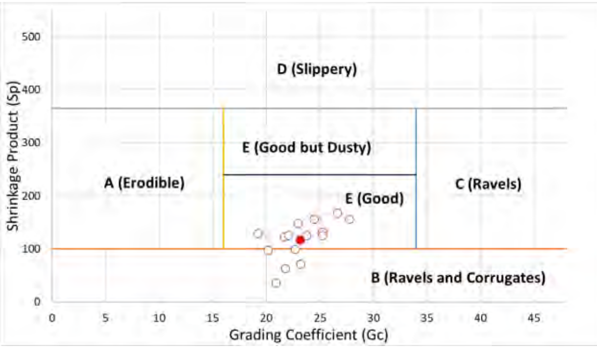


Figure 9: Before crushing for the greywacke trial section on DR1689

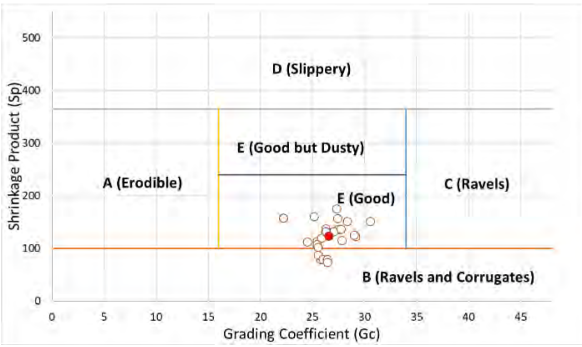


Figure 10: After crushing for the greywacke trial section DR1689

To evaluate the effect of crushing on the performance of the gravel wearing courses tested, the average and coefficient of variance (COV) for the percentage passing the 28mm, 5mm, 2mm and 0.425mm sieves and the difference between the percentage passing the 28mm and the 2mm sieves were calculated for all the gradings performed as part of the trial sections. The results of the calculations are shown in **Table 1** below.
The following conclusions are drawn from the information in **Table 1**, **Figure 9** and **Figure 10:**

Table 1: Grading analyses for before and after crushing

Road No	Material	Before/After Crushing	No. of Samples	%P 28 mm Sieve		%P 5 mm Sieve		%P 2 mm Sieve		%P 0.425 mm Sieve		Difference between %P 28 and 2 mm sieves
				Avg	COV	Avg	COV	Avg	COV	Avg	COV	
DR1693	Quartzite	BC	21	90	5	69	12	59	14	43	19	31
		AC	23	97	2	75	8	65	11	48	15	32
		% increase		8%		9%		10%		12%		
DR1689	Greywacke	BC	28	87	10	61	13	52	13	38	14	36
		AC	50	93	7	65	12	55	12	40	12	38
		% increase		7%		7%		6%		5%		
DR1655	Shale	BC	9	85	10	47	15	37	16	26	20	47
		AC	11	93	3	52	11	41	11	26	14	52
		% increase		9%		11%		11%		0%		

i. There is a slight increase in the Shrinkage Product caused by the increase in the percentage passing the 0.425mm sieve before and after crushing. The linear shrinkage is not expected to change with crushing of the material.

ii. There is an increase in the Grading Coefficient. This is caused by an increase in both the difference between the percentage passing the 28mm and 2mm sieves and the percentage passing the 5mm sieve with crushing of the material.
iii. There is an increase in percentage passing on all the sieve sizes that are variables in the Shrinkage Product and Grading Coefficient equations. The material therefore becomes finer on all the sieve sizes and not only the larger sieve sizes.
iv. The percentage increase in the percentage passing after crushing does not show any significant trends for the different sieve sizes and are of the same order for a specific material type (except for the shale on the 0.425mm sieve, which cannot be explained other than being an outlier). It follows that the stone sizes for the range of sieves that determines the performance of a gravel wearing course are broken down equally in the crushing process. The complete grading becomes finer during crushing and not only one stone size.
v. The percentage increase in the percentage passing after crushing does not show a significantly higher percentage for the soft material (shale) than for the harder materials (quartzite and greywacke).
vi. The COVs are lower after crushing than before crushing, indicating that the material becomes more uniform during crushing. This is truer for the larger stone sizes, as can be expected. This is also evident from the before and after plots on the TRH 20 materials performance classification graph (see **Figure 9** and **Figure 10**).

It follows from above that the grading becomes finer during crushing for the sieve sizes that control the performance of the gravel wearing course, but that one stone size is not broken down unproportionally to other stone sizes. This is significant for the materials tested in that a continuous grading will stay continuous and that crushing will not have a detrimental effect on the bearing capacity and compaction of the material, by for example generating a large proportion of fines.

The changes in oversize index before and after crushing are shown in **Table 2** below for the materials present in the different trial sections. The values shown are the averages for all the grading tests conducted.

Table 2: Change in Oversize Index before and after crushing for the materials in the trial sections

Material	Oversize Index Before Crushing	Oversize Index After Crushing	Percent Decrease
Quartzite	5.4%	1.3%	77
Greywacke	7.5%	3.2%	58
Shale	9.6%	2.5%	74

Although oversize material is still present after crushing, the percentage is reduced to below the TMH 20 specified value of 5% for all trial sections. As can be expected, there is a significant decrease in the Oversize Index after crushing.

It follows from the preceding discussion that the linear crusher performs the function that it was acquired for and is effective in reducing the percentage of oversize material present in the gravel wearing course, but without changes to the grading that would negatively affect bearing capacity and compaction of the material.

8. Time and cost study

Divisional Road 1689 (DR1689) was selected as study area to conduct the production phase. A road section with a significant percentage of hard greywacke oversize material situated within existing wearing course and subgrade layers was selected. The existing road surface was processed to a 150mm depth and 7.5m road width. The objective of the production phase was to improve in-situ wearing course material by reducing the oversize material, assess the work method based on plant unit performance and determine operational cost.

Time studies were conducted on each machine activity over an 18 workday period to determine individual plant performance rates. Daily costing was done using the departmental Integrated Maintenance Management System (IMMS). The allocated resources comprised the following:

i. 1x FAE STC200 linear crusher and a John Deere 8245R tractor
ii. 1x CAT D7H dozer with modified ripper attachment
iii. 2x Construction graders (Bell 670G and CAT 140G)
iv. 2x 11 000l water bowsers
v. 1x 12 ton vibratory steel drum roller
vi. 1x 27 ton pneumatic roller.

The human resources component comprised one civil engineering technician, four operators and eight labourers. Rotation of operators between machines was therefore necessary.

A typical production day entails crushing a road section to full width followed by mixing and placing the previous day's crushed section. It should be noted that the import of materials was limited to construction water only which was sourced near the site. An average production rate of 500m per day was achieved during the 18-workday period. Analysis of time study data has shown that production was limited by grader activities and operator availability. Further investigation into this matter indicated that production rates of more than one kilometre per day are possible should the necessary support plant be provided.

Project costs obtained from the IMMS system indicated an all-inclusive operational unit cost in the order of R134 000 per kilometre for this operation. A relative cost comparison using in-house cost reporting systems indicate an approximate 50% reduction in costs compared to traditional methods, mainly as a result of increased production.

9. Performance of production section over time

The performance of a section of DR1689 from km 5.00 to km 10.00, that was constructed as part of a production section during August 2019, was monitored on a regular basis in terms of maintainability, visual condition and roughness.

Blading cycle and maintainability

The scheduled blading frequency for DR1689 km 5.00 to km 10.00 is six times per annum, which translates to once every two months. Interviews with the deputy manager responsible for the maintenance of this section of DR1689 indicated that no changes were made to the blading frequency post the rework [4]. The grader operator and deputy manager indicated that the efficiency and effectiveness of the blading operation improved after the rework. This can mainly be attributed to the reduction in oversize material and improved drainage that was a result of the rework process.

TMH 12 Visual assessments

During May 2019 and September 2021 network level visual assessments according to TMH 12 [1] were conducted along DR1689 from km 5.00 to km 10.00 (refer to **Table 3**). These assessments were conducted by independent professionally trained consultants.

From the data in **Table 3** the following observations are made:

i. The structural assessment indicates improved behaviour with respect to potholes, rutting and stoniness fixed, while the ratings for loose material and longitudinal erosion worsened.

ii. With respect to functional assessment, the riding quality and side drainage improved from fair to good.

iii. The Visual Condition Index (VCI) shows a significant improvement after the linear crusher operation. The VCI is calculated through a combination of the rating for degree and extent of the distress type, together with a weight factor based on the importance of the distress type. The general condition of this section improved from fair to good.

Table 3: Visual assessment data (improvements in green)

DR1689 - Visuals				
Authority	Garden Route	**Road No.**	DR01689	
Road Type	Gravel	**From (km)**	5.00	
Width (m)	8-10 m	**To (km)**	10.00	
Moisture	Dry	**Terrain**	Rolling	
	May 2019 (Before)		**Sep 2021 (After)**	
Structural Assessment	Degree	Extent	Degree	Extent
Potholes	3	1	2	1
Corrugation	2	2	2	2
Rutting	2	2	2	1
Loose Material	1	3	2	4
Stoniness: Fixed	**4**	**3**	**3**	**2**
Stoniness: Loose	1	1	3	1
Erosion: Transverse	0	0	0	0
Erosion: Longitudinal	0	0	2	1
Functional Assessment				
Riding Quality	Fair		Good	
Skid Resistance	Fair		Fair	
Dust	Minor		Minor	
Drainage on Surface	Fair		Fair	
Drainage on Side	Fair		Good	
Problems	None		None	
Riding Quality				
General Condition	Fair		Good	
VCI	61.45		80.80	

The objective of the operation was to reduce stoniness fixed on gravel roads. A reduction in stoniness fixed is expected to improve riding quality, as well as addressing other defects such as inter alia potholes, corrugations and poor drainage. With reference to the before and after visual assessment this goal was achieved as the degree and extent of stoniness fixed was reduced by the operation.

International Roughness Index

The International Roughness Index (IRI) is one of the key performance indicators for the measurement of the riding quality of a road [3]. No IRI data was captured before the production section was constructed. The last IRI values were captured in 2016 with an average value of 6.6mm/m on DR1689 from km 5.00 to km 7.00. IRI values were captured on 29th of July 2020, approximately one year after the completion of the production section, with an average value of 3.97mm/m, as shown in **Figure 11**.

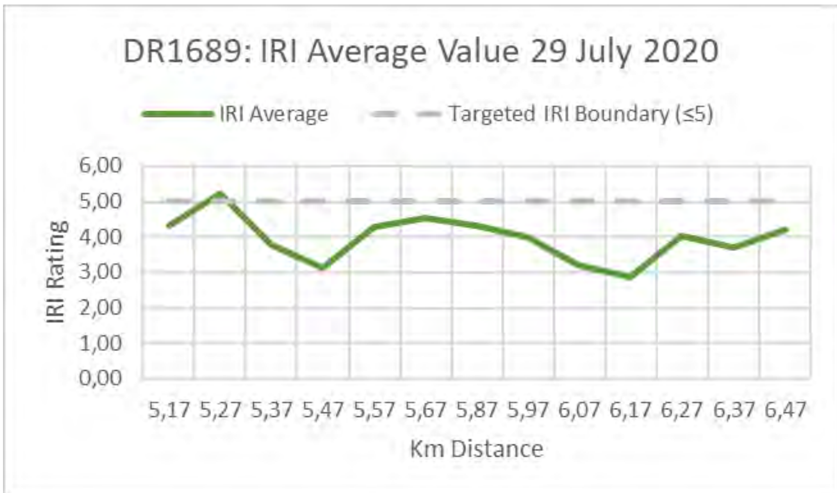


Figure 11: Average IRI rating for DR1689 test section

DR1689 falls within a medium level of service on maintenance with an Average Annual Daily Traffic (AADT) of between 100 and 150 vehicles per day (vpd). The target average IRI

on this class of road is an average value of five or less, with intervention to be taken when an IRI value of ten is reached [5].
A combined IRI average value of 3.97 mm/m was obtained when incorporating all IRI data points captured on the section. This falls well within the IRI target value of five.
The IRI data indicates that the road surface would provide a comfortable ride for road users.

10. Conclusions and recommendations

The paper describes the process of acquiring a linear crusher and tractor combination and various field trials conducted to address the most frequently occurring defect on the Department's gravel road network, namely stoniness fixed.
A summary of the work done, and certain conclusions drawn, is described below:

i. The Directorate Mechanical Services of the Department did a detailed study on 24 types of crusher and tractor combinations that could be suitable for the application the Department envisaged. A FAE STC200 linear crusher and a John Deere 8245R tractor were acquired after the detailed analyses of available types and models.
ii. The linear crusher was utilised on four trial sections consisting of material of various hardness, namely quartzite, greywacke, dorbank and shale. The trials were conducted in the period June to July 2019.
iii. Trial sections were 250m long and 6 to 7.5m wide and sampling positions were demarcated with survey poles planted every 50m.
iv. The existing road surface was ripped to a depth of 150mm with a CAT D7H dozer, loose material on the side of the road containing a high percentage of oversize material that was previously bladed of the road, was bladed back onto the road. This material was then crushed with the linear crusher. Samples of the material were taken before and after crushing for grading and Atterberg Limit tests.
v. The road width was covered by four pulls of the linear crusher with a 250mm overlap between pulls. Traffic was accommodated in half-widths.
vi. The crushed material was windrowed to the LHS of the road with a grader and mixed with water to optimum moisture content. The crushed material was then placed by a grader to construct the new wearing course. After placement, compaction was done with a vibratory smooth steel drum roller (±12 ton) to achieve compaction, followed by a pneumatic roller (±27 ton) to finish the layer off with a closely knit surface.
vii. Dust control during the crushing process was done by pre-wetting the surface of the road the afternoon before crushing the next day. The application of water just before crushing is not recommended because the wet material can form a grinding paste within the linear crusher chamber which could damage the equipment.
viii. The material properties before and after crushing were evaluated in terms of the TRH 20 materials performance classification graph. The following were concluded from the evaluation:
    a. There is an increase in percentage passing on all the sieve sizes that are variables in the Shrinkage Product and Grading Coefficient equations. The material therefore becomes finer on all the sieve sizes and not only the larger sieve sizes.
    b. The percentage increase in the percentage passing after crushing does not show any significant trends for the different sieve sizes and are of the same order for a specific material type. It follows that the stone sizes for the range of sieves that determines the performance of a gravel wearing course are broken down equally in the crushing process. The complete grading becomes finer during crushing and not only one stone size.

c. The percentage increase in the percentage passing after crushing does not show a significant higher percentage for the soft material (shale) than for the harder materials (quartzite and greywacke).
d. The COVs are lower after crushing than before crushing, indicating that the material becomes more uniform during crushing. This is also evident from the before and after plots on the TRH 20 materials performance classification graph.

ix. There is a significant reduction in the oversize index for the materials tested before and after crushing, namely 77 percent for the quartzite, 58 percent for the greywacke and 74 percent for the shale.

x. It is evident from the test results that the linear crusher performs the function it was acquired for and is effective in reducing the percentage of oversize material present in the gravel wearing course, but without changes to the grading that would negatively affect bearing capacity and compaction of the material.

xi. Following the success of the trial sections, the linear crusher and tractor combination was put into production in August 2019 on Divisional Road 1689 (DR1689) where the material on the existing road was crushed to a depth of 150mm and reworked to a width of 7.5m. A time and cost study were conducted over a period of 18 workdays. An average production rate of 500m per day was achieved at a cost of R134 000 per kilometre. Production was limited by grader activities and operator availability.

xii. The performance of a section of DR1689 from km 5.00 to km 10.00, that was constructed as part of the production section, was monitored on a regular basis to assess its performance over time in terms of maintainability, visual condition and roughness. The grader operator and deputy manager responsible for maintenance of the road section indicated that the efficiency and effectiveness of the blading operation improved after the rework. This can mainly be attributed to the reduction in oversize material and improved drainage that was a result of the rework process.

xiii. During May 2019 (before crushing and reworking) and September 2021 (after crushing and reworking) network level visual assessments according to TMH 12 were conducted by independent professionally trained consultants. The assessment indicated improved behaviour in terms of degree and extent with respect to potholes, rutting and stoniness fixed, while the riding quality and side drainage improved from fair to good. The Visual Condition Index (VCI) showed a significant improvement from 61 to 81 (33 percent improvement) after the linear crusher and rework operation. The general condition of this section improved from fair to good.

xiv. International Roughness Index (IRI) measurements were done on the road section in 2016 and again in 2020. The roughness decreased from 6.6mm/m to 4.0mm/m, a reduction of 39 percent.

xv. Considering the success of using the linear crusher to crush and rework road sections with primarily the stoniness fixed defect, it is recommended that the following be investigated:
a. Further time and cost studies on material types with varying hardness using also grid rollers and mobile crushers as the breaking down mechanism, and the cost of such methods be compared to one another.
b. Linear crushing as part of the periodic re-gravel operation.
c. Screening out of material larger than 300mm at the borrow pit prior to linear crushing as part of the re-gravel operation.
d. The introduction of a powerful agricultural tractor into unpaved road operations with multiple proven attachments (e.g. towed graders, compacters) being used to raise power unit utilisation and lower overall costs as a

replacement for dedicated single use heavy equipment (e.g. grader, dozer, roller).

11. References

[1] Committee of Land Transport Officials, "TMH 12 Pavement Management Systems: Standard Visual Assessment Manual for Unsealed Roads Volume 1," CSIR, Pretoria, 2000.

[2] Provincial Administration of the Western Cape, "Gravel Roads Manual: Chapter 6 Construction and Quality Assurance Rev 0," Western Cape Provincial Administration, 2006.

[3] Department of Transport, "Draft TRH 20 Unsealed Roads: Design, Construction and Maintenance Version 1.6 - March 2013," Department of Transport, Pretoria, March 2013.

[4] G. Verwey and B. Hartzenberg, Interviewees, *Deputy Manager Maintenance GRDM.* [Interview]. May 2022.

[5] Western Cape Government, "Unpaved Road Network Maintenance Strategy," Unpublished, Cape Town, 2018.