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Suitability of Chrome Slag as an Aggregate for Asphalt in South Africa

M.W. Heyns[1], Mohamed M H Mostafa[2*] and E. Mukandila[3]

[1]Civil Technologist, Pr Tech Eng., Jodan Construction, South Africa

[2]Sustainable Transportation research group (STRg), Civil Engineering, School of Engineering, University of Kwa-ulu Natal, https://orcid.org/0000-0002-5163-5861; South Africa

[3]Civil Engineer. Pr Eng., Technical Director: Roads Division, IX Engineers, South Africa

***Corresponding author:** *Mohamed M H Mostafa, Sustainable Transportation research group (STRg), Civil Engineering, School of Engineering, University of Kwa-ulu Natal, South Africa, Email: mostafam@ukzn.ac.za*

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Abstract

Large quantities of natural materials are traditionally used in road construction which leads to depletion of non-renewable natural resources. Concurrently the world faces the problem of management of an increasing quantity of waste so that linking the two issues leads to a simple solution: growing and more diverse application of waste materials in roads and other areas of civil engineering similarly.

Approximately 20 million tons have accumulated on Chrome Slag dumps in South Africa, and a further 0.5 million tons are added every year. The total amount of one area (Witbank area) alone is 450 000 tons and increases every month. Complete elimination of the production of Slag is impossible at this stage. Consequently, the suitability of this material to be used as aggregates in asphalt mixes can be significantly important. Therefore, a large study is established to design asphalt mixes incorporating Chrome Slag.

This preliminary study investigated the suitability of Chrome Slag as a replacement of natural Dolorite for asphalt mixtures as the Slag conforms to the requirements as set out in design procedures developed for South African conditions. The material was tested for physical properties, hardness, toughness, and durability. Chrome Slag showed generally favourable results when compared with the Dolerite samples. It, however, showed softer toughness values than that of the Dolerite. The Slag showed that it conforms to enough requirements, and the test revealed and can be a viable option as asphalt aggregate. The results encouraged continuation with the large project to arrive at proper mixes incorporating Chrome Slag.

Keywords: Natural Aggregate; Chrome Slag; Durability; Non-conventional materials; Asphalt

Introduction

Pavement design is grounded on attaining structural quality for each layer of material (Guyer, 2011). Each layer in the design must be resistant to shearing, excessive deflections that will cause fatigue cracking within the layer or in the overlying layers and prevent permanent deformation through densification (Guyer, 2011). The inclusive performance of an asphalt mix depends on, amongst others, the properties of the aggregate, binder, filler, and additives if used.

Aggregate is one of the main components of an asphalt mix design as it constitutes the more substantial portion of material used in the manufacture of hot mix asphalt. The physical properties of aggregate are generally regarded as the most critical aspect of aggregate selection. The physical properties of aggregates are affected by several factors including, but not limited to, mineralogy of the parent rock; the extent to which the parent rock has been altered by leaching, oxidation etc.; as well as by the processes required to produce graded and blended aggregates. The majority of aggregate sources are rarely totally uniform in quality. The existence of distinct geological formations can significantly affect the quality of the aggregate (SAPEM, 2011). Hard and rough textured aggregate results in stable and rut-resistant hot mix asphalt mixes (Komba J, 2014). Durability is another significant feature that should be influenced by aggregates used in the manufacture of Asphalt. The aggregate should be able to resist breaking down and disintegration under environmental conditions.

Equal dimensional aggregate is preferred over flat and elongated aggregates in terms of shape. Flat and elongated aggregate particles tend to lock up and resist orientation which results in difficulty during the compaction process (Button, et al., 1990; Arasan, et al., 2011). Angular aggregate particles are favoured over round-shaped aggregates as they improve aggregate interlock providing improved resistance to rutting and improve the resilient response of asphalt mixes (Pan et al., 2005).

Dolerite is one of the naturally abundant road building materials for the construction of high-quality pavement road layers in South Africa. It is associated with the primary crystalline group of rocks. Dolerite is a common type of felsic intrusive igneous rock that primarily contains feldspar, quartz, hornblende andmica. As aggregate needs to be durable and, testing requirements have been established to ensure the durability of the required materials, reactivity and near lack of cleavage give Dolerite a significant amount of desirable durability properties that are required for road pavement construction

On the other hand, Slag falls in a category of aggregate named “manufactured aggregate” due to being a by-product of an industrial process. The manufactured aggregate can also be crushed and serve the purpose in a civil engineering environment. The Slag is straight granulated during drumming where ferrochrome is tapped into scoops. The excess from the scoops flows along the slag launder to the granulation pond, where high-pressure water breaks Slag into small fractions and efficiently it cools down, and the final Slag is then dumped on-site (Niemela, 2007; Hattingh, 2003).

This study will investigate some aspects of aggregate testing specifications by comparing the use of a waste by-product (Slag) to a naturally occurring aggregate (Dolerite).

Literature Review

Slag is a waste material produced in cathartic metals, their casting and alloying. In South Africa, the submerged electrode arc-smelting process is mainly used. During this process, the chromite ore is blended with carbon-rich material (reductants) and fluxes (coke, char and coal) to produce the feedstock. The feedstock is fed into an electric-arc furnace where it is melted (Papp, 2000).

The use of Slag has been recorded as early as 700 B.C. (Barisic, 2010). Slag was used for the first time in road construction as early as the Roman era, when slag rubble from the processing of crude iron was utilised in building the roadbeds. The first modern roads constructed with Slag were built in England in 1813. The first actual record in road building with Slag was in 1830. Some years after the use of Slag in road construction, with very good experiences, the railway started using Slag in the construction of lines as well (Barisic,2010).

The first experience of Slag in asphalt mixtures is dated as 1969. The results obtained showed very good properties in terms of bearing capacity, resistance to external impacts, and durability (Emery, 1982). Slaghas become known as secondary aggregates which have similar physical properties to the conventional, primary aggregate and can be processed, crushed and screened into practical size for easy batching into both surfacing and base asphalt surfacing (Mikoc, 2010). The most significant difference between Slag and most natural aggregates is its high particle density, which is the consequence of the presence of iron compounds.

Slag is also known as a pozzolanic material as it has a significant quantity of calcium oxide, CaO. The amount of CaO indicates the existence of the possibility of utilising Slag as a binder (Barisic, 2010). The partialreplacement was alsopossible.

South Africa has an excess of Slag that covers hectares of ground. Some plants have been recording slag dumps in excess of 5 million tons, which occupy approximately 5 ha. Plants are planning to increase steel production, thus increasing slag dumps. An example of a plant is found in Machadodorp, which has a planned increase in Slag to over 8.5 million tons by the year 2025.

Paige-green et al.; 2013, noted that aggregate plays a vital role in determining the overall performance of asphalt mixes in pavements. Slag conforms to all the properties that are significant to the performance of a Hot Mix Asphalt (HMA). Niemela et al.; 2007, further stated that Slag is hard and stable and is well suited for demanding structures. The study concluded that the slag products could be used for road construction in the filtering and supporting layers and also as aggregate in Asphalt. The use of slag products will also speed up the construction and thus make the slag products more economical (Niemela et al.,2007).

Natural aggregate sources are depleting due to high demand and the amount of disposed waste material keeps increasing. Therefore, researchers are exploring the use of alternative materials to reserve natural aggregates and save the environment. The utilization of Slag will reduce landfill, preserve natural resources and improve the properties of pavement. This will shift the gear in sustainable pavement construction, which is most desirable in today’s energy-deficient world (Hainin, 2012).

This preliminary study, which conforms part of a larger study, investigated the suitability of Chrome Slag as a replacement of natural Dolorite for asphalt mixtures as the Slag conforms to the requirements as set out in design procedures developed for South African conditions.

Materials and Methodology

The materials supplied for the study is natural crushed Dolerite and chrome slag. The aggregate testing is completed as per the following:

1. Interim Guidelines for the Design of Hot-mix Asphalt in South Africa, 2001 (IGDHMSA,2001).
2. Committee of Land Transport Officials, 1998 (COLTO,1998).

Results validation are undertaken using Interim Guidelines for the Design of Hot-Mix Asphalt in South Africa, table 3.1. The tests were completed on both natural (Dolerite) and slag aggregates, and these specifications are summarised in table 1.

Table 1: Tests used to evaluate the Physical Properties of Aggregates

Property	Test	Designation	Criteria
Hardness/Toughness	Fines Aggregate Crushing Test (10% FACT) (-10,0mm + 7,1mm fraction) & (-7,1mm +5mm Fraction)	SANS 3001 – AG10&AG15	Minimum: 160kN
	Aggregate Crushing Value (ACV)	SANS 3001 – AG10	Max: 25%
Durability/Soundness	Methylene Blue Adsorption	SANS1243	No standards Specified. Indicators: <5: High quality filler >5: Additional Testing Required
	Ethylene Glycol	SANS 3001 – AG14	Visual evaluation
Particle Shape and Texture	Flakiness Index Test	SANS 3001 – AG4	Max: 9,5mm Aggregate - 30 6,7mm Aggregate - 30
	Polished Stone Value (PSV)	SANS 3001 – AG11	Min: 50
Absorption	Water Absorption	SANS 3001 – AG20& AG21	Max: 1% by mass
Cleanliness	Sand Equivalent Test	SANS 3001 – AG5	Min: 50 on Total Fines Fraction

ACV and 10% Fines Aggregate Crushing Values (FACT)

The straight dry and wet aggregate crushing test is normally carried out using either ACV or 10% FACT. The test assesses the strength properties of the aggregate. The difference between ACV and 10% FACT is that ACV determines the percentage fines produced under a load of 40kN/min up to 400kN over 10 minutes while the 10% FACT determines the load required to produce 10% fines. ACV is less reliable for an indication of weaker materials; therefore, the 10% FACT is the preferred method. For the durability of aggregates, the wet 10% FACT is carried out as part of the normal 10% FACT test. Aggregates are prepared as for the standard test requirements but are soaked in water for 24 hrs. The test is carried out for both dry and soaked aggregate, and the results are reported in percentage. A wet/dry ratio of greater than 75% indicates satisfactory durability. Table 2 shows the results of the comparison materials. In addition to the testing, aggregate soaked in Ethylene Glycol for 4 days must also be subjected to the ACV and 10% FACT test procedures. The results of the Ethylene Glycol test procedures must conform to the requirements as specified in the documents to ensure durability. (SANS3001– AG10; SANS3001– AG14; SANS3001– AG15; SAPEM, 2014; COLTO, 1998; IGDHSA, 2001).

Table 2: Hardness results of the aggregates

Description	Test Method	UOM	Material Description			
			Slag		Aggregate	
			9,5mm	6,7mm	9,5mm	6,7mm
ACV Dry	SANS 3001 - AG10	%	12,5	12,7	5,5	6,1
ACV Wet	SANS 3001 - AG10	%	13,9	13,4	7,9	8,1
ACV Wet (E.G.)[1]	SANS 3001 - AG10	%	14,2	14,7	8,2	7,9
10 % FACT Wet/Dry Ratio	SANS 3001 - AG9	%	91	95	66	68
10 % FACT Wet/Dry Ratio (E.G.)	SANS 3001 - AG9	%	93	93	61	69
10% FACT Dry	SANS 3001 - AG9	kN	305	294	799	737
10% FACT wet	SANS 3001 - AG9	kN	277	279	527	504
10% FACT Wet (E.G.)	SANS 3001 - AG9	kN	282	272	488	506

Durability/Soundness

Durability and Soundness is the ability of the aggregate to resist breakdown and disintegration under the action of theenvironment. The tests included in this section are namely; Ethylene Glycol Durability Index and the Methylene Blue test.

Ethylene Glycol Durability Index (EGDI)

Ethylene Glycol is used to check the durability of the Acid/ Basic Crystalline rock groups and now Slag.The test is a good indicator of the potential breakdown of the aggregates in medium to long term after exposure to the atmosphere. Rapid weathering does occur when rocks contain smectite clay minerals and Dolerites, which are known for the primary minerals in the rock to be altered to active clay smectite (Jenkins, 2011; Paige-Green, 2007; SANS 3001 – AG14). The test includes soaking rock fragments in ethylene glycol while observing deterioration on a daily basis. The durability index is obtained by adding the disintegration classification (which indicates the severity of the disintegration) to the time classification (which indicates the number of days taken for the most severe disintegration to take place). A modified technique, suggested by Paige- Green, uses 40 pieces of aggregate placed in a fixed position. This technique is to assess each aggregate and its behavior with the time recorded. The inspection should take place after 5, 10 and 20 days. The individual pieces are recorded with the following 3 assessments:

1. Shed of small fragments fromedges
2. Fractured into not more than 3pieces
3. Disintegrated, samples split into more than 3pieces

The results of the test will indicate possible problematic aggregates that will affect long term durability. As the effect of the ethylene glycol depends on the accessibility of the liquid to the deleterious clays within the aggregate pieces, the test was carried out for 20 days to find out if there could be a longer-term durabilityproblem. Paige-Green reported that the EGDI after 20 days will be greater than 1.5 times the EGDI after 5 days. Moreover, the materials durability will be a suspect. The results of the EGDI following criteria should apply:

1. Subbase – EGDI< 20 (modified Ethylene Glycol DurabilityIndex)
2. Base Course – EGDI<10
3. EGDI after 20 days < 1,5 x EGDI after 5days

The results are combined in Table3. The reason is that all the aggregates observed during the required time of specified testing showed no physical change when the subdued to the Ethylene Glycol solution. Figures 1 and 2 shows the condition of the aggregate Slag and the natural Dolerite soaked in ethylene glycol after 20days.

Figure 1: Slag soaked in Ethylene Glycol

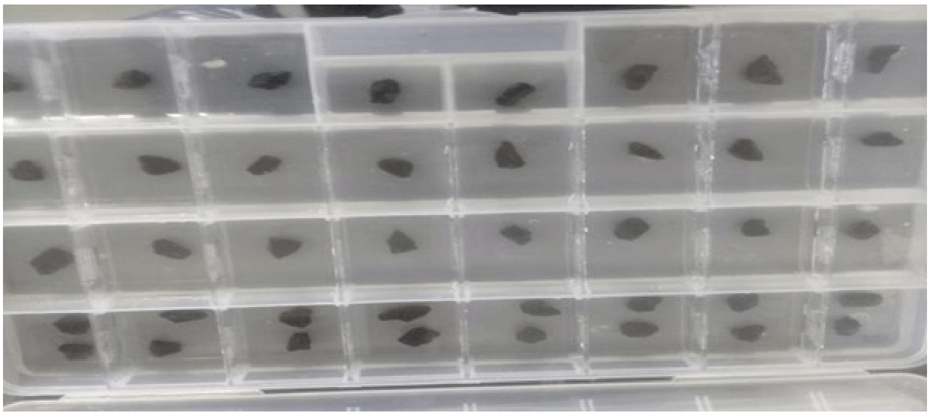

Figure 2: Dolerite Aggregate soaked in Ethylene Glycol

Table 3: Concluded EGDI results for both Slag and natural aggregate

Day	Spall-ed [a]	Ds	Frac-tured [b]	Df	Disintegrated [c]	Dd	Dura-bility Index
1	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
a	Weighting Factor		0,5				
b	Weighting Factor		1				
c	Weighting Factor		2,5				

Type of deterioration	Definition
Spalled (Ds)	Shedding of small fragments from aggregate edges
fractured (Df)	Splitting into two or three pieces
Disintegrated (Dd)	Splitting into more than three pieces

5-dayEGDI	20-dayEGDI	1,5 x 5-dayEGDI
0	0	0

Note: Both slag and aggregate results have produced exact same results; therefore, the above table was inserted to show what the results were for both materials in the study. 0=No change in aggregates observed during the required time frame of thetest.

Methylene Blue Test

Methylene Blue Test is a rapid qualitative test for determining whether the clay content of the fines of an aggregate contains deleterious swelling clay minerals which could adversely affect the quality of the asphalt mixture (SAPEM, 2011). The deleterious swelling clay materials usually results in the weathering of rock. Experience shows that the methylene blue values of 5 or less are indicative of high-quality filler that can be used in asphalt mixtures. Fillers with methylene blue values above 5 should further be evaluated by means of hydrometer analysis and Atterberg analysis (IGDHSA, 2001).

The test is completed by weighing out by and dispersing 1g of a sample of material passing 0.075 mm sieve in water. The sample is then titrated with an indicator dissolved solution of methylene blue. Quantity of the solution is added in increments of 0.5ml until a fine halo appears. The amount of the solution is then calculated to achieve the effect (SANS 1243, 2012) as shown in Table4.

Table 4: Methylene Blue test results

Reference sample	Test Method	Requirement	Result
Dolerite	SANS 1243	<5: High quality filler >5: Additonal Testing Required	0,1
Slag	SANS 1243	<5: High quality filler >5: Additonal Testing Required	0,15

Particle Shape and Texture

The workability and stability of an asphalt mixture are affected by the shape of the aggregate particles. Angular aggregates promote stability while rounder aggregates tolerate the work ability. It is recommended that during the design and evaluation of the aggregates, 95% of the aggregates have at least 3 fractured faces. Flat, elongated and thin aggregates should be avoided as these types of shapes will cause problems during paving and compaction of the asphalt layer (SAPEM, 2014; IDGHSA, 2001). The tests discussed and evaluated are namely; Flakiness Index and Polish Stone Value.

Flakiness Index

The flakiness index of a coarse aggregate is known as the mass of particles in that aggregate which will pass the slots of specified width for the appropriate size fraction. This is expressed as a percentage of the total mass of that aggregate. The width of the slots is half that of the sieve openings through which each of the fractions passes (SAPEM, 2014; COLTO, 1998; IGDHSA, 2001; SANS 3001 – AG4, 2012).

The test is carried out by determining the percentage of the total mass of the aggregate that passes through slots of a specified width in a metal plate. The standards specify that the test should be carried out on two fractions of the aggregate. COLTO specifies maximum for flakiness index for aggregates (COLTO, 1998). The results of the testing are shown in Table 5. The flakiness index is a rough guide to describe the shape of the aggregate.

Table 5: Flakiness results according to specification (COLTO, 1998)

Nominal size of the aggregate	Maximum flakiness index	Slag	Natural Aggregate (Dolerite)
9,5mm	30	13,4	14.1
6,7mm	30	12,5	12,6

Polish Stone Value (PSV)

The PSV indicates a measure of the resistance of pavement stones to the polishing action of the vehicle tires under conditions similar to those occurring on the surface of a road (SANS 5848, 2008).

The PSV test is applicable to aggregates as it plays a major role in macro surface texture. The aggregates are subjected to accelerated polishing machine using emery abrasive powders and water. The PSV values relate to general conditions of traffic flow. For high and heavy traffic values, it is recommended that the PSV values are at a minimum value of 55 whereas, for low traffic volumes, the minimum value of 47 can be adopted. According to the SAPEM manual and COLTO, the required minimum specification should be at least 50 (SAPEM, 2014; COLTO, 1998; IGDHSA, 2001; SANS3001– AG11, 2012). The test is in two parts, namely;

1. Samples of stone subjected to a polishing action in a polishingmachine

2. State of polish reached is measured by means of a friction test and is expressed as the laboratory determined PSV.

Table 6: Polish Stone Value results

Ref	Test Method	Requirement	Result
Dolerite	SABS 848	Min: 50	53
Slag	SABS 848	Min: 50	52

Absorption

The test assesses the quality of the aggregates. Aggregate with high water absorption indicates poor qualities. Two tests are completed to finalise the concluded results. The tests are completed with aggregates retained on the 5mm sieve and then on material passing the 5mm sieve fractions. The water absorption test samples are soaked in water for 24hrs before being brought to a saturated surface dry condition and the weighed. The samples are then oven-dried and weighed. The results are expressed as a percentage defined as the loss of mass between saturated surface dry of the oven-dried aggregates. Table 7 shows the result comparison between the Slag and the Doleritesamples.

Table 7: Water absorption results

Test Method	Requirement	Dolerite				Slag			
		9,5mm	6,7mm	4,7mm	0-2,75mm	9,5mm	6,7mm	4,7mm	0-2,75mm
SANS3001– AG20&AG21	Max:1%bymass	0,6	0,4	0,7	0,4	0,8	0,7	0,9	0,4

Sand Equivalent

Sand equivalent test indicates the relative proportion of clay-like materials to sand particles in the granular material. The higher the sand equivalent value is, indicates that there is less clay-like material in the samples. Clay-like materials have a through effect on the performance of asphalt mixes, and the amount should be controlled. A large number of clay-like particles can coat the aggregate surfaces and prevent the binder from completely coating and adhering to the aggregate.

The test consists of fine aggregate passing the 5mm sieve. The sample is then oven dried and transferred into a transparent measuring cylinder. A solution of calcium chloride, glycerine and formaldehyde diluted in water is added to the sample. The transparent cylinder is thoroughly shaken after which a metal irrigator is used to flush fines upwards. The cylinder is then left to stand undisturbed. A weighted foot is inserted into the cylinder after 20 minutes at the top of the fines reading; it is then further lowered onto the sand readings. The sand equivalent is then calculated by expressing the fines reading as a percentage of the sand reading. High sand equivalent values specify improved quality fine aggregate compared to those with low sand equivalent values (SAPEM, 2014; SANS 3001 – AG5). Table 8 shows the sand equivalent results of both the Slag and the Dolerite samples.

Table 8: Sand Equivalent results

Reference sample	Test Method	Requirement	Result
Dolerite	SANS 3001 - AG6	Min: 50 on Total Fines Fraction	86,4
Slag	SANS 3001 - AG7	Min: 50 on Total Fines Fraction	79,2

Results and Discussion

It must be considered that for an effective asphalt layer, aggregates must display more rough angular material than smooth material. The properties of the aggregates must conform to the following set standards:

1. Hardness/ toughness
2. Durability
3. Shape and surfacetexture
4. Absorption and cleanliness

The Slag conformed well when compared to the natural aggregate. Ethylene Glycol test was included in the hardness/ toughness test, as the results must also conform to the set standard. Both Slag and the natural aggregate have performed well above the requirements of the hardness/toughness tests. However, the 6.7mm slag fraction has shown that it is "softer" than the natural aggregate but still is within the required specifications.

Both the natural aggregate and Slag conformed to the durability values of EGDI and Methylene Blue tests. All samples showed a zero effect when soaked in the EGDI and that, there are no substantial deleterious clays found with results of 0.1 for the natural aggregate and 0.15 for the Slag which would affect the asphalt mixture. Both the materials in this study showed high durability for a required life spandesign.

Shape and surface texture of the aggregates play an important role for work ability and compatibility of the asphalt mixture; therefore, it is critical that polish stone values and flakiness index are adhered to in the design process. The polish stone values are very close for both the materials in this study; values of 53 for the natural aggregate and 52 for the Slag respectively. No problems are foreseen in the workability and compatibility of the materials as each has very low flakiness index results. Both are very close to each other, thus showing that the Slag will have the same durability values required by the standards. The surface texture of these aggregates in this study affects the skid resistance of the layer. Both provide harsh textures, thus increase the skid resistance at low speeds.

Water absorption is another critical property, as this will indicate whether the aggregate is prone to exponential absorption that will affect the binding of the binder to the aggregate. It is thus critical that all results must be below 1% by mass. Calculating the average results obtained per grading, as shown in table 6, the results are 0.5 for the natural aggregate and 0.7 for the Slag. It has been known that Slag will absorb more binder that aggregates as they do contain more pores, but this will not affect the mixture as a result are still below the required standard.

The sand equivalent results show that very little clay-like materials are found with values of 79.2 for the Slag and 86.4 for the aggregate. This does show that the binder used for the specific mixture will have an affective bond, thus increasing the stability/ durability of the mixture.

Conclusion

The materials in this study are used to replace conventional materials that must be mined and processed; using by-product materials preserves natural resources and reduces the energy use and pollution associated with these activities. Using by-products could and probably will make the roads more durable. Therefore, maintenance is envisaged to be less frequent, which is good for the environment because to conserves natural resources andenergy.

It is shown in this study, that industrial materials offer significant performance enhancement benefits. Chrome slag in the asphalt layer is envisaged to have a high-friction surface that makes driving safer. The used Slag has comparable physical properties to the conventional aggregate and can be produced into desired practical sizes for easy batching into both surfacing and base asphalt layers. The utmost noteworthy difference between steel slag and most conventional aggregates is its high particle density, as a result of iron compounds.

This study has shown that the use of Slag as are placement of natural aggregate can be utilized in an asphalt mixture as the Slag conforms to the requirements as set out in design procedures developed for South African conditions. The study further showed that slag products are suitable materials for road construction and that the use of slag products will speed up the construction, as they are readily available and thus making the slag products more economical. The results can, therefore, be concluded that although the Slag does show softer toughness values than that of the Dolerite, it can still be used as a replacement for the natural aggregate with high conclusive foreseen performance. It is recommended, however, that all slagmaterials be thoroughly tested to ensure all physical properties are met for a specificproject.

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