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Understanding Durability Problems with Dolerite in Roads in South Africa

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Abstract

Dolerite is one of the most widely used road pavement construction materials in South Africa and is classified as a basic crystalline rock. The variable performance of road pavements constructed with such rocks in South Africa has frequently been linked to the durability of the freshly crushed dolerite which can undergo rapid deterioration in service. This poor durability affects the life cycle of the road as they can fail prematurely. The prevailing conditions under which rapid deterioration of dolerite occurred on the road are somewhat contradictory. The objective of this study was to provide insight into what influences rapid deterioration in dolerite when used in the base course of road pavements. The evaluation was completed by conducting surveys, field investigations and laboratory experiments comprising mineralogical analyses and engineering tests. Surveys were done to identify the investigation sites. Field investigations comprise visual condition assessment of road pavement surface and pavement structure using test pits. Field investigations were followed by a sampling of material from the identified investigation sites for laboratory material testing. Laboratory testing included standard engineering soil tests and specialised techniques for mineralogical analysis. Two approaches for durability investigations were followed. For each approach, two samples were used (control sample and investigated sample), and the results of the sample investigated were compared with the control sample results. Findings from both approaches were compared. An interesting finding was that, contrary to conventional wisdom, not all of the dolerites investigated contained discernible smectite contents.

Keywords

Dolerite, Crushed Stone, Road Pavement, Climate, Deterioration, Performance

1. Introduction

The poor durability of some dolerites affects the life cycle of the road as they can deteriorate rapidly when used in the base course. The life cycle of road pavements is based on their anticipated behavior under the prevailing conditions. From the literature, the prevailing conditions under which rapid deterioration of dolerite occurred on the road are somewhat contradictory.

Deterioration of road pavements located in wet and moderate areas was evidenced by the presence of swelling secondary minerals (smectites) in the material inherited from the source (*i.e.* caused by deuteric alteration during or shortly after its crystallisation). Road samples that inherited secondary minerals with smectites showed unacceptablely high Plasticity Index (PI) values. The alteration observed in wet and moderate areas did not affect the PIs, but the availability of smectite inherited from the source affected the PIs. Road Samples that inherited secondary minerals with no swell potential showed acceptable PI values. Not all dolerites were found to be problematic in terms of mineral composition.

[1] indicates that dolerite is situated mostly in the main basin of the Karoo Supergroup in South Africa which covers approximately 700,000 km^2 (57%) of the country's land surface area. Investigations into the durability of basic crystalline rocks and specifications for their use as road base aggregate have been conducted for many years in South Africa [1]-[8].

[2] reported the phenomenon of accelerated deterioration of dolerite when in service and carried out early research to identify the causes. Different research studies with different approaches have subsequently been conducted, but the results were partially different.

[7] established relationships in durability, physical, mechanical, and mineralogical results in samples that were drilled in various localities of Kwa-Zulu Natal. There were no control samples to indicate whether the problem influencing deterioration was inherited or developed when the material was in service.

[1] was widespread in the eastern areas of South Africa and the Karoo main basin. It was done in areas where N-values range between 3 and 9, where climatic conditions do not always favour chemical decomposition. Material sampled included crushed stone G1 and G2 base and samples were obtained from quarries and existing road pavements. Tests carried out included petrographic examinations, XRD, AIV, DMI, Compressive and shear wave velocity, PI, Modified ethylene glycol durability index, and water absorption. The plasticity index was obtained during the Durability Mill Index (DMI) test.

[9] was focused on the eastern parts of the Free state, the Gauteng/Mpumalanga border area and southern Mpumalanga. The study was based in areas where the N-value is below 3, where climatic conditions favour chemical decomposition. Material sampled included highly decomposed dolerite and crushed dolerite and the samples were obtained from borrow pits and quarries. Tests carried out included the semi-quantitative X-ray diffraction analysis to determine the mineralogical composition, and the plasticity index (PI). Material passing sieve 0.425

mm and 0.075 mm was used for PI determination.

[1] [10] indicated that the material has undergone some form of degradation as the petrographic properties of some case study sites were different due to evidence of secondary mineral alteration to smectite clays. The process of deterioration, whereby there is a change in mineral composition (decomposition), occurs mostly in wet regions where Weinert N-value is less than 3. Decomposition is the change of primary minerals into secondary minerals by oxidation, hydrolysis and hydration, and only rocks which consist of minerals able to undergo these changes decompose if environmental conditions favour chemical action on them, otherwise, they disintegrate [11]. An extended investigation has been done in this research study, as [9] indicated that the deterioration was not due to decomposition.

[9] indicated that the short-term artificial weathering does not result in an increase in smectite content and therefore dolerite does not decompose and generate clay in the short term. Rapid deterioration of material is not caused by the accelerated decomposition of the dolerite minerals, but due to mechanical exposure, the harsh operating environment of road pavement and subsequent release of the inherent clay minerals to participate in the PI measurement. An extended investigation has been done in this research study, as [1] reported the evidence of alteration to smectite clays.

[9] confirmed that to obtain a fuller picture, the investigation should be extended to dolerites where Weinert N-value is higher than 3. [9] and [1] required to be extended to drier and wetter areas respectively. Findings are also partially contradictory and therefore necessitate the study that will take into consideration both the [9] and [1] methods using a common sample and differing climates. In this study, the investigation done by [9] and [1] has been partially extended to drier and wetter areas respectively. This study focused mainly on the mineralogical composition, durability and plasticity index (PI) of the material as rapid deterioration of dolerite material has mostly been linked to these properties.

The objective of the study was to provide insight into what influences rapid deterioration in dolerite when used in the base of the road pavement by conducting field investigations and laboratory experiments which comprise mineralogical analysis and standard engineering tests. The Specific objectives of the study were to determine changes in mineralogical and engineering properties that lead to deterioration of dolerite when it is in service, to determine the effect of secondary minerals on engineering properties in dolerite, to determine the phase (material in service/material in source) on which rapid deterioration of dolerite takes place, to identify environmental conditions and other confounding factors that enable changes in mineralogical and engineering properties when dolerite is in service, and to identify dolerites that are susceptible to rapid deterioration when in service.

2. Methods Used for Investigation

A quantitative research approach was used for this study. Various investigation methods were used, and these research methods comprised field investigations, laboratory testing and instrumental analytical techniques.

A process was followed whereby two samples (control sample from quarry and investigated sample from road) were considered for laboratory testing where the results of the sample being investigated were compared with the control test sample results. Areas that have been included in the research are those located on the eastern side of South Africa. The targeted population for research comprises crushed dolerites located in wet, moderate, and dry regions.

Methods of evaluation and measurement are indicated in **Table 1**. The requirements of materials investigated were according to [12]. All test results were evaluated for compliance with material requirements indicated in [12] and cross checked with [13].

2.1. Approach for Investigation

The approach followed for the investigation is indicated in **Table 2**.

2.2. Criteria for Site Selection

Criteria for identification of investigation sites were as follows:

- Since the problems were encountered when the material was used in road pavement layers and recent studies cover mostly fresh rock, the investigation was conducted on a crushed stone found in the areas of concern (eastern parts) of the country.
- In sites where the base course was constructed with crushed dolerite.
- Sites that experienced pavement structural failures on which base course was suspected to be an issue resulting in the failure. Of course, other issues such as vehicle overloading, poor construction, poor drainage, etc. may also have

Table 1. Methods of evaluation and measurements.

Test	Method
Grading	SANS 3001-GR1 & GR2
Atterberg limits	SANS 3001-GR10, GR12
Glycol Soaking test	SANS 3001-AG14
Durability Mill Index	SANS 3001-AG16
Mineral Analysis	X-Ray Diffraction

Table 2. Approach followed for investigation.

Crushed dolerite Method	Fines Method
The material was sampled directly from the base layers of the road pavements and test results were compared with test results of materials that were obtained from the quarries.	Two sets of quarry fines (old and fresh) were obtained. The sampled fines included dust that was not exposed to the elements and the dust that was exposed to the elements for more than three months where it was present.

contributed to the problems, and these were considered as far as possible.

2.3. Investigation Sites

The location and climatic zones of the investigation sites are indicated in Table 3 and Figure 1. Surface and pavement distresses observed during visual condition assessment (VCA) are discussed in Table 4 and shown in Figures 2(a)-(d). The VCA was conducted following the [14] guidelines.

2.4. Sampling

Samples were obtained in areas with different environmental conditions. A single-stage sampling was done according to the procedure described in [15]. Four samples were obtained from each site investigated. The four samples comprise

Table 3. Location of investigation and control sites.

Area name	Co-ordinates of the Investigation site	Co-ordinates of the material sources (Quarries)	Reference to this research study
Flagstaff	30˚56'00.43"S: 29˚34'31.29"E	30˚55'13.97"S: 29˚34'41.76"E	Site A
Ermelo	26˚34'31.59"S: 30˚04'05.86"E	26˚36'28.29"S: 29˚56'50.73"E	Site B
Elliotdale	31˚58'07.07"S: 28˚39'40.97"E	31˚50'19.06"S: 28˚33'31.22"E	Site C
Jansenville	32˚27'35.38"S: 24˚38'17.87"E	32˚37'55.80"S: 24˚41'31.09"E	Site D

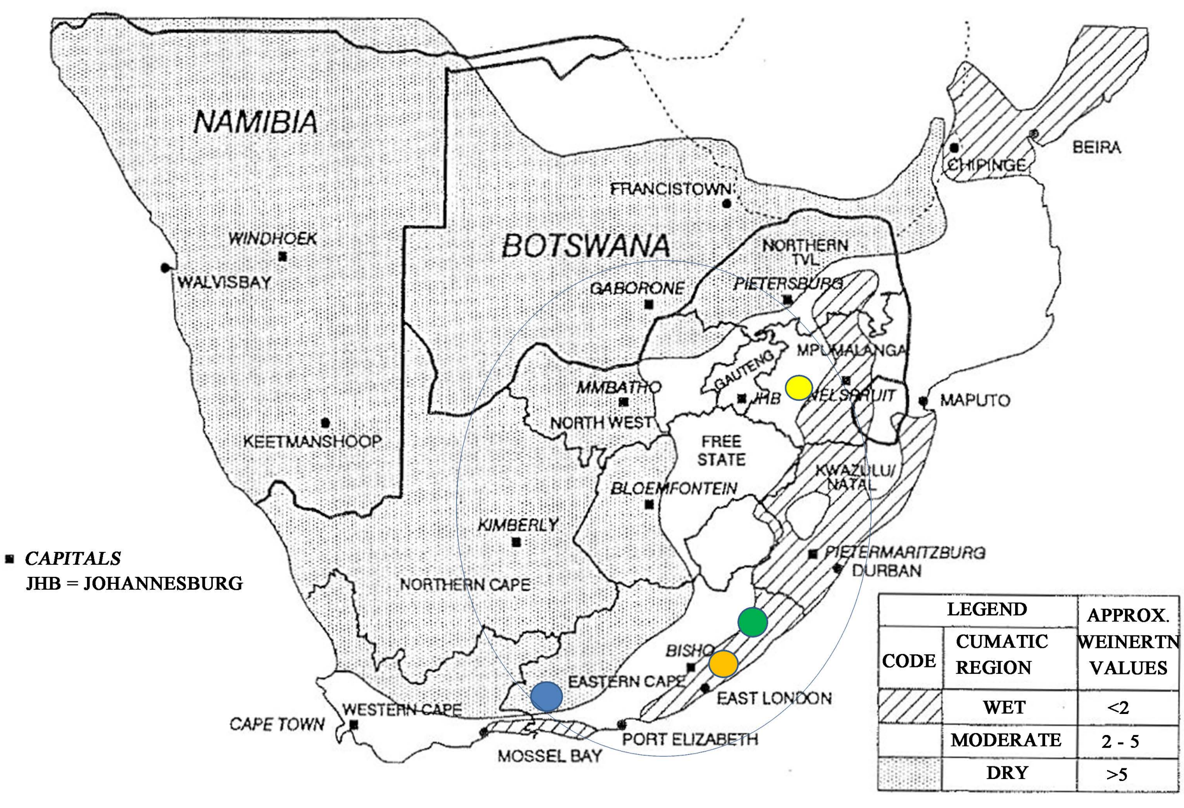


Figure 1. Climatic conditions of the investigation sites [2].

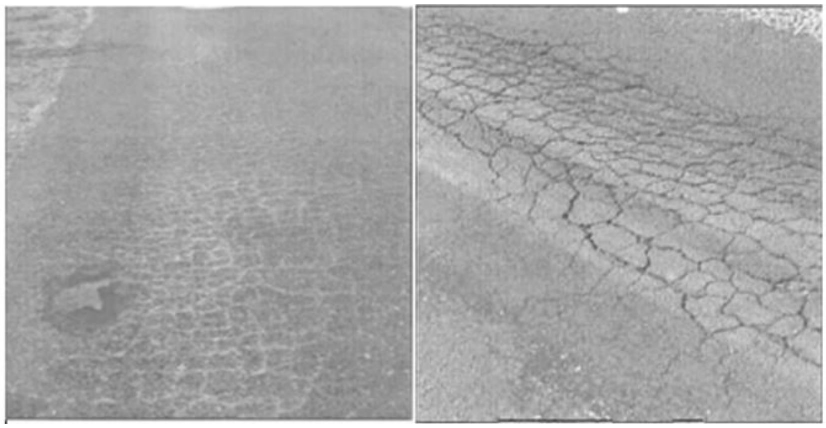
Table 4. Surface defects and pavement failures.

Site	Findings
A	Rutting was dominant. The reason for rutting was due to the deformation of the base and specifically because the quality of the base has been compromised. The reason was not very clear, but it was expected that secondary weathering of the dolerite had taken place. It was noted that even though the same material was used in the subbase, the PI in the subbase was less due to better protection and reduced traffic loads.
B	The failures consisted of crocodile cracking observed in the continuous medium grade asphalt layer with rolled in chips (RIC), occurring randomly on all the traffic lanes constructed recently, both in the southbound and northbound direction carriageway.
C	Several isolated small potholes were found along the road which was badly damaged due to the structural pavement layers failing. Potholes formed extensively and have to be repaired often. All road distress features have resulted in the premature failure of the pavement.
D	The dominant distress along the road was crocodile cracks with associated pumping located in the wheel tracks. Some of the repairs to these distressed areas exhibit the same type of distress. The assessment of the mechanical surveys largely confirmed the observation made based on the visual assessments. It was clear that the changes in condition coincide with changes in the pavement structure. The dominant distress along the road was crocodile cracks with associated.

(a)

(b)

(c)



(d)

Figure 2. (a) Surface defects and pavement failures (site A); (b) Surface defects and pavement failures (site B); (c) Surface defects and pavement failures (site C); (d) Surface defects and pavement failures (site D).

one control sample and one investigated sample for Crushed Stone Base method and one control sample and one investigated sample for the Fines method

Crushed Stone Method: Investigated samples comprise crushed dolerite obtained directly from test pits (TP) in the base of the road pavement. Control samples comprise crushed dolerite obtained from the source quarry. The quarries from which the control samples were obtained were identified as sources of the road material that was investigated. Table 5 discusses how sampling was conducted.

Fines Method: Investigated samples comprised old fines that were obtained from the quarry. Control samples comprise fresh fines obtained from the quarry. The sources on which the control and investigated samples for fines method were obtained, were the same sources on which the control samples for crushed stone method were obtained.

3. Results from Laboratory Testing

The results comprise both engineering and mineralogical test results. For engineering testing, test methods contained in [16] were followed.

3.1. Engineering Test Results

3.1.1. Engineering Test Results

Engineering test results for the Crushed Stone method are summarised from Tables 6-11, and for the Fines method are indicated in Table 12.

3.1.2. Durability Mill Index

According to [17], DMI is a standard specification requirement for G4 quality materials but can be used as an indicator of problems for G1 and G2 crushed

Table 5. Sampling for crushed stone method.

Site	Sampling
A	The locations of test pits were strategically selected at areas that exhibited certain defects while at the same time distributing the tests pits equally among the uniform sections.
B	Five test pits were identified consisting of different types of failures varying in extent and degree. Three additional test pits were also identified in areas where no failures occurred.
C	The test pit was located at an area that exhibited certain defects.
D	A centerline survey was conducted over the full length of the road section. The test pits were more or less 1 km apart in the outer wheel path in either Northbound or South bound lane so as to not hinder the daily traffic flows.

Table 6. Base layer indicator, and moisture test results, site A

	Layer thickness	MC (%)	OMC (%)	PI (0.425)	GM	PI (0.075)
G3 Requirements	n/a			≤6		≤12
Average measured	148.7	4.3	5.9	6.7	2.4	11.3
Coefficient of variation	14.4	33.0	10.3	44.2	5.8	31.8

Average EMC/OMC ratio = 0.73.

Table 7. Base layer indicator test results, site B.

	Gradings							
Sieve	S1	S2	S3	S4	S5	S6	S7	S8
37.5 mm	100	100	100	100	100	100	100	100
26.5 mm	95	93	95	95	91	88	93	95
19.0 mm	83	84	84	85	85	75	81	83
13.2 mm	76	78	78	79	75	68	75	73
4.75 mm	56	59	60	57	53	47	53	50
2 mm	40	43	44	42	37	34	37	34
0.425 mm	24	26	27	28	22	21	22	20
0.075 mm	12,5	13,2	14,0	14,6	11,6	11,1	11,2	10,1

Table 8. Base layer PI test results, site B.

PI	Requirements	Project specification	Avg PI Measured	CoV
PI (0.425 mm)	G1	4	5.9	13.6
PI (0.075 mm)	G1	12	10.8	5.1

Table 9. Base layer indicator, and moisture test results, Site C

	Layer thickness	MC (%)	OMC (%)	PI (0.425)	GM
G2 Requirements	n/a			≤6	
Findings	150	4.0	4.5	4	2.65

Table 10. Base layer indicator, and moisture test results, site D.

	Layer thickness	MC (%)	OMC (%)	PI (0.425)	GM
G2 Requirements	n/a			≤6	
Average Measured	116.9	5.2	6.9	6.1	2.4
Coefficient of variation	755.9	0.15	0.43	15.6	4.2

Average EMC/OMC ratio = 0.75.

Table 11. DMI test results.

Test	Requirements	Findings			
		Site A	Site B	Site C	Site D
Durability mill test (dry material test): Index	≤80	52	338	0.0	12.3
Product of maximum increase in PI and maximum increase in P0.425 mm. between the DMIdry and the DMIglycol soaked for 5 days (3)	≤7%	1.5%	13%	SP	NP

stone dolerite bases. DMI results are presented in Table 11.

The results of the single Durability Mill Index test carried out on a quarry sample (reference source) material from each of the Sites, A, C and D shows no signs of material being susceptible to significant breakdown.

For site B, the results of the single Durability Mill Index test carried out on a composite sample of the "failed" test pit materials show clearly that the material was susceptible to significant breakdown. Only the treatment with balls and no water produced a significant PI (13%) resulting in a DMI value of 338, considerably higher than that allowed even for a G1 basic crystalline material.

3.1.3. Plasticity Index: (Fines Method)

The plasticity test results of the fresh and old fines obtained from the quarry generally show values that meet the requirements specified in both [12] and [13].

3.1.4. Mineralogical Composition

Mineralogical results based on quantified X-Ray diffraction analyses for the Crushed Stone method are indicated in Table 13, and for the Fines method are indicated in Table 14.

The mineral composition of Investigated samples and Control samples for the Crushed Stone Method are indicated in Table 13. The results of the control samples are shown in parentheses. The results are also shown from Figures 3(a)-(d) presented as Control sample and Investigated sample.

The mineral composition of Investigated samples and Control samples for the Fines Method are indicated in Table 14 and shown from Figures 3(a)-(d) presented as Old fines and Fresh fines. The results of the control samples are shown

Table 12. PI tests results (quarry fines).

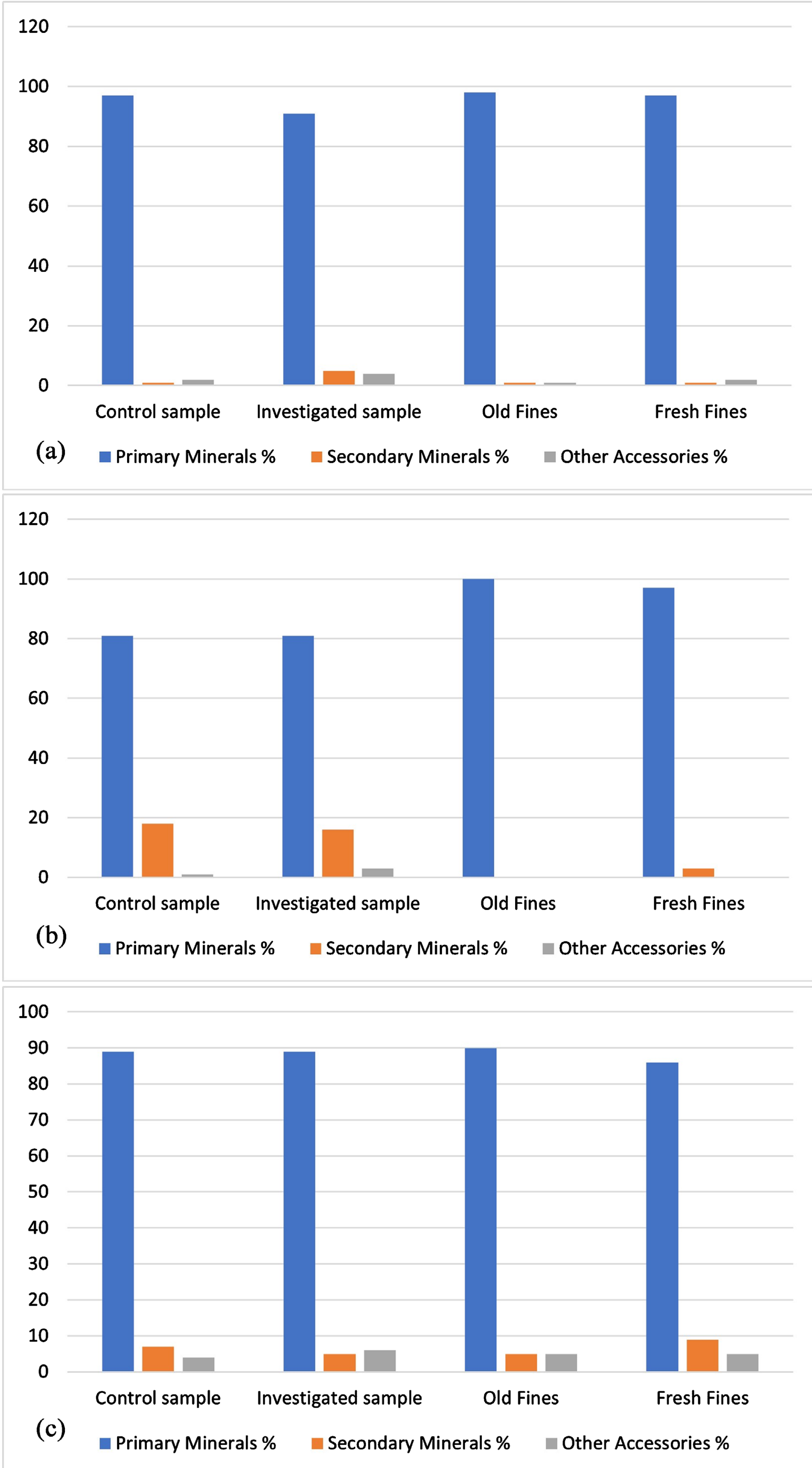
Site	0.425 mm requirements	Liquid Limit		Plasticity Index		Linear Shrinkage	
	LL: PI: LS	QFF	QOF	QFF	QOF	QFF	QOF
A	25:6:3	18	10	NP	NP	0	0
B	25:5:2	19	18	3	2	0	0
C	25:6:3	17	15	SP	NP	0.5	0
D	25:6:3	17	18	5	2	0	1

QFF: Quarry Fresh Fines, QOF: Quarry Old Fines.

Table 13. Mineral composition and quantification (crushed stone method).

	Site A	Site B	Site C	Site D
Amphibole	4 (2)		1 (1)	3 (0)
Clinopyroxene	19 (24)	8 (9)	17 (24)	28 (21)
Ilmenite	2 (2)		4 (2)	
Kaolinite	1 (-)		1 (1)	6 (9)
K-Feldspar	2 (3)	1 (2)	2 (-)	
Mica (muscovite),	4 (1)	2 (1)	4 (6)	Tc (4)
Plagioclase	63 (66)	56 (57)	66 (59)	50 (33)
Quartz	3 (2)	7 (5)	3 (5)	13 (33)
Talc	2 (-)		2 (2)	
Actinolite		1 (-)		
Calcite		2 (-)		
Chlorite		3 (-)		
Magnetite		- (1)		
Smectite		9 (15)		

Tc/tc: Traces.


120
100
80
60
40
20
0
Control sample
Investigated sample
Old Fines
Fresh Fines
(a)
Primary Minerals %
Secondary Minerals %
Other Accessories %
120
100
80
60
40
20
0
Control sample
Investigated sample
Old Fines
Fresh Fines
(b)
Primary Minerals %
Secondary Minerals %
Other Accessories %
100
90
80
70
60
50
40
30
20
10
0
Control sample
Investigated sample
Old Fines
Fresh Fines
(c)
Primary Minerals %
Secondary Minerals %
Other Accessories %

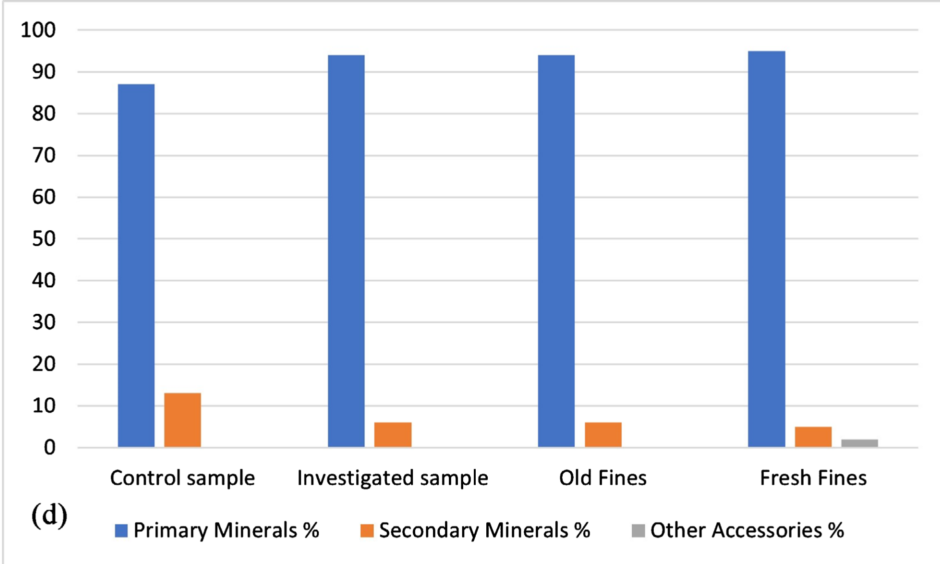


Figure 3. (a) Mineral composition and quantification (site A); (b) Mineral composition and quantification (site B); (c) Mineral composition and quantification (site C); (d) Mineral composition and quantification (site D).

Table 14. Mineral composition and quantification (fines method).

	Site A	Site B	Site C	Site D
Amphibole	2 (2)	- (tc)	2 (-)	0 (3)
Clinopyroxene	24 (24)	34 (23)	23 (27)	21 (17)
Ilmenite	1 (2)		3 (3)	
Kaolinite		Tc (tc)	Tc (1)	9 (5)
K-Feldspar	- (3)		- (2)	
Mica (muscovite),	1 (1)	Tc (3)	5 (8)	4 (tc)
Plagioclase	70 (66)	59 (66)	57 (52)	33 (69)
Quartz	2 (2)	7 (8)	8 (5)	33 (6)
Talc		- (tc)	2 (2)	
Actinolite				
Calcite				
Chlorite		3 (-)		
Magnetite		- (1)		
Smectite		9 (15)		

Tc/tc: Traces

in parentheses.

3.1.5. Additional Testing (Clay Analysis)

The mineralogical analyses on some samples were carried out only on crushed powder samples and none showed any smectite. As smectite is the most problematic mineral in dolerites, additional testing on which XRD analysis was carried out on the minus 0.075 mm fraction for clay analysis was conducted. Clay analyses results for the Investigated and Control samples from the Crushed Stone method are indicated in Table 15, and for the Fines method are indicated in Table 16. The results of the control samples are shown in parentheses.

The clay analysis of the Investigated samples and Control samples for the Fines Method are indicated in Table 16. The results of the control samples are shown in parentheses.

4. Comparison of Methods

Findings from the two methods that were followed for investigation were compared.

Table 15. Clay Analysis (crushed stone method).

	Site A	Site C	Site D
Quartz low	3 (4)	4.2 (3.3)	14.3 (27.0)
Anorthite (Sodian),	47.4 (43.4)	47.6 (47.2)	37.4 (29.2)
Diopside	29.8 (35.0)	30.9 (34.0)	19.8 (14.6)
Clinochlore llb-2	0.4 (0.0)	0.1 (0.2)	6.4 (5.5)
Enstatite (Ferroan)	18.4 (18.3)	11.0 (10.0)	18.9 (19.0)
Muscovite 2M1	0.9 (2.1)	3.4 (3.9)	1.6 (4.2)
Actinolite	0.1 (0.6)	0.1 (0.8)	1.0 (0.4)
Kaolinite	- (-)	- (-)	0.5 (0.2)
Talc 1A	0.1 (0.0)	0.1 (0.7)	
Palygorskite O		2.4 (-)	
Smectite	Tc (tc)		

Table 16. Clay Analysis (fines method).

	Site A	Site B	Site C	Site D
Quartz low	0.5 (0.4)	5.5 (6.3)	6.8 (3.4)	27.0 (7.8)
Anorthite (Sodian)	41.3 (43.4)	48.0 (46.6)	45.4 (51.2)	29.2 (36.6)
Diopside	34.2 (35.0)	19.1 (25.0)	33.3 (28.1)	14.6 (22.8)
Clinochlore llb-2	0.3 (0.0)	0.1 (1.4)	0.2 (0.1)	5.5 (1.5)
Enstatite (Ferroan)	21.9 (18.3)	19.5 (15.6)	9.9 (11.1)	19.0 (28.4)
Muscovite 2M1	0.9 (2.1)	0.4 (1.8)	2.7 (5.7)	4.2 (0.6)
Actinolite	0.1 (0.6)	0.1 (0.1)	1.6 (0.1)	0.4 (2.1)
Kaolinite	- (-)	- (-)		0.2 (0.1)
Talc 1A	0.8 (0.0)	0.1 (-)	0.1 (0.2)	
Palygorskite O	0.1 (2.3)		- (-)	
Smectite	- (tc)	7.1 (-)		

Table 17. Comparison of the crushed stone base and quarry fines methods.

Test	Crushed stone base Method (Road sample VS Quarry sample)	Results Quarry Fines Method (Old Fines VS Fresh Fines)
Atterberg Limits	PI values higher than the specifications were identified in samples obtained in wet and moderate climatic regions.	The PI values of samples obtained in wet and moderate climatic regions generally showed values that met the requirements.
	The plasticity test results of samples obtained in the dry region generally showed values that met the requirements.	The plasticity test results of samples obtained in the dry region generally showed values that met the requirements.
XRD (Site A)	Two new minerals were identified in an investigated sample. One of those minerals was a secondary mineral (clinochlore), an alteration product of clinopyroxene; however, it does not have high swell potential. Traces of smectites, an alteration product of pyroxene were identified in both control and investigated samples	Two new minerals were identified in an investigated sample. One of those minerals was a secondary mineral (clinochlore), an alteration product of clinopyroxene; however, it does not have high swell potential. Traces of smectites were identified in the control sample. No Traces of smectites were identified in the investigated sample.
XRD (Site B)	Two new minerals were identified in the road sample. One of them was a secondary mineral (chlorite), an alteration product of clinopyroxene. Smectites, an alteration product of pyroxene were identified in both control and investigated samples.	There were new minerals identified. Significant quantities of smectite were evident in the investigated sample. Smectites are an alteration product of pyroxene (and possibly plagioclase) in the form of clay. No signs of smectite identified in the control sample.
XRD (Site C)	No signs of alteration identified.	No signs of alteration identified.
XRD (Site D)	No signs of alteration. The Secondary minerals detected in the investigation sample were already in the control sample and they do have high swelling potential	No signs of alteration. The Secondary minerals detected in the investigation sample were already in the control sample and they do have high swelling potential.

The comparison is indicated in Table 17.

Discussion

- **Crushed dolerite base Method**: In wet and moderate areas, there were signs of alteration evidenced by the identification of new secondary minerals in the samples investigated. Secondary minerals (smectites) with high swelling potential and plasticities were already part of the fresh dolerite (control sample). The PI values of the investigated samples were unacceptable for crushed stone aggregate as the values mostly exceeded the specified limits.

In dry areas, there were no signs of alteration identified in the samples investigated. The secondary minerals were already part of the fresh dolerite. The PI values were acceptable as the values were within the specified limits. The presence of secondary minerals and high moisture content did not affect the PI requirements.

- **Fines Method**: In wet and moderate areas, there were signs of alteration evidenced by the identification of new secondary minerals in the samples investigated. Samples for this method were all obtained from the quarry (source). Smectites were also identified in either control or investigated sample. The presence of smectites, however, did not affect the PIs, which were within the specified limits. This could be due to the conditions where the fines exposed were not the same as crushed dolerite base. The material was not in-service. In addition to the atmospheric influences, material properties can be influenced by the other factors that include traffic loading, pavement moisture content, drainage conditions, temperature, etc.

In dry areas, there were no signs of alteration identified in the samples investigated. The secondary minerals were already part of the fresh dolerite, and they had no swell potential. The PI values were acceptable as the values were within the limits. According to the durability requirements of [2] it is clear that what is generally accepted, is that the secondary minerals were already part of the fresh dolerite. In this case, the presence of secondary minerals and high moisture content in the investigated samples did not affect the PI values.

The mineralogical findings using both methods were slightly different. The Fines method only revealed problematic dolerites (an indication that the source contains smectite) and non-problematic dolerites. There are no clear signs of alteration revealed by this method. This could be due to the conditions where the fines exposed were not the same as the crushed dolerite base. The material tested was not from in-service bases. In addition to the climatic effects, material properties can be influenced by other factors that include traffic loading, pavement moisture content, drainage conditions, temperature, etc).

The Crushed dolerite base Method revealed problematic dolerites and clear signs that alteration took place in dolerites that have a potential to alter. Alteration could not have affected the PIs and influenced the deterioration significantly as the alteration products were found to have no swell potential, but the availability of swelling secondary minerals (smectites) in the material inherited from the source affected the PIs and could lead to deterioration. Samples that inherited secondary minerals with no swell potential showed acceptable PI values. Samples that inherited secondary minerals that included smectites showed unacceptable PI values.

It can be concluded that both methods revealed that the problematic dolerites inherited the secondary minerals (smectites) with swelling potential from the original material sources (control samples).

There were no problems in engineering material properties revealed by the fines method. This could be due to the conditions where the fines exposed were not the same as crushed dolerite base. The material was not in-service.

It must be noted that it is not only mineral composition that influences deterioration of dolerite when it is in service as some secondary minerals do not have high swell potential, but other engineering properties of material might have an impact. In dry areas, no mineralogical alteration took place: however, material deterioration had taken place. According to [18], the temperature variation directly influences the stiffness of the overlying bituminous surfacing layers, which alters the stress, strain and deflection conditions through the pavement. That could lead to the loss of particle interlock and affect the performance of the crushed dolerite base.

The grading of nearly all samples was out of specification. It is expected that slushing should remove a large percentage of the fines from the road; however, it is not always the case because some samples exhibited a large quantity of fines that exceeded the upper limit of the specification.

Of particular interest, was the fact that many of the samples tested showed no smectite presence. This is an important finding, as it is generally believed in South Africa that almost all basic crystalline rocks, especially dolerites, have an inherent smectite content. Additional X-ray diffraction testing was carried out to ensure that the first indications of this were correct.

5. Conclusions

The conclusions below are made based on the outcomes of the study:

There was deterioration of dolerite used in base course of road pavements located in wet and moderate areas. It was evidenced by the availability of swelling secondary minerals (smectites) in the material inherited from the source. Smectites were released from the aggregate particles during construction and trafficking and affected the PIs when material was in service. The alteration of primary minerals to secondary minerals could not have affected the PIs and influenced the deterioration as the alteration products were found to have no swell potential.

Alteration observed in wet and moderate areas did not affect the PIs, but the availability of smectite inherited from the source materials affected the PIs. Samples that inherited secondary minerals with no swell potential showed acceptable PI values in service. Samples that inherited secondary minerals that included smectites showed unacceptably high PI values. The distribution of fines after slushing is unknown, but it is expected that slushing should remove a large percentage of the fines (including clays already present in the crushed material) from the road. This suggests future research on changes undergone by material after construction.

According to [2] the amount of secondary minerals acceptable in fresh rock should be less than 15% in wet areas, increasing to up to 80% in dry areas ($N > 7$). The amounts of smectites detected in the investigated samples were still within the permissible limit, but were found to have triggered the deterioration of road pavements built with dolerite. Research that will be based on adjustment of durability lines should be considered.

High average moisture contents measured in wet and moderate areas were probably due to the ingress of water through the cracking that was present. The ingress of water could encourage swelling in smectites contained in the material, and that would have led to some of the failures.

It is proven that the low plasticity in crushed dolerite is not necessarily an indication of the absence of deleterious minerals available in the material. One of the fines samples with significant amounts of smectite registered PIs that met the specification.

An interesting conclusion was that, contrary to conventional wisdom, not all of the dolerites investigated contained discernible smectite contents.

6. Recommendations

Based on the findings and results of the study, the following recommendations are made:

- In wet and moderate areas, the presence of secondary minerals with high swell potential in dolerite can affect the PI values when material is in service regardless of amount present. Therefore, the secondary minerals accepted in crushed rock should not include smectites, and Weinert's durability limits should be considered only as a guideline.
- Stabilisation of crushed dolerite base with a small amount (1%) of lime (or cement) should be considered when dolerites are used, even if the percentage of smectite content is within the permissible limit specified by [13] to ensure that materials will perform well when in a road pavement.
- Not only standard engineering properties should be determined when assessing the suitability of dolerite for base course, but mineralogical composition should be included. One set of tests alone (either engineering or mineralogical) does not fully reveal the overall properties of material.
- Requirements for G1, G2, and G3 materials are specified in [13]. Expectations on material after construction should be clarified better. The distribution of fines after slushing is unknown, but it is expected that slushing should remove a large percentage of the fines (including clays already present in the crushed material) from the road. The as-built records of dolerite base courses should include full testing of material for engineering properties, and durability in particular.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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