A NEW APPROACH TO ASSESSING THE DURABILITY OF BASIC CRYSTALLINE ROCKS AS ROAD AGGREGATES

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ABSTRACT

Despite ongoing research covering more than 60 years in southern Africa, the assessment of the potential durability of basic crystalline rock aggregates for use in road construction is still a major problem. Over the years various innovative test methods and specifications have evolved to the point where currently, more than half a dozen tests are carried out with specifications for each. Frequently, the materials pass most of the tests but may be rejected by one or two, leading to indecision about their use and often probably incorrect rejection of a potentially useful material source. This paper describes the development of a weighted durability rating system, as used in a variety of road engineering disciplines, to quantify the potential durability and allow a better- informed decision on the material usage.

1. INTRODUCTION

More than 60 years ago the problem of “degrading” dolerite in crushed stone bases produced from “unweathered” material was identified in South Africa (Weinert, 1964). Significant research has been carried out since then to identify suitable tests and limits to eliminate the problem (Weinert, 1980; Orr, 1979; Van Rooy, 1991; Haskins & Bell, 1995; Paige-Green, 2007; Paige-Green, 2008; Kleyn et al., 2009; Leyland, 2014, and many others).

The primary cause of poor durability of basic crystalline rocks (BCRs) is the presence of smectite group clays in the materials, either formed by deuteric alteration of the original igneous material (lava) (Haskins & Bell, 1997) or through subsequent weathering of the material (Weinert, 1980). These clays are prone to expansion in the presence of water and if the induced expansive forces exceed the tensile strength of the surrounding material, fracture and disintegration will occur, with a resultant increase in PI, reduction in shear strength and eventually premature failure.

Findings from these research activities have been included in local specifications (COLTO, 1998; COTO, 2020) but testing of materials often produces conflicting results making the selection of materials difficult and usually resulting in rejection of potentially good material sources such that users rather err on the conservative side.

This paper reviews some of the work leading up to the most recent specifications and proposes a weighted rating system to take the wide range of recommended tests into account when assessing basic crystalline rocks for use as road aggregate.

2. CURRENT TESTING STATUS QUO

The current standard specification for aggregates in South Africa (COTO, 2020) includes a range of test methods and specifications. Tables A4.1.5-5 and A4.1.5-6 in COTO (2020) specify the normal material requirements for crushed aggregates and gravels and refer to other tables (A4.1.5-15 and A4.1.5.16) regarding durability. Section A4.1.5.16 (COTO, 220) shown below (Table 1) is specifically for basic crystalline rocks and is of primary interest in this paper. It should, however, be noted that certain properties such as flakiness and plasticity can be directly related to some of these durability requirements. For example, it has been shown that there is a strong relationship between aggregate flakiness and crushing test results (Ramsay et al., 1994).

Table 1: Durability of basic crystalline materials (Section A4.1.5.15, COTO, 2020)

Test [1]		***Requirement***	
		Base material	***Subbase material***
1. 10 % FACT[2] value after soaking in ethylene glycol for 1 day, compared to the dry value		≥ 80 %	≥ 70 %
2. Ethylene Glycol Durability Index (EGDI)	5 days soaking	EGDI < 10	EGDI < 15
	20 day : 5 day soaking ratio	Ratio < 1,5 if 20 day EGDI > 10	None specified
2. Durability mill test (dry material test):			
2.1 Index		≤ 80	≤ 125
2.2 Percentage passing 0,425 mm after the test		None specified	≤ 35
2. Product of maximum increase in PI and maximum increase in P0,425 mm, between the DMIdry and the $DMI_{glycol\ soaked\ for\ 5\ days}$ [3]		≤ 7	None specified
3. Smectite content using the Spot Counting[4] and/or the Rietveld quantitative XRD (X-ray diffraction) tests		≤ 5 %	None specified
3. Percentage secondary minerals as in the publication "The natural road construction materials of Southern Africa", by HH Weinert		Durability lines in Table 11 on page 95 of the publication	

Notes:

(1) Tests to be carried out in sequence of numbering. Results in a set to be assessed, thereafter samples that fall way below (or above) the limiting values shall be disqualified without further testing.

(2) i) 10% FACT can be estimated from the Aggregate Impact Value (AIV) (test method BS 812-112:1990):
10% FACT = 10(2,915 – 0,03AIV)
ii) After soaking, rinse aggregates with water followed by immediate towel drying and air drying at temperatures not exceeding 70 °C.

(3) i) Gradings of samples shall be identical.
ii) Soaking only of material retained on the 2,0 mm sieve.
iii) After soaking, rinse and dry material as for 10% FACT.

(4) Spot Counting test to be carried out by an experienced geologist.

Also included in the COTO (2020) specification is the following section (Table 2). For all other aggregate types (different requirements for the 10%FACT wet/dry ratio and the Durability Mill Index (DMI) are specified. The ratio of wet/dry 10%FACT of 75% is often applied to Basic Crystalline Rocks (BCR) as an additional property, based on the original work of Weinert (1980) as discussed below. This section also makes it clear that in wet areas (N<2) all BCRs shall be treated with lime.

Specifications such as these shown above shall be fully complied with in practice, and should one or two of these numerous criteria fail, the material must be rejected. However, it has been noted that even when most of the critical criteria are complied with, but the smectite contents are marginal the materials are rejected. This problem needs to be overcome and is the objective of this paper.

Table 2: Durability of other materials (Section A4.1.5.16, COTO, 2020)

Rock Group	*10%FACT Wet/dry ratio(1) minimum*	*Durability Mill Test*	
		Index (maximum)	*% passing 0,425 mm sieve after the test (maximum)*
Acid crystalline, high silica and carbonate rocks	*75*	*420*	*35*
Arenaceous rocks with a siliceous cementing matrix (quartzitic sandstone)	*75*	*125*	*35*
Arenaceous rocks with non-siliceous material (not to be use for types G1 and G2 material)	*75*	*125*	*35*
Diamictites	*70*	*125*	*35*
Calcretes	*60*	*480*	*40*

Notes:

(i) Materials with a 10%FACT wet to dry ratio of less than the minimum ratio, except for calcrete, may be used, provided that the soaked value is equal to or more than the specified dry limit in Table A4.1.5-6.
(ii) All other rocks: Disintegration of all rocks is the predominant form of weathering, and the durability of compliant crushed rocks shall comply with the requirements in Table A4.1.5-16.

2.1 Test Methods

The test methods used for identification of durability have evolved over time from simple petrographic analyses to more specific methods using ethylene glycol to accelerate material degradation, as discussed below:

Mineralogy: The mineralogy and their distribution/texture in the aggregate material is the primary cause of durability problems, usually related to the smectite content. Typically, an X-Ray Diffraction (XRD) test is carried out (using about 1g of material) and the mineralogy (including clays) is identified. To ensure that the smectite is differentiated from other clay mineral types, various treatments are often necessary, particularly glycolation of smectites and heat treatments. This should always be requested from the XRD service provider when evaluating the clay mineralogy of aggregates.

The XRD analysis should also be accompanied by a petrographic analysis of thin sections of the material to determine the overall material mineralogy and to observe whether there is any indication (and its extent) of mineral alteration and what primary minerals are affected.

XRD analyses are notoriously known for their poor quantification of smectite contents (Leyland et at., 2015) and the smectite contents should be considered with some circumspection.

Secondary Mineral Content: This is carried out on the thin section petrographic slides described above under a microscope using a point counting apparatus and should be done by a trained geologist (Weinert, 1980:123). The method, however, does not discriminate between deleterious (e.g., smectites) and innocuous secondary minerals (i.e., iron oxides, illite, kaolinite, etc.) In fact, smectite is generally colourless and/or isotropic in thin section (Dana, 1949) and has particles less than 0,002 mm in size, which are almost impossible to discern, even under a conventional petrographic microscope. Petrographic analyses should be done on at least 3 slides with a total aggregate volume investigated of about 0,04 cm^3 each. In other words, about 1 cm^3 of each material source (core, truckload, stockpile, etc.) is actually investigated.

The quantity of secondary minerals has been related (Weinert 1980) to the material acceptability by the "durability line" as a function of the climate with increasing allowable secondary minerals as the climate (Weinert N-value) becomes drier (Figure 1).

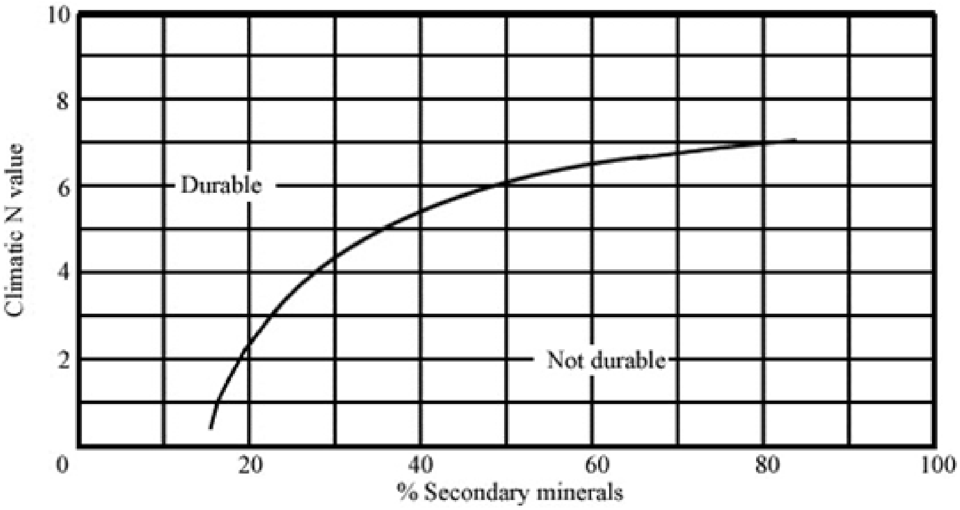

Figure 1: "Durability line" for base course aggregate (after Weinert 1980)

Pick and Click: Weinert (1980:131) described this test which requires a visual assessment of the materials "colour and lustre", "hardness and consistency" and "state of crystallization" and rating of each on a scale of 1 to 4. The sum of these gives an indication of the state of weathering and the potential durability of the material. However, although a larger sample is assessed than in the secondary mineral counts, the result can be somewhat subjective.

10% Fine Aggregate Crushing Test (10% FACT)*:* This was the original South African test for "durability" with a comparison of the wet and dry strengths and a minimum dry strength (Weinert, 1980) and still comprises part of the standard specification. The test result is based on only a single fraction of the material (9,5 to 13,5 mm - now 10 to 14 mm) and requires at least 9 kg of this fraction per single test excluding water and glycol soaking).

Although not a direct indication of durability it does relate to the effect of water on the aggregate strength. With the combination, however, of ethylene glycol to "activate" the problematic expansive smectite minerals, it does become more of a durability test. Many specifications now include glycol-soaked samples in the test regime. However, research has indicated that the washing of the glycol-soaked samples with water prior to the 10%FACT test can lead to a significant deterioration of the material (Fielding & Maccarrone, 1982; Leyland et al, 2013).

Durability Mill Index (DMI): This test was developed in the 1980's following increasing durability problems with various rock types in South Africa (Sampson & Netterberg 1989). This showed good results with many materials, but some basic crystalline rocks continued to indicate problems in service. The test was subsequently extended by including a sample where the fraction retained on the 2 mm sieve is soaked in ethylene glycol for 5 days prior to testing (COTO, 2020). The test makes use of the plasticity index generated by abrasion of the material in a wet environment, this plasticity being related to the clays released from the aggregate.

COTO (2020) includes a glycol-soaked sample used in the DMI. This is soaked for 5 days and the Fineness Product (FP = PI x percentage passing 0,425 mm) of the result is compared with the FP of the dry sample.

Modified Ethylene Glycol Durability Index (mEGDI)*:* Following the problems with materials passing the DMI which failed in service, the modified ethylene glycol durability test was developed (Paige-Green, 2008; Paige-Green & Leyland, 2013). Many ethylene glycol tests were being used at the time, but few allowed a quantitative estimate of the result. The test was developed to do this and tests 40 random samples from each source. Tentative specification limits were proposed.

Plasticity Index (PI): Smectite clays have a significantly higher Plasticity Index than other clay minerals and the PI of a material can thus be a useful indicator of potential problems. Typically, the PI should be carried out on the natural fines of the material produced during quarry processing (on both the 0,425 mm and 0,075 mm fractions) as well as on the fresh aggregate material crushed to produce a 0,075 mm powder.

Water Absorption: A relationship between water absorption and durability has been identified for materials other than basic crystalline rocks (Paige-Green, 1984). The water absorption is related both to porosity of the material (i.e. ease of penetration of water into the material to promote decomposition of the aggregate) as well as the propensity of the minerals, especially the clay minerals, in the rock to absorb water.

Other Tests*:* Other tests such as the methylene blue absorption, sulphate soundness and Los Angeles abrasion have been used to identify durability or the presence of smectite in aggregate. The results and methods are often highly variable, little performance-related information is available and the tests are often cumbersome and messy. These are not considered locally but some could be considered for use.

3. DISCUSSION

It is clear from typical test results that even if most, but not all, of the “necessary” specifications are met, materials would be rejected for use, particularly on the grounds of the “high” smectite contents, which appear to be the main concern of many engineers.

The use of rating systems using weighted input parameters is not unusual in civil engineering and a typical example is that for identifying dispersive soils (Bell & Walker, 2000). Other applications are in road asset management, visual condition surveys, vulnerability assessments, etc. Such rating systems consider the wide range of properties with emphasis on the test results most closely indicating the potential problems and considering interactions between these tests and the fundamental problems.

In a similar vein to other rating systems, the following tentative assessment method (Table 3) is proposed using the 12 relevant material properties now included in the COTO (2020) specifications with proposed ratings (weightings) based on the accuracy and relevance of the test method, experience, and the associated interactions.

Table 3: Proposed durability rating system

Test	Class and Rating				Fatal Limit
DMI	Class	<90	90 - 100	>100	**>250**
	Rating	0	2	5	-
DMI dry test	Class	<80	80 - 120	>120	**>180**
	Rating	0	2	4	-
DMI (max PIxP425 between dry and 5 day glycol soaked)	Class	<7	7 - 10	>10	**>15**
	Rating	0	2	4	-
10%FACT	Class	>150	110 - 150	<110	**< 90**
	Rating	0	3	5	-
10%FACT wet	Class	>150	110 - 150	<110	**< 80**
	Rating	0	2	5	-
10%FACT w/d ratio	Class	>80	70 - 80	<70	**< 60**
	Rating	0	1	4	-
10%FACT 24h glycol (% of dry)	Class	>80	70 - 80	<70	**< 60**
	Rating	0	3	4	-
EGDI 5 d soak	Class	<10	10 - 15	>15	**>20**
	Rating	0	3	5	-
EGDI 20 day	Class	<10	10 - 20	>20	**>30**
	Rating	-	-	-	-
EGDI 20:5 day	Class	<1,5	1,5 - 2,0	>2,0	-
	Rating	0	4	5	-
Smectite (%)	Class	<5	5 - 10	>10	**>20**
	Rating	0	3	6	-
Plasticity Index (0,425mm %)	Class	<4	4 - 6	>6	**>10**
	Rating	0	2	5	-
Plasticity Index (0,075mm %)	Class	<8	8 - 12	>12	**>15**
	Rating	0	2	5	-
Water absorption (%)	Class	<1	1 - 2	>2	**>2,5**
	Rating	0	2	4	-
Durability		**Good**	**Warning**	**Poor**	**-**
		<15	**15-30**	**>30**	**-**

Notes:

(1) The wet/dry and 24h glycol soaked 10%FACT ratio “fatal” rating should be ignored if the water or glycol soaked value exceeds 200 kN.

Limits have been placed on each property indicating a “fatal” result, in which materials failing this limit should be discarded from any further investigation. Typically, only the battery of 10% FACT tests would initially be carried out and those failing any of these requirements in terms of the “fatal” limit would indicate that no additional testing is warranted on the material. If it has not been possible to conduct all of the required tests but not more than 2 tests have been omitted, the overall durability ratings should be reduced by the respective weightings of these tests. If more than 2 of the properties are not determined, the rating should not be used - however, this means that the testing programme has not complied with the requirements of COTO 2020.

4. RESULTS

A selection of some recent test results is provided in Table 4 as an indication of typical material properties of a dolerite from a single potential quarry. Six composite samples derived from crushed cores were used to carry out all the tests.

Table 4: Some recent test results on dolerites

Test	Specification	Result	Durability Rating		
			Mean result	95% confidence	Max/min result
CRUSHED STONE					
DMI	125	0	0	0	0
DMI dry	125	22 - 23	0	0	0
DMI (max PIxP425 between dry and 5-day glycol soaked)	7	-			
10%FACT (dry)	110 kN	213 - 282 kN	0	0	0
10%FACT (wet)	83 kN (0,75*110)	117 - 200 kN	0	0	0
10%FACT (wet/dry)	75%	70 - 89%	0	4	1
10%FACT (4-day glycol/dry)	1 day - 80% of dry	41 - 76%	3	3	3
mEGDI (5 days)	<10	0 - 1	0	0	0
mEGDI (20: 5-day ratio)		4,5 - 9,0	0	0	0
Smectite content	< 5%	9,1 - 12,8%	2	4	4
Plasticity Index (<0,425 mm)	0 or < 4%	0	0	0	0
Plasticity Index (<0,075 mm)	< 8%	0 - 4%	0	0	0
Water absorption (%)	1	10 -17%	0	0	0
Durability total			**5**	**11**	**8**
Durability Rating			**Good**	**Good**	**Good**

The first assumption was to “fail” or discard this material due to the marginal smectite contents. However, assessment of the remaining results indicated that the material shows no other potential problems. Use of the proposed durability rating system classifies the material as good. The mean, worst and 95% confidence (mean ± 2 Standard Deviation/SQRT(n-1)) values all classify the material as having a good durability.

The system has been tested on other recently sampled borehole materials. Table 5 analyses the results from 101 samples including some obviously weathered materials, using the mean, 95% confidence and worst results. It is clear that the majority of the materials pass the criteria, but the worst materials are immediately indicated as poor.

The results obtained by Leyland (2014) based on various roads, performing both poorly and well, have also been analysed as shown in Table 6.

The average of all materials shows mixed results but indicate that the 95% confidence values and worst results are better indicators of performance than the mean results. However, it is better to assess the results individually as shown in Figure 2.

Table 5: Test results from 101 different dolerites

Test	Specification	Result			Durability Rating		
		Range	Mean	95% Conf	Mean result	95% Conf	Worst result
QUARRY SAMPLES							
DMI	125	0 - 242	4,8	0	0	0	5
DMI dry	125	0 - 192	5	0	0	0	4
DMI (max PIxP425 between dry and 5-day glycol soaked)	-	-	-	-	0	-2	-2
10%FACT (dry)	110 kN	74 - 528 kN	322	304	0	0	5
10%FACT (wet)	83 kN (0,75*110)	56 - 488 kN	247	233	0	0	5
10%FACT (wet/dry)	75%	52 - 98%	87	86	0	0	4
10%FACT (24 h glycol/dry)	80% of dry	26 - 95%	62	57	4	0	4
mEGDI (5 days)	<10	0 - 8	1,13	5,9	0	0	0
mEGDI (20: 5-day ratio)	-	1 - 5,6	1,4	2,7	0	5	5
Smectite content	<5%	1,4 - 16,6%	10,4	9,5	6	3	6
Plasticity Index (<0,425 mm)	0 or <4%	0 - 13%	0,9	0,7	0	0	5
Plasticity Index (<0,075 mm)	<8%	0 - 20%	1,6	0,6	0	0	5
Water absorption (%)	1	0,08 - 0,66%	0,3	0,3	0	0	0
				Durability Total	**10**	**6**	**44**
				Durability Rating	**Good**	**Good**	**Poor**

Table 6: Application of rating system to materials investigated by Leyland (2014)

Test	Specification	Result			Durability Rating		
		Range	Mean	95% Conf	Mean result	95% Conf	Worst result
QUARRY SAMPLES							
DMI	125	28 - 166	61,5	49	0	0	5
DMI dry	125	0 - 90	17	9	0	0	0
DMI (max PIxP425 between dry and 5-day glycol soaked)	-	-	-	-	0	-2	-4
10%FACT (dry)	110 kN	232 - 494 kN	397	376	0	0	0
10%FACT (wet)	83 kN (0,75*110)	63 - 492 kN	317	281	0	0	5
10%FACT (wet/dry)	75%	17 - 103%	78	71,5	1	2	4
10%FACT (24 h glycol/dry)	80% of dry	17 - 121%	78	69,9	3	4	4
mEGDI (5 days)	<10	0 - 58	10	5,7	3	0	5
mEGDI (20: 5-day ratio)	-	1,2 - 2,1	1,6	1,5	4	4	5
Smectite content	<5%	0 - 27%	7,5	5,1	3	3	6
Plasticity Index (<0,425 mm)	0 or <4%	0 - 6%	1,9	1,4	0	0	2
Plasticity Index (<0,075 mm)	<8%	0 - 12%	3,0	0,75	0	0	5
Water absorption (%)	1	0,5 - 1,0%	0,8	0,76	0	0	0
				Durability Total	**14**	**11**	**40**
				Durability Rating	**Good**	**Good**	**Poor**

The average of all materials shows mixed results, but the data indicates that the 95% confidence values and worst results are better indicators of performance than the mean results. However, it is better to assess the results individually as shown in Figure 2. This figure shows the data obtained from the drilled cores (shown as core in legend) as well as those from Leyland (2014) (shown as RL in legend).

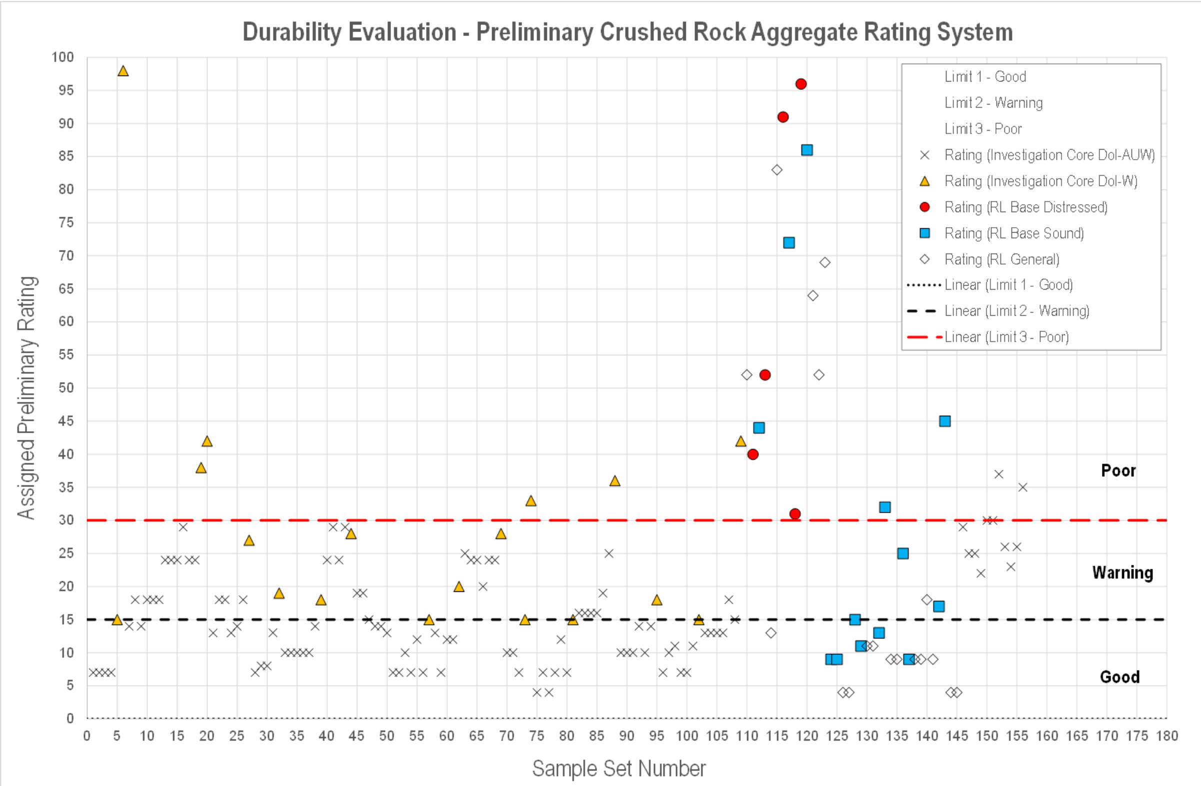

Figure 2: Plots of durability ratings for all samples

It is noted that some of Leyland's sound materials have high ratings, probably indicating good drainage or dry conditions, or low trafficked areas, and although sound at the time of sampling could fail in future.

5. CONCLUSIONS

The ongoing problems with identifying potentially non-durable basic crystalline rocks have led to the rejection of numerous potential dolerite sources with concomitant increased construction costs related to longer aggregate haul distances. Most of these rejected materials are related to "high" smectite contents, irrespective of how the smectite is incorporated within the mineral structures and "overriding" other test results, many of which are probably more relevant and appropriate.

A weighted rating system consisting of the 12 test parameters currently specified in South Africa for the durability of basic crystalline rocks is proposed. This system reduces the influence of single or a few test results in approving crushed dolerite aggregate for use in roads and requires no additional testing to that already required by the standard specifications.

6. RECOMMENDATIONS

It is proposed that this rating system is "tested" on various aggregate sources being assessed or developed for roads for confirmation of its use or for modification of weightings and properties where necessary. It is also recommended that any roads constructed using basic crystalline rocks that fail prematurely be sampled and tested and the results compared with the proposed durability limits.

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