Durability testing of basic crystalline rocks and specification for use as road base aggregate

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Abstract:

One of the most important materials for the construction of high quality pavement layers in roads in South Africa is the Basic Crystalline group of rocks. The major deposits of these materials are associated with the dolerites and basaltic lavas of the Karoo Supergroup. Problems related to the in-service deterioration of road aggregates produced from the crushing of these materials, despite their conforming to the necessary specifications, have been experienced in southern Africa for many years. This has usually resulted in the use of more expensive materials being transported further to the road project.

An investigation in which 12 such materials were collected from various areas of southern Africa and tested for their durability using the standard specified tests as well as a range of non-standard and new tests was carried out. Based on the results, new test methods and tentative specification limits have been proposed for assessing and predicting the durability of basic crystalline materials obtained by crushing unweathered material sources for more confident use.

Keywords:

Road, aggregate, basic crystalline rock, durability

Résumé

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Mots clés

Introduction

The construction and maintenance of paved roads requires large quantities of rock materials. A typical pavement layer (of which a road carrying high traffic volumes can consist of up to 5 or more layers beneath a bituminous seal) requires about 2000 m^3 of selected material per kilometre. The most important layers in paved roads are the upper ones, primarily the base course, which distributes the loads applied by traffic to avoid overstressing of the weaker materials beneath it. In most cases the base course consists of a high quality aggregate produced by quarrying and crushing selected rock material.

Roads in South Africa are typically designed to provide a service of 20 years during which time deterioration of the materials used in the pavement layers should be minimal, ie, they should be durable. The most widely used crushed aggregates for road pavements in South Africa are those derived from the Basic Crystalline group of rocks as described by Weinert (1980) and include, among other rock types, basalt, dolerite, diabase (this term is currently being phased out in South Africa as the material is essentially identical to dolerite)and gabbro. These materials contain no quartz and are comprised of minerals that have the propensity to weather and deteriorate to relatively unstable secondary minerals (mostly clays) under appropriate environmental conditions. The raised temperature and moisture conditions within road pavements are particularly conducive to rapid deterioration of such materials, resulting in an aggregate that is considerably weaker and more moisture sensitive to any applied stresses.

Although various techniques for the assessment of their durability are specified for local use, past experience with these materials in South Africa has resulted in their use with caution. Frequently, more costly materials are hauled to the construction site over longer distances in preference to using local basic crystalline materials. This added haulage cost can more than double the cost of construction of a base course, which would typically be about US$58 000 per kilometre.

This paper discusses a programme to investigate test methods for better prediction of the durability of basic crystalline materials using innovative tests not routinely applied to construction materials. The findings are expected to allow practitioners to make more confident selection of road construction aggregates with the associated cost savings.

Background

A review (Paige-Green, 2004) of more than 65 publications related to aggregate durability indicated that the problem of poor durability of road aggregates in general was identified in the USA during the 1880s and various tests to identify materials prone to deterioration were developed or adapted from other uses. During the early 1900s problems particularly associated with basic crystalline rocks were reported in the United States and Europe and related to the presence of secondary minerals (clays).

During the early 1960s, a number of problems with the use of basic crystalline materials in roads in South Africa occurred. Weinert of the then National Institute of Road Research, CSIR, investigated these in detail and carried out detailed field and laboratory evaluations culminating in various recommendations for durability testing (Weinert, 1964; 1970; 1980; 1984).

Any igneous material that crystallizes under high temperature conditions is inherently unstable under current atmospheric conditions and the minerals therein slowly convert to secondary minerals that are better in equilibrium with their surroundings. This is the result of chemical reactions such as hydration, hydrolysis, oxidation, reduction and carbonation. The resulting clayey minerals tend to be water sensitive and have low shear strengths, thus reducing the bearing capacity of the pavement structure. Weathered materials can usually be easily identified in the field by their reddish or orange colour, which results from the oxidation of iron, and can thus be avoided for use as high quality materials. The selection of the typical dark grey to blackish material, containing predominantly primary minerals, for processing as an aggregate is thus relatively straightforward.

Over the years, a wide range of test techniques and specifications, pertaining to specific material groups and not limited to basic crystalline materials has been identified and implemented. Despite this, many cases of road failure related to poor durability have been recorded resulting in a lack of confidence in the test methods (and thus the materials accepted) and increased road construction costs as “better” materials are imported from further away.

The majority of the southern African basic crystalline rocks used (or which are potentially available) for road construction are basalts or dolerites belonging to the Karoo Supergroup. Although having an unweathered appearance, many on these materials have proved to be non-durable, deteriorating in service (Orr, 1979). However, although only limited investigations of natural weathering rates of basic crystalline materials have been carried out, it has been concluded that weathering processes take place over time scales of decades to many thousands of years.

How then do materials deteriorate during the service life of a pavement, which is usually 20 to 30 years? Research (Orr, 1979; Haskins and Bell, 1995) has shown that many of the dolerites and basalts of the Karoo Supergroup have been subjected to deuteric alteration during their cooling and crystallization as a result of vapours and volatiles derived from the magma itself moving through the cooling rock mass. This has caused some of the primary minerals in the rock to partially alter to active (swelling) clays of the chlorite and smectite groups. These minerals are not associated with significant discolouration of the rock and are thus part of an apparently unweathered material.

Weinert (1980) recognised the importance of secondary minerals and related their percentage obtained from point counting of thin sections to the durability of basic crystalline materials. Essentially, the drier the climate becomes, the greater the percentage of secondary minerals permitted in base materials with only up to 15 per cent secondary minerals being permitted in wet areas. In dry areas, between 75 and 100 per cent secondary minerals are permitted.

Current specifications

The majority of major roads in South Africa are built to the requirements of the Standard Specifications for Roads and Bridge Works for Road Authorities (COLTO, 1998). This specification for crushed stone specifies that the aggregate "shall not contain any deleterious materials such as weathered rock, clay, shale or mica". This is an ambiguous and wide statement and would theoretically exclude the majority of South African rock materials from use as crushed aggregate for base on the basis of their clay contents.

These specifications also make specific reference to durability requirements for natural gravel and crushed stone and are based on various test methods with limits primarily suggested by Weinert (1980), Paige-Green (1980), Venter (1980) and Sampson (1990).

The test techniques specified include the 10% Fines Aggregate Crushing Value (10%FACT) which is a wet and dry crushing test, the Durability Mill Index (Sampson and Netterberg, 1989), which is a wet abrasion and impact test and a water soaking disintegration test. For basic crystalline materials in particular, only the Durability Mill Index specifically caters for its unusual characteristics.

Summarising the current specification limits, basic crystalline materials should have a maximum Durability Mill index of 125, not more than 35 per cent passing 0.425 mm after the test, a minimum dry 10%FACT of 110 kN and a minimum ratio of the wet to dry 10%FACT of 75 per cent.

These limits, unfortunately do not take into account the unique property of many of these materials where potentially deleterious clays are incorporated into the primary minerals of the unweathered rock. During the last decade or so, work has been carried out using ethylene glycol to induce swelling of the deleterious clays, but the results have not been incorporated into any standard specifications and no properly defined test protocol using these techniques currently exists.

Experimental program and methods

Sampling

A field sampling and laboratory testing programme was developed that would investigate the durability properties of a range of basic crystalline materials that were reported or suspected to vary from good to poor durabilty. The sources of some of these samples were based on discussions with local practitioners with others selected to cover as wide a geographic area as possible. Material was sampled from operating quarries as well as from old quarries no longer in use from five provinces in South Africa, as well as from Zambia and Lesotho (Table 1).

Table 1

Large samples of various size fractions (normal crusher run, and single sized stone with nominal sizes of 26.5, 19 and 13 mm) were collected from the operating crushing plants as well as boulders for extraction of drilled cores for specialised testing. At sources where crushing was not being carried out, large, boulders were collected. These were manually broken down to about fist-sized particles before being passed through a small laboratory jaw crusher to provide the specific material sizes necessary for testing.

Testing

Each material was subjected to a range of testing including chemical and mineralogical analysis, laboratory testing using standard specified test methods, testing using methods that are non-specified but used periodically and other methods developed or adapted to simulate the expected nature of deterioration of the materials.

The test methods utilised include:

- Mineralogy by thin section (Council for Geoscience)
- Mineralogy by X-ray diffraction (Council for Geoscience)
- Chemical analysis (X-ray fluorescence (XRF)) (Council for Geoscience)
- "Pick and click" test (Weinert, 1980)
- Los Angeles Abrasion (AASHTO T96-99; Grading B)
- Relative Density and Water Absorption (TMH 1, B14 and B15)
- Aggregate Crushing Value (ACV) (TMH 1, B1)
- Aggregate Impact Value (AIV) (BS 812 Part 3)
- 10% Fines Aggregate Crushing Value (10%FACT) (BS 812, Part 2)
- Durability Mill Index (Sampson & Netterberg, 1989)
- Sand Equivalent (ASTM D2419-74)
- Ethylene Glycol (Durability) Index test (various methods)
- Indirect tensile strength (ITS) (ASTM D3967-95A)
- Point Load Strength Index (ISRM, Document 1)
- Washington Degradation Value (Marshall, 1967)
- Aggregate Durability Index (production of plastic fines in aggregates) (AASHTO T210-72)

There was a strong bias in the testing towards ethylene glycol (EG) soaking, based on the discussion in the following section, with direct EG tests as well as various EG soaking regimes applied to a number of the crushing tests.

Preliminary performance ranking

As only limited and subjective field performance data was available for some of the materials sampled, it was necessary to develop a preliminary performance ranking to assess the most appropriate material properties and test results. This was based on the observed disintegration of aggregate pieces soaked in ethylene glycol combined with past testing of basic crystalline materials by the author and opinions of engineers and other users of the materials sampled. It is generally accepted that the deterioration of basic crystalline materials is the result of expansion of smectite clays in the rock during the absorption of water. This deterioration can be accelerated by soaking the material in ethylene glycol but is also a function of accessibility of the clays to the glycol. The effects of glycol soaking on the twelve materials sampled (Figures 1 and 2) and the associated performance rankings are summarised in Table 2.

Figures 1 and 2

Table 2

Based on past experience it would be estimated that materials D7, D8 and D10 and perhaps D6 would be unsuitable for use as base course materials in high standard roads, conforming to the performance rankings obtained.

Because of the difficulty in rating the performance, the individual performance of each material according to each test was ranked on a scale of 1 (best) to 12 (worst) and the sum of all of these rankings determined for each sample (total ranking in Table 3). The mean ranking (total divided by number of rankings) of each sample is also indicated as well as the overall sample ranking based on these results (sequential). This ranking is obviously biased towards the crushing test results as the Aggregate Crushing Value (ACV), 10% Fines Aggregate Crushing test (10%FACT) and Mod Aggregate Impact Value (AIV) are all included. In addition, six or seven different treatments are included. For this reason a modified ranking scale was also developed using only selected results for each type of index (Table 3).

Although there are some differences, the rankings all show similar general trends.

Table 3

Table 3 indicates that samples D6, D7, D9 and D11 are likely to be the least durable when all results are used for the ranking. When only selected results are used, a very similar trend is seen although sample D2 rates worse than D9. When these rankings are compared with the preliminary rankings summarised in Table 2, similar trends are also observed with materials D6, D7, D8 and D10 being ranked worst.

Although this is a rather indirect means of assessing the performance of the material, without actual in-service performance data it appeared to be the most practical method. Irrespective, it can be concluded that samples D11, D6 and D7 are probably those most likely to give durability problems in practice with samples D2, D8, D9 and D12 giving mixed results.

Test results

Table 4 includes the statistics of various selected and pertinent test results. The complete test results are provided elsewhere (Paige-Green, 2005).

Table 4

The results are typical of conventional testing of basic crystalline rocks and indicate that the materials generally pass the existing specifications. Wider ranges of results are obtained using the non-conventional and innovative test methods such as the wet abrasion tests that are not used in existing specifications. The implications of the results are, however, discussed further in the following section.

Discussion of test results

The full analyses of the results of each test technique have been presented elsewhere (Paige-Green, 2005). Only the major findings are summarised in the paper.

Mineralogy

Although the trends in mineralogy were similar, there were some differences in the smectite and secondary mineral contents determined using different techniques and particle fractions.

The performance of the materials in the various tests did not correlate with the clay contents, particularly the smectite, content. Other properties seem therefore to play a major role, probably the ease of access of water to the clay minerals being an important one.

Van Rooy (1994) tentatively concluded that basalts with no visible clay and less than 20 per cent smectite and less than 10 per cent amygdales could be classified as suitable for use in concrete, roads and for rip rap. All of the samples tested in this project except one (D6) had smectite contents of less than 20 per cent. Despite this, a number of the materials were considered to be unsuitable for use, based on the testing carried out during this project. It was, however, noted that none of the materials containing amygdales deteriorated during the glycol soaking.

The existing limits recommended for durable materials based on secondary mineral contents do not adequately discriminate between materials that are expected to perform well and those likely to degrade in service.

Abrasion tests

The smallest loss was from the andesite control as expected but the second highest loss was from the norite control (the only coarse grained material investigated). This indicates that the result of the LAA test seems to be influenced by the grain size of the material probably more than its durability.

The AASHTO specification would permit the use of all of the materials for base course aggregate. However, as explained previously, not all of the materials tested are considered suitable for use.

The Durability Mill Index test identified what was considered to be potentially the worst material, which exceeded the upper specification limit. All other materials complied with the specification limits. The test, however, should be modified to improve its repeatability. The sub-samples for each treatment should have identical particle size distributions and the Plasticity Index (PI) should be determined on both the fractions finer than both the 0.425 and 0.075 mm sieves.

The Washington Degradation Value (WDV) test (and the Aggregate Durability Index (ADI), which was derived from it and uses similar principles) was developed specifically for durability assessment of basic crystalline materials in the United States. These two tests provided the best relationship with the rated performance (Figures 3 and 4) although they did not produce definite results in the borderline areas (about 60 to 80 for the WDV and 80 to 90 for the ADI).

Figures 3 and 4

Relative Density and Water Absorption Tests

Relative Density and Water Absorption of aggregates are not normally considered indicators of durability, but local research has shown that low and high values respectively are indicative of weathering and the potential for moisture to gain access into the aggregate particles. A maximum value of 2 per cent for the water absorption has been applied to tillites ((Paige-Green, 1980) and basalts (Van Rooy and Nixon, 1990). Four of the results on the coarse aggregate fraction and 8 on the fine aggregate fraction exceed 2 per cent.

Aggregate Crushing Tests

Aggregate Impact Value (AIV) testing yielded results similar to those determined using the ACV, a test that correlates well with the AIV. Soaking in water and glycol produced a range of results, not all corresponding with each other.

The results of all of the specimens tested using the 10% Fines Aggregate Crushing Test (10%FACT) and Aggregate Crushing Value (ACV) test complied with the South African specifications. However, five of the materials would be rejected on the basis of the ratios of their soaked to dry 10%FACT strengths.

The current specification using the ratio of the wet and dry 10%FACT produced mixed results but is in general a reasonable predictor. However, in practice it has been found that too much reliance is placed on the specified limit of the wet to dry ratio, with materials that are very close to the limit often being rejected outright, despite the material having both very high dry and wet values.

Glycol soaking tests

The various glycol index tests produced a range of results, the biggest problems being their applicability to road aggregates. Only small samples of specific size fractions are used in the current methods of test. It is suggested that a modified technique in which 40 pieces of aggregate are placed in a tray and covered by ethylene glycol be used. The aggregate pieces should be placed in a fixed pattern (eg, five rows of eight pieces) so that each one can be assessed and its behaviour with time recorded. The material should be inspected after 5, 10 and 20 days and the number (and location in the tray) of pieces of aggregate that have spalled (shed small fragments from their edges), fractured (split into not more than three pieces) and disintegrated (spilt into more than 3 pieces) be recorded at each assessment.

The effect of ethylene glycol on materials containing smectite clays is rapid and severe. A soaking period of 4 days (ad hoc testing in the past required between 2 and 28 days) was found to be the optimum period to allow time for the relatively viscous ethylene glycol to permeate the material but not to have to wait excessively long periods for the test results.

Analysis of results

It is clear that the test results indicate various attributes of the materials with no single test seemingly giving a definitive indication of the durability of crushed basic crystalline rocks. Some important observations, however, are made below.

The existing limits for durability based on secondary mineral contents do not adequately discriminate between materials that will perform well and those that are likely to degrade in service.

Crushing and strength tests appear to affect coarser materials more. Their indiscriminate use as indicators of durability for any material type could lead to potentially good materials being excluded from use. Relatively poor results were obtained on the coarse grained norite (D3) in all of the crushing, strength and abrasion tests. This trend is illustrated in Figure 5 showing the Los Angeles Abrasion loss (LAA) and Aggregate Impact Value (AIV) plotted against the particle size where very fine materials are rated as 1, fine as 2, fine to medium as 3 and the only medium grained material (norite) is rated as 4.

Figure 5

Many test methods using ethylene glycol are available, but the combination of ethylene glycol soaking with a strength test appears to have the greatest merit to be included in specifications. The other methods are based on the testing of single or specific numbers of aggregate and appear to relate the performance of the overall aggregate sample to the behaviour of the poorest fragments in the material.

Existing strength and water soaking methods that have been specified seem to be poor in discriminating durable from non-durable materials.

Dry abrasion testing using the Los Angeles apparatus yields poor results. Although not carried out, the testing of the abraded product or the use of relative results after various numbers of revolutions could be useful. However, abrasion in the presence of water (eg, DMI test) appears to be far more satisfactory.

The existing Durability Mill Index test only indicated that one of the materials would be unsatisfactory for use. This was certainly the material that was ranked as likely to give the worst performance but other materials that were considered likely to perform poorly were not identified. The suggested improvements may make the results more repeatable.

Other wet abrasion tests such as the Washington Degradation and Aggregate Durability Index show significant promise, particularly the latter, as it tests a more representative portion of the material. No limits are currently available in South Africa for their use, however.

Direct strength tests such as the indirect tensile strength and point load seem to be poor indicators of durability. However, their combination with water or glycol soaking may make them more useful.

Material Variability and Sample size

One of the major problems with all of the tests is handling the inherent variability of the material. Although only 12 samples from different sources were tested in this project, it would probably be necessary in practice to test 12 samples from each source to account for variability. The problem then arises as to how to assess the results of such testing when some samples fail and others pass. Typically, specific material horizons are targeted as source materials but during large-scale quarry operations, this is expensive and difficult to control and any or all of the materials are processed together. In these cases, testing of the bulk material produced will give representative results but unsatisfactory results after processing will have resulted in substantial costs and the production of large volumes of wasted material.

An additional problem is the preliminary evaluation of small samples such as drill cores obtained during exploratory work, where only limited material is available for testing. Special test techniques, for example the Aggregate Impact Value on a small size fraction, will need to be developed to cater for this situation.

Suggested test methods and performance criteria

The range and variability of results and data from the samples tested make the selection of specific tests and development of acceptance criteria difficult. There is, however, no doubt that more than one test is necessary to ensure that any material will be durable, as conflicting results appear to be the norm. Bearing in mind that as few tests as possible should be included in good specifications in order to minimise costs and time of testing, the following test techniques are thus suggested:

- Petrographic and mineralogical analysis
- Durability Mill Index
- 10% FACT or ACV
- AIV or Modified AIV
- Glycol soaking test

The proposed specification limits for these tests are discussed in the following sections and summarised in Table 5.

Table 5

Petrographic analysis

The petrographic analysis should include a careful examination of the secondary mineral types and quantities in thin section. If the smectite content is less than 10 per cent, the material is likely to prove durable in service. If the smectite content exceeds 10 per cent, the material has the potential to be non-durable in service and the following testing is recommended:

Durability Mill Index

It is recommended that the existing test method be modified to ensure that each grading tested is identical. This will involve screening and reconstitution of the material to an exact grading for each sub-sample. Where the material is obtained from cores or crushed boulders, the grading should comply with that shown in Table 6.

Table 6

The plasticity index (PI) should be determined on representative samples of both the minus 0.425 and minus 0.075 mm fractions. If no PI or a slightly plastic result is obtained on the minus 0.425 mm fraction, the DMI must be calculated using the PI on the minus 0.075 mm fraction. If there is no PI on the minus 0.075 mm fraction, the DMI will be zero. Tentatively, a maximum DMI of 125 using either plasticity index should be adopted. If the DMI is zero, the percentage passing the 0.425 mm fraction for any treatment should not exceed 35.

10%FACT or ACV

Conventional dry and wet aggregate crushing testing should be carried out using either the ACV or 10%FACT. In addition material soaked in ethylene glycol for 4 days should be tested. The limits shown in table 5 should be achieved:

AIV or modified AIV test

For crushed unweathered rock the standard AIV test can be carried out, although it is recommended that the modified AIV tests be used in case the water or glycol soaking results in excessive breakdown. The specification of Sampson for the modified AIV had a limit of 40 with a wet/dry ratio maximum of 1.14 and a maximum increase in the 24-hour glycol soaked value over the wet value of 4 percentage units. This work indicated that all but three materials meet the requirements. However, of the five materials rated worst, two passed and three failed, purely on the increase in AIV after 4 days soaking. On this basis, the tentative specification given in Table 5 is proposed.

Glycol soaking test

This test is a good indicator of the potential breakdown of basic crystalline aggregates in the medium to long term. Although many different techniques/methods are available, none of them appears to be suitable for road aggregates. It is suggested that a modified technique in which 40 pieces of aggregate are placed in a tray and covered by ethylene glycol be used. The aggregate pieces should be placed in a fixed pattern (eg, five rows of eight pieces) so that each one can be assessed and its behaviour with time recorded. The material should be inspected after 5, 10 and 20 days and the number (and location in the tray) of pieces of aggregate that have spalled (shed small fragments from their edges), fractured (split into not more than three pieces) and disintegrated (spilt into more than 3 pieces) be recorded at each assessment. The results can be tentatively interpreted for base course use as shown in Table 5.

The results should, however, also be subjectively assessed in terms of the 5 day rating and the spalling. Rapid deterioration or extensive spalling indicate that the long term durability may be a problem not indicated by this relatively rapid test and will require extra judgement by the user.

As discussed previously, none of the test methods individually appears to provide sufficiently conclusive results and it is recommended that a combination of the tests described above be carried out. If more than two of the tests indicate any shortcomings in the material, use of the material should be carefully reconsidered, especially for roads designed to carry more than 500 000 standard axles. The inherent variability of these materials must also be taken into account.

Conclusions

Ensuring durability of road pavement layer materials prior to construction will result in more cost effective road pavements. An assessment of various test methods to indicate the durability of basic crystalline materials has been carried out. The results show that no single test method indicates potential durability problems for the materials.

Based on the test results obtained and a close review of the test methods and variation of results, a range of tests (including some modification to existing methods) and tentative specification limits has been proposed for assessing the durability of basic crystalline materials obtained by crushing unweathered material sources. The methods include:

- Petrographic and mineralogical analysis
- Durability Mill Index
- 10% FACT or ACV
- AIV or Modified AIV
- Glycol soaking test

If a material fails the proposed limits for more than two of these tests, its use should be reconsidered.

The proposed specification limits are based on a limited number of samples and it is suggested that where this classification of materials is used, records of the properties and performance of the materials be kept and reviewed on an ongoing basis. Adjustments to either the test methods or the specification limits can then be made as necessary.

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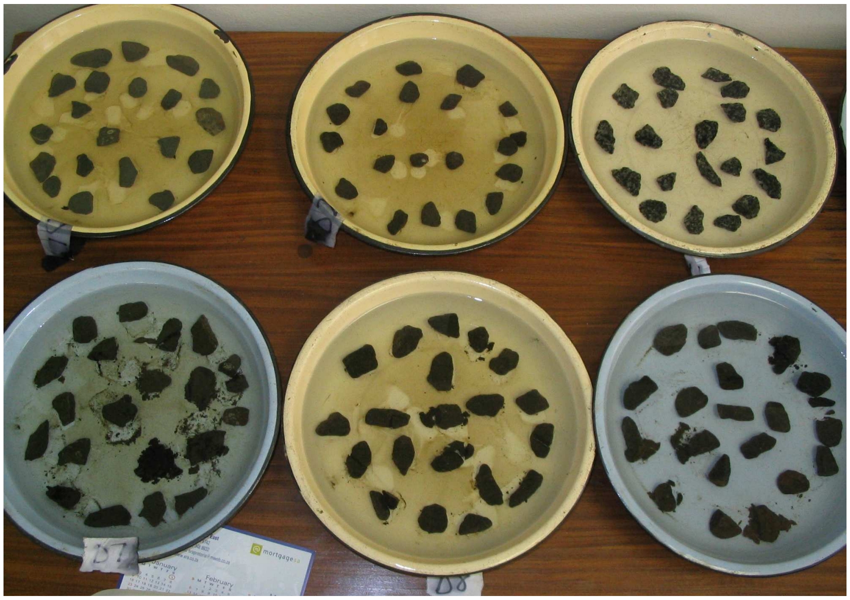

Figure 1: Samples D1 to D3 (top row) and D7 to D9 (bottom row) after soaking in glycol for 45 days

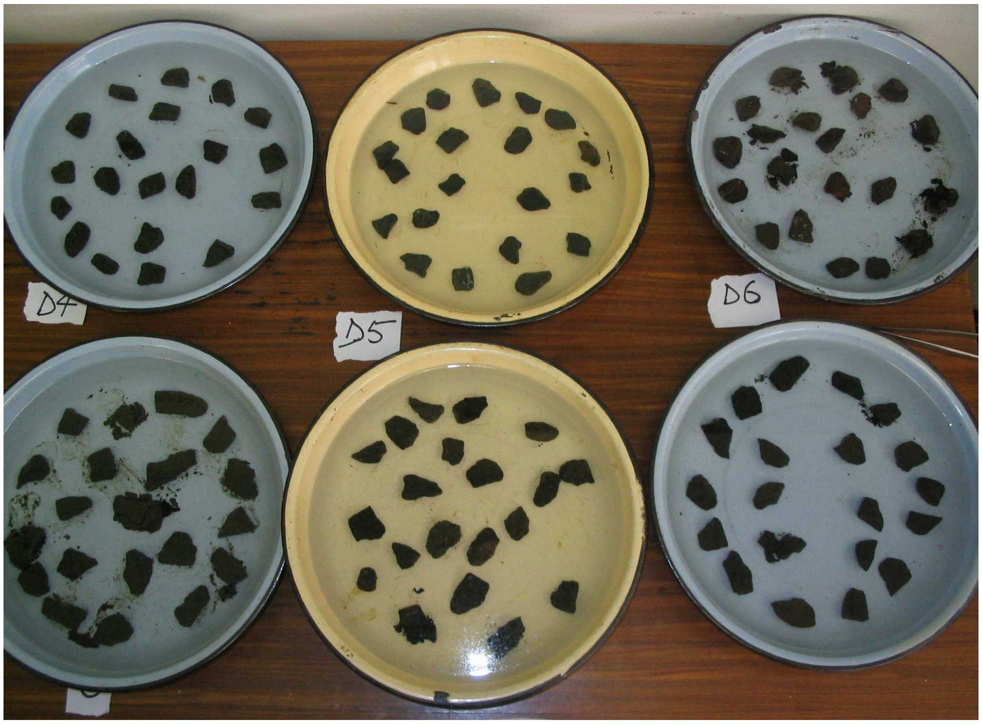

Figure 2: Samples D4 to D6 (top row) and D10 to D12 (bottom row) after soaking in glycol for 45 days

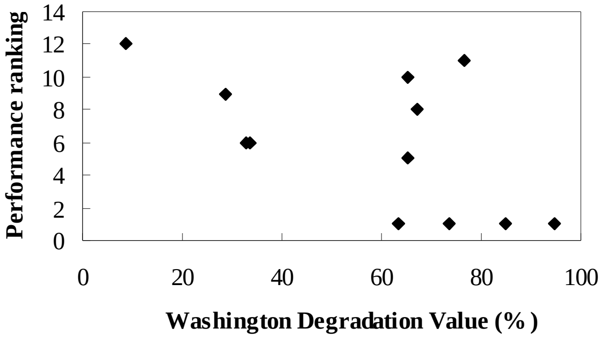

Figure 3: Plot of Washington Degradation Value against the ranked performance

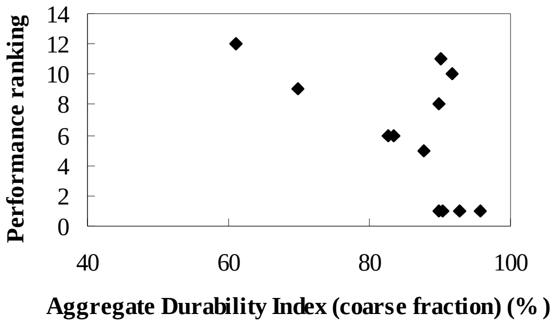

Figure 4: Plot of Aggregate Durability Index of the coarse fraction against the ranked performance

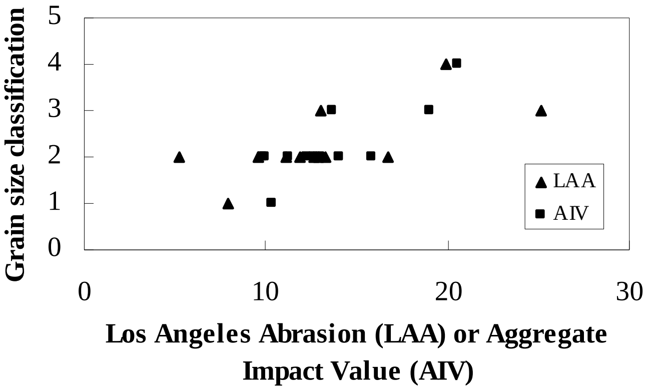

Figure 5: Plot of classified grain size versus Los Angeles Abrasion (LAA) and Aggregate Impact Value (AIV) results

Source	**Material**	**Material classification**	**Reference Number**
Eikenhof Quarry, Johannesburg	Andesite	basaltic trachyandesite	D1
Van Vuuren farm, Settlers, Limpopo	Basalt	basalt	D2
Bon Accord Quarry, Tshwane	Norite	basalt	D3
Lancaster Quarry, Qwa Qwa	Dolerite	basalt	D4
Wearne Quarry, Makhado, Limpopo	Basalt	basaltic andesite	D5
Silolo Quarry, Zambia	Basalt	basalt	D6
Mtuba Crushers, Mtubatuba, KwaZulu Natal	Basalt	basaltic andesite	D7
Rexford Store, Paul Roux, Free State	Dolerite	basalt	D8
Labrador, Paul Roux, Free State	Dolerite	basalt	D9
Moradi (Pty) Ltd, Morija, Lesotho	Dolerite	basalt	D10
Southern Sky, Nazareth, Lesotho	Dolerite	basaltic andesite	D11
Trichardt Crushers, Secunda	Dolerite	basaltic andesite	D12

Table 1: Samples used for durability investigation

Sample No	**Effect**	**Ranking**
D1	None	1
D2	None	1
D3	None	1
D4	Minor spalling	5
D5	None	1
D6	Significant spalling, some fracturing	9
D7	Significant fracturing and disintegration	12
D8	Significant fracturing, some disintegration	11
D9	Significant fracturing	8
D10	Significant fracturing, some disintegration	10
D11	Significant fracturing, minor disintegration	6
D12	Significant fracturing, minor disintegration	6

Table 2: Preliminary ranking of material performance based on behaviour in ethylene glycol

	Ranking using all tests			Ranking using selected tests	
Sample	Total ranking	Mean ranking	Overall ranking	Total	Ranking
D1	70	1.1	1	19	1
D2	234	4.3	6	98	9
D3	227	3.5	5	58	2
D4	188	3.4	4	83	5
D5	155	2.4	2	67	3
D6	368	6.4	11	124	10
D7	369	6.3	12	126	11
D8	279	4.2	8	90	7
D9	301	4.8	9	84	6
D10	186	3.1	3	68	4
D11	362	6.3	10	130	12
D12	276	4.9	7	96	8

Table 3: Ranking of sample durability based on test results

Property	**Mean**	**Standard deviation**	**Maximum**	**Min**
Mineralogical testing				
Smectite content (X-Ray diffraction) (%)	8.833	6.41	21	0
Smectite (petrographic) (%)	6.750	4.97	14	0
Secondary mineral (petrographic) (%)	10.583	9.09	31	0
Abrasion tests				
Los Angeles Abrasion (%)	13.267	5.31	25.1	5.2
Aggregate durability index (coarse and fine)	26.7	17.27	48	10
Durability Mill Index	21.5	50.52	172.7	0
Maximum percentage passing 0.425 mm	14.1	6.82	27.6	2.3
Water Absorption and relative density				
Water absorption (+4.75 mm fraction) (%)	1.796	1.11	4.400	0.399
Water absorption (-4.75 mm fraction) (%)	2.473	1.35	4.309	0.305
Weighted Apparent Relative Density (ARD)	2.944	0.04	2.991	2.860
Weighted Bulk Relative Density (BRD)	2.792	0.09	2.951	2.639
Glycol testing				
Glycol durability index (aggregate)	4.500	2.68	8	1
Glycol index (core)	1.833	1.99	7	1
Modified SATS glycol index	11.7	13.37	35	0
Aggregate Crushing Value (ACV) (%)				
dry	11.3	3.89	19.4	5.3
wet	13.7	4.43	20.3	6.8
4 day glycol soaked	18.4	9.63	34.7	5.6
10%FACT (kN)				
dry	385	100.20	595	236
wet	306	113.58	595	182
24 hour glycol soaked	313	169.59	675	130
4 day glycol soaked	261	181.26	580	0
wet/dry ratio	0.78	0.11	1.00	0.66
4day glycol soaked minus wet				
Aggregate Impact Value (%)				
dry	13.5	3.45	20.6	9.8
wet	14.6	4.53	24.1	8.5
24 hour glycol soaked	15.0	4.74	22.7	8.2
4 day glycol soaked	18.7	10.22	42.8	8.6
7 day glycol soaked	19.9	10.98	45.3	7.9

wet/dry ratio	1.071	0.14	1.31	0.87
4 day glycol soaked minus wet	4.13	9.20	28.1	-4
Mod AIV (%)				
dry	15.6	4.47	24.9	10.9
wet	17.0	5.99	29.9	9.4
24 hour glycol soaked	17.6	6.19	27.9	9.0
4 day glycol soaked	23.1	14.90	60.1	9.5
7 day glycol soaked	24.9	16.12	64.5	8.6
wet/dry ratio	1.08	0.16	1.35	0.86
4 day glycol soaked minus wet	6.12	13.76	43.0	-4.9

Table 4: Summary of selected test results

Property	**Limit**
Mineralogy	If smectite > 10% carry out following testing
Crushing strength	
10% FACT (kN)	
Dry	210
Wet	160
4-day glycol soak	120
ACV (%)	
Dry	18.5
Wet	20.5
4-day glycol soak	22.2
Impact strength	
Mod AIV (%)	
Dry	25
Wet	30
4-day glycol minus wet	< 2
AIV (%)	
Dry	20
Wet	31
4-day glycol minus wet	< 2
Abrasion	
DMI (max)	125 (using highest of 0.425 or 0.075 mm PI)
If DMI = 0 % then % < 0.425 mm for any treatment should not exceed 35.	
Glycol soaking	< 10 pieces disintegrated after 20 days **or** < 15 pieces disintegrated & fractured after 20 days

Table 5: Suggested limits for prediction of durability of basic crystalline materials

Sieve size (mm)	**Percentage passing**
26.5	100
19.0	90
13.2	78
4.75	51
2.00	36
0.425	20
0.075	9

Table 6: Recommended grading for Durability Mill Index test