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Comparison of technical and short-term environmental characteristics of weathered and fresh blast furnace slag aggregates for road base applications in South Africa

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ABSTRACT

This study investigated chemical, physical-mechanical and environmental characteristics of weathered blast furnace slag (WBFS) and freshly produced slag (FBFS) for their potential utilisation as granular road base and subbase aggregates. The X-ray fluorescence analysis revealed that each material exhibited a strong $CaO\text{-}SiO_2\text{-}MgO\text{-}Al_2O_3$ chemical system. The X-ray diffraction analysis detected the major mineral phases in WFBS as akermanite, gehlenite and monticellite that accounted for 91.4% of the total mineralogical phase composition. Akermanite and gehlenite accounted for 91% of the total mineralogical phase composition in FBFS. Both slags have weak cementitious properties. The aggregate crushing value, 10% fines aggregate crushing value, flakiness index, plasticity and compaction characteristics of both slag aggregates complied with the South African specifications for crushed stone base and subbase aggregate materials. Soaked California bearing ratio (CBR) values of 153% and 128% for WBFS and FBFS respectively meet the bearing strength requirement for their use in base and subbases. The two materials may also be considered as solid waste with low-risk environmental pollution. Low long term expansion values of 0.32% and 0.39% were observed for WBFS and FBFS respectively. The investigated characteristics indicate that these slags are suitable alternative materials for granular road base construction.

1. Introduction

Blast furnace slag (BFS) is a by-product from the iron manufacturing process where iron ore is reduced to molten iron when burned with coke material in a blast furnace. The quantity of blast furnace slag produced depends on the raw materials charged into the blast furnace. The amount ranges between 0.2 and 0.6 tons per ton of iron produced [1–3]. Worldwide production of iron from blast furnaces was approximately 10.6 billion tons between 2005 and 2016, while South Africa produced approximately 61.5 million tons of blast furnace iron over this period [4]. These production statistics denote a global generation of between 2.1 and 6.4 billion tons of blast furnace slag over this 12 year period. For South Africa, the iron World Steel Association production statistics translate to a generation of between 12 and 37 million tons of blast furnace slag over the indicated 12 year period.

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Iron ore mining and smelting in South Africa date back to pre-historic times, with evidence of historical slag accumulations in various parts of the country. Slags found in the Transvaal region date from the 4th century AD. Furthermore, with a history of industrial/large-scale blast furnace smelting in the country traced back to 1918 [5], there definitely are huge amounts of existing blast furnace slag accumulations around South Africa. The continued demand for iron and steel requires increasing land areas for disposal of the generated slags. Additionally, these by-products could potentially pollute the environment and may lead to human health challenges and loss of biodiversity. Slag re-use and recycling is thus an attractive alternative to reduce these potential environmental problems. It is also a means to conserve non-renewable aggregate resources which have been exploited for many centuries. Many of these natural aggregate resources are almost depleted or are of inadequate quality [6]. Blast furnace slag has great potential for use as an alternative coarse aggregate to replace conventional/natural coarse aggregates in constructing road subbase and bituminous surfacing layers [7].

Between 2000 and 2012, Japan reported a re-use of about 74% of air-cooled blast furnace in various road works [8]. An average of 31% of blast furnace slag generated in Europe was used in road construction over the same period [9]. Regrettably, there is scant documented literature on the utilisation of this by-product in road construction in South Africa. Some of the literature include an acknowledgement from the South African Roads Agency Limited (SANRAL) that despite blast furnace slag having different chemical and physical characteristics compared with conventional aggregates, crushed and screened blast furnace slag is of good quality, has good frictional and adhesion properties and therefore has potential for use in surfacing and in unbound subbase road layers [10].

1.1. Blast furnace slag aggregates in granular road bases

Successful utilisation of any slag as road aggregate material requires an understanding of the various properties of the particular slag product. Slag aggregates for use in road infrastructure, like any other aggregates, need to have physical, mechanical and chemical characteristics that can withstand long term static and dynamic forces and environmental effects. They also need to be environmentally acceptable [11,12] in terms of potential ground or groundwater contamination. Wang [13] underscores the need to characterise slags for their optimum use. This involves examining the slags' chemical, physical, mechanical, and environmental characteristics.

Poor slag aggregate materials can result in costly maintenance and reduced road pavement life. Failure modes related to poor aggregates in flexible pavements include rutting, depressions, corrugations, frost heave, fatigue cracking and longitudinal cracking. In rigid pavements, unsuitable aggregates can lead to pumping, cracking and corner breaks.

Literature reveals that air-cooled BFS aggregate has inherent properties that make it suitable for use in road base and subbases, with great potential for better engineering performance, durability and conservation of natural aggregates [14]. The slag exhibits high porosity and friction characteristics which makes it suitable for producing highly stable unbound base and subbase layers which are negligibly affected by water content variations. Furthermore the latent hydraulic properties in BFS can be exploited for the construction of hydraulically bound base layers [15]. The volumetric stability of BFS when compared with the instability of steel slags has also been highlighted in literature. Unlike steel slags BFS contains insignificant amounts of free lime (f-CaO) that makes it volumetrically stable [13]. The volumetric stability of BF slag implies that it can be used in road bases with little concern of possible volumetric expansion challenges. Other properties that make BFS a suitable material for granular base applications include its potential to stabilise moist and soft underlying soils if present, its capacity to exhibit negligible settlement once compacted, its high insulating value (a property that helps minimise frost heave) and its ease of placement in almost any weather. These good material characteristics have led to successful utilisation of air-cooled BFS as granular road base or subbase material in the United States of America [16].

Studies on BFS done in Australia have indicated that this by-product is a good alternative material in place of high quality crushed rock aggregates for constructing bound and unbound road bases [17]. It is no surprise therefore that BFS has been successfully used in the construction of subbase and base layers of motor ways and an airport runway in Australia [18]. In the Netherlands, BFS is one of the many secondary materials that has been successfully used as road base and subbase material since the 1970s. A recent study has, however, indicated that the material can pose some durability challenges that are related to potential chemical alterations (hydraulic reactions) within the slag grains and at the slag-slag grains interphases in a compacted slag layer. Over a long time this hydration reaction can cause volume changes and cracks in the BFS base layer, leading to failure of a road pavement [19]. Other challenges of using BFS in especially unbound road base layers include; leaching of some chemical elements that bring about elevated pH values, discolouration of ground water in contact with the slag and off-odour conditions of the ground in which it is placed [20].

This paper compares and discusses some technical and short-term environmental characteristics of two blast furnace slags; a freshly produced blast furnace slag (FBFS) and naturally weathered blast furnace slag (WBFS). The article aims at furthering the knowledge and understanding of weathered and freshly produced South African blast furnace slags as alternative raw materials for application in road construction. The work is a contribution to existing air cooled blast furnace slag technical knowledge that can be referred to for effective utilisation of this by-product in construction and civil engineering applications generally, and in granular road base and subbase designs and construction specifically.

2. Materials and methods

The investigated materials were obtained from two sources in South Africa's Gauteng Province. The freshly produced air cooled blast furnace slag (FBFS) was obtained from an operating iron production plant, while the weathered air cooled blast furnace slag (WBFS) was obtained from an aggregate crusher plant which processes slag aggregate from a slag dumpsite comprising historical blast furnace slag deposits. This dumpsite operated from 1934 until the 1980s. It therefore holds historical air-cooled blast furnace slag deposits that have been dumped there for more than 25 years. Over time, the slag has been exposed to outdoor rainfall and other weather changes and hence considered as naturally weathered.

The micro characteristics of the slag in this study have been investigated using the following analytical techniques: chemical analysis by X-ray fluorescence (XRF) spectrometry, mineralogical analysis by X-ray diffraction (XRD), microstructural analysis and chemical microanalysis by scanning electron microscopy and energy dispersive spectroscopy (SEM-EDS)

The XRD analysis was performed on slag samples ground to finer than 75 μm. The equipment used is a PANalytical X'Pert Pro powder diffractometer in 2θ configuration with an X'Celerator detector, variable divergence and fixed receiving slits with Fe filtered Co-Kα radiation ($\lambda = 1.789$ Å). The mineralogical phases were identified using the X'Pert Highscore plus software. The relative phase amounts (weight %) were estimated using the Rietveld method's Autoquan Program.

For the XRF analysis, the samples were prepared as pressed powders. The ARL Perform'X Sequential XRF Spectrometer with Uniquant software was used for analysis. The software determines all elements in the periodic table between Na and U, but only elements found above the detection limits were reported.

The slags' macro characteristics were investigated using laboratory test procedures outlined in the South African National Standards (SANS) test procedures. The tests included: Particle size distribution (PSD) (SANS 3001-GR2:2011); bulk density (BD), apparent relative density (ARD) and water absorption (WA) of aggregate (SANS 3001 – AG21:2011); aggregate crushing value (ACV) and 10% fines aggregate crushing test (10%FACT) (SANS 3001-AG10:2012); flakiness index (FI) (SANS 3001 – AG4:2009); maximum dry density and optimum moisture content (MDD and OMC) (SANS 3001-GR30:2010) and California bearing ratio (CBR) - (SANS 3001-GR40:2013).

The toxicity characteristic leaching procedure (TCLP) test (US EPA Method 1311) was used to assess the slags' short-term environmental characteristics.

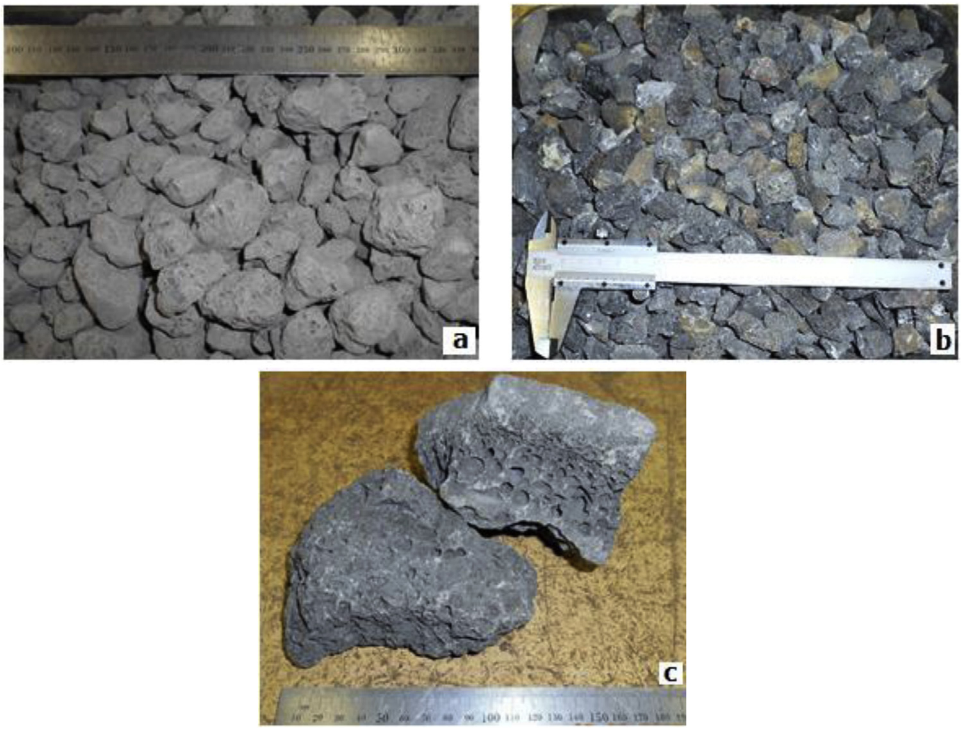

Fig. 1. Physical appearance of slag; a) crushed WBFS, b) crushed FBFS, c) and uncrushed FBFS cobble.

3. Results and discussion

3.1. Macro-structural description

The WBFS was obtained as already crushed and screened aggregate (Fig. 1a) from which aggregate of nominal size of -2 mm, 6.75 mm, 9.5 mm, 13.5 mm, 19 mm and 26.5 mm could be obtained. The coarse particles have angular, roughly cubical shapes with vesicular surfaces. The FBFS was obtained as non-metallic cobbles and boulders. The physical appearance of these rock-like pieces had varied angular and cubical shapes with rough honey combed/vesicular structure appearing as unconnected blind holes on the particle surfaces (Fig. 1c). Some of the cobbles and boulders also revealed glassy surfaces with conchoidal fractures. These cobbles and boulders were crushed using a laboratory jaw crusher. The crushed particles resulted in irregular, slightly flaky and angular aggregates.

3.2. Chemical and mineralogical micro-characteristics

3.2.1. X-ray florescence (XRF) results

The XRF results of the WBFS and FBFS presented in Table 1 reveal that despite these materials being produced at two different iron manufacturing plants at different times, their chemical compositions are very similar. The CaO-SiO_2-MgO-Al_2O_3 (lime, silica, magnesia and alumina) chemical system forms more than 93% of the total oxide composition of both slag samples. These results compare closely with other data reported in the literature ([21–24]) on the chemical constituents of blast furnace slags. Nonetheless, it is noted that apart from the MgO and marginally for the S and P_2O_5, all the oxides in WBFS had generally lower percentage weight compositions than those of FBFS, although the differences are very small. The differences, especially with regard to MgO could be attributed to different fluxes used in the blast furnace during the production of the slags. For these slags, dolomite flux was used in the production of WBFS, hence the higher MgO content. A limestone flux was used for the FBFS production.

The CaO, MgO, and Al_2O_3 oxides represent the major elements that enhance the hydraulic reactivity of slags and contribute to increased chemical cementation when water, lime and other materials are added to the slag [25,26]. The SiO_2 compound, on the other hand tends to reduce slag hydraulicity [26]. Various relationships involving CaO, MgO, Al_2O_3 and SiO_2 have, in this regard, been proposed to evaluate the potential hydraulicity of steel and blast furnace slags. Some of these relationships are presented in Table 2, and have been used to assess the hydraulicity potential (HP) ratio of the WBFS and FBFS aggregates.

The HP ratio calculations, especially from the second and third relationships in Table 2 indicate that the FBFS has marginal hydraulicity and may be considered to have very low self-cementing capacity. The WBFS can be said to have moderate hydraulicity and may be considered to have some self-cementing capacity.

3.2.2. X-ray diffraction (XRD) results

The XRD patterns of the two slag samples are shown in Figs. 2 and 3 while the main mineralogical phases identified in the slags are shown in Table 3.

Both FBFS and WBFS are rich in magnesium and/or calcium silicate compounds. The major mineralogical phases are akermanite, gehlenite and monticellite making up 91.4% of the total mineralogical phase composition in WFBS, and akermanite and gehlenite comprising 91% of the total mineralogical phase composition in the FBFS.

Ettringite, identified in WBFS is a calcium-aluminium-sulphate mineral. It is a phase that is formed intentionally during the early hydration stages of most Portland cements [28], due to the intentional addition of gypsum in cement manufacture to control the rate of formation of the calcium aluminates.

In concrete, ettringite is a product of the reaction of sulphates with aluminate hydrates. It can be an immediate product of, for example, the reaction of gypsum with anhydrous calcium aluminate, occurring within a few hours of the concrete production. This early ettringite formation (EEF) product is destroyed by high temperature (>70 °C) steam curing and therefore cause insignificant expansion problems in concrete [29]. When ettringite precipitates in small pores of hardened concrete over a long time, a phenomenon called delayed ettringite formation (DEF) occurs [29,30]. Under DEF, ettringite can extensively form in concrete due to internal sulphate attack. This happens when concrete is exposed to conditions of intermittent or permanent water wetting, combined with late sulphate release, micro-cracking and reactive aggregates.

Table 1
Oxide chemical compositions of WBFS and FBFS from XRF analysis.

	CaO	SiO_2	MgO	Al_2O_3	Fe_2O_3	S	MnO	K_2O	TiO_2	BaO	N_2O	SrO	P_2O_5	ZrO_2	Others
WBFS (% wt)	32.54	32.53	17.60	12.14	1.59	1.05	1.03	0.60	0.44	0.15	0.12	0.06	0.05	0.04	0.06*
FBFS (% wt)	35.09	35.51	9.16	13.72	1.75	0.59	1.37	1.26	0.63	0.36	0.30	0.10	0.02	0.05	0.09*

[*] Others include Cr_2O_3, Y_2O_3, CeO_2, MoO_3, Cl, ZnO, CuO, Nd_2O_3, V_2O_5, Co_3O_4, Nb_2O_5. The quantities of each of these elements were 0.01% or less in both material samples.

Table 2
Assessment of the hydraulicity of slags.

	Formula and hydraulicity potential (HP) ratio – adapted from [27]		HP ratio of studied slags	
	Relationship	HP ratio indicating material is cementitious	WBFS	FBFS
1	CaO/SiO_2	1.3 – 1.4	1.0	0.99
2	$(CaO + MgO)/SiO_2$	>1.4	1.54	1.25
3	$(CaO + MgO)/(SiO_2 + Al_2O_3)$	1.0 – 1.3	1.12	0.90

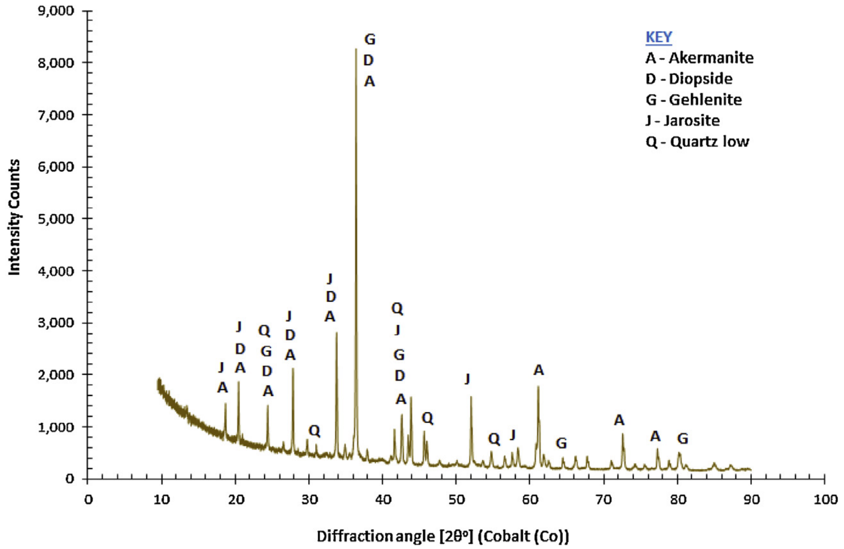

Fig. 2. XRD pattern of FBFS.

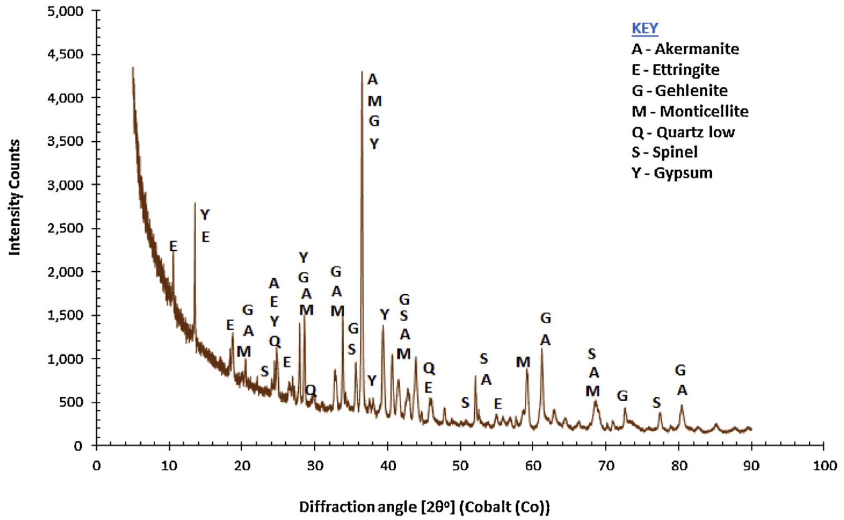

Fig. 3. XRD pattern of WBFS.

Ettringite thus formed causes significant volume expansion of concrete, leading to damage of structures. The DEF phenomenon particularly occurs in steam cured concrete and takes place many years after concrete curing [29,31].

Gypsum, a minor mineral phase identified in WBFS is a hydration reaction product from a combination of $CaSO_2$ and H_2O. The ettringite and gypsum in WBFS point to occurrence of hydration reactions in the stockpile/dump of this material, due to its exposure to wetting and drying cycles over many years.

Table 3
Main mineralogical phases identified in the two slag samples.

WBFS			FBFS		
Mineralogical phase	Chemical formula	Weight (%)	Mineralogical phase	Chemical formula	Weight (%)
Akermanite	$Ca_2MgSi_2O_7$	36.28	Akermanite	$Ca_2MgSi_2O_7$	66.49
Gehlenite (C_2AS)	$Ca_2Al(AlSi)O_7$	22.89	Gehlenite (C_2AS)	$Ca_2Al(AlSi)O_7$	24.5
Ettringite	$Ca_6Al_2(SO_4)_3(OH)_{12}\bullet 26H_2O$	3.46	Diopside	$CaMgSi_2O_6$	5.81
Gypsum	$CaSO_4\bullet 2H_2O$	2.54	Jarosite	$KFe_3^{3+}(SO_4)_2(OH)_6$	1.57
Monticellite	$CaMgSiO_4$	32.18	Quartz	SiO_2	1.63
Quartz	SiO_2	0.19			
Spinel	$MgAl_2O_4$	2.46			

Four mineralogical phases in the WBFS and FBFS namely, monticellite, arkermanite, diopside and spinel contain the MgO chemical component, an oxide relevant to cement chemistry if it occurs in suitable amounts that do not lead to material expansion problems [28]. If present in its free form (Periclase), and especially as large clusteres, it can hydrate and lead to significant expansion problems in slags. Snellings et al. [32], however, assert that the MgO present in blast furnace slag, in contrast to that occuring in some steel slags, is unlikely to lead to destructive expansion. This can be attributed to its occurrence as small particles and also its wide distribution through the blast furnace slags.

Absence of portlandite ($Ca(OH)_2$), a hydration product in slag materials with free calcium oxide (f-CaO) indicates that these blast furnace slags contain insignificant or no f-CaO and may not cause volumetric expansion problems when these materials are used in road construction.

3.2.3. Element atomic composition by EDS

Two main image sectors observed as dark and light areas from the scanning electron microscope (SEM) images of the surfaces of gravel sized slag particles are shown in Figs. 4 and 6 . Some focus points on these images were targeted for further characterization using the energy dispersive spectroscopy (EDS). These spots are represented as spectra 1, 2, 3 and 4 in Figs. 4 and 6. A total number of four analyses were made for the FBFS. Fig. 4 is an example of one of the four.

Heterogeneous composition results for individual chemical elements were obtained at all the four spectra points indicated in Fig. 4 for the FBFS. Analysis of results from the four spectra points resulted in large error bars especially for elements C, O, Si, Al and Ca plotted in Fig. 5. This indicates a wide spread of values around the averages for the elements observed at the four spectra points.

The combination of atomic elements Ca, Si, Mg, Al and O make up atleast 51% of the total element composition of the FBFS. This, correlates quite well with the CaO-SiO_2-MgO-Al_2O_3 oxide combination from the XRF analysis. The high content of element C detected from the EDS analysis could be indicative of the presence of some unburnt coal in the examined slag particle.

Homogeneous composition results for individual chemical elements were obtained at all the four spectrum points for the WBFS. This is reflected by small error bars plotted in Fig. 7, implying that the plotted data are very close to the average values. The EDS analyses of all focus points reveal that the combination of elements Ca, Si, Mg, Al and O makes up more than 80% of

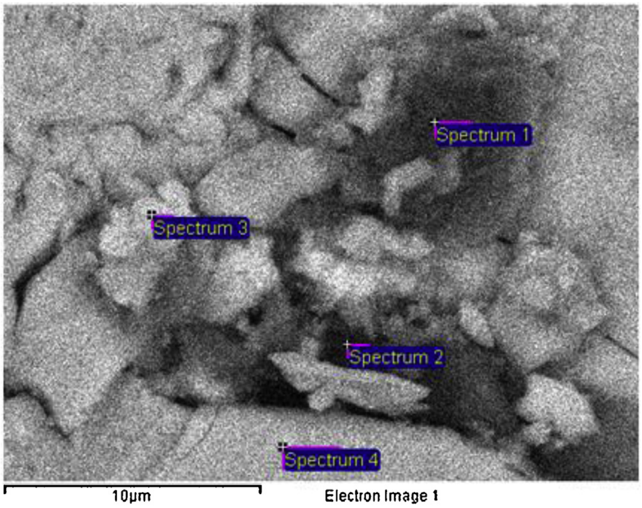

Fig. 4. SEM micrograph of gravel-sized FBFS with spectra 1, 2, 3 and 4 used for elemental analysis.

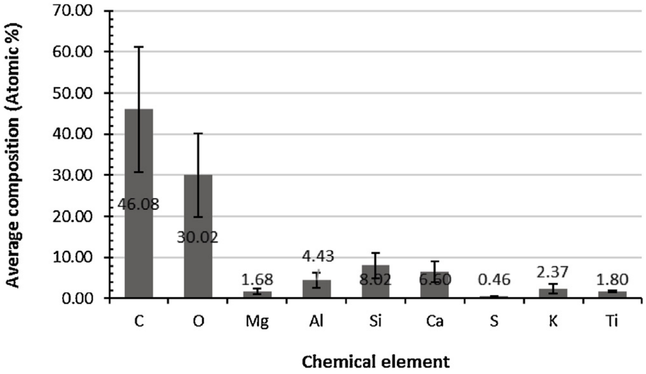

Fig. 5. Combined average atomic composition of chemical elements in FBFS from spectra 1, 2, 3 and 4.

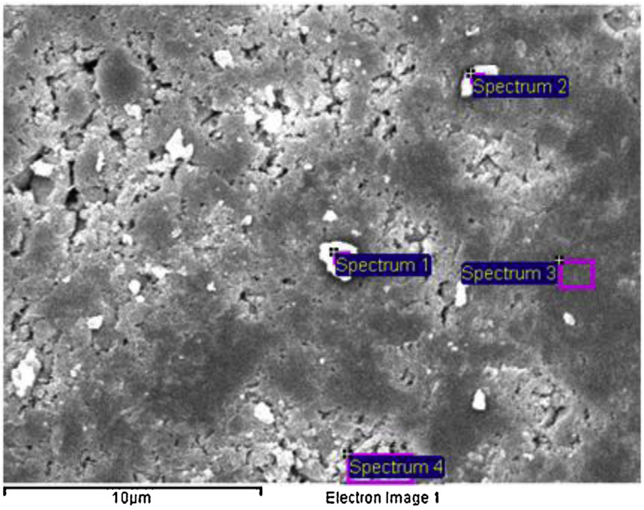

Fig. 6. SEM micrograph of gravel-sized WBFS with spectra 1, 2, 3 and 4 used for elemental analysis.

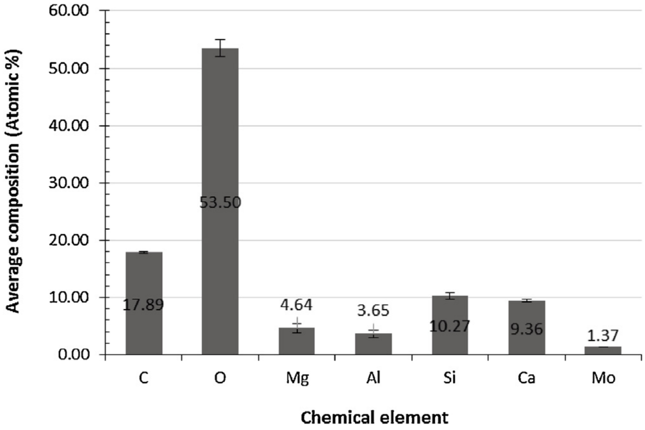

Fig. 7. Combined average atomic composition of chemical elements in WBFS from spectra 1, 2, 3 and 4.

the total composition. This is in strong agreement with the WBFS's strong CaO-SiO_2-MgO-Al_2O_3 oxide combination in the XRF analysis (Table 1). A total number of four analyses were made for the WBFS. Fig. 7 is an example of one of the four.

The microstructure images of the two slags showed some marked differences. Micropores on the surface of the WBFS slag particle could be clearly seen at the SEM image magnification of 10 μm as opposed to FBFS. This indicates a more porous WBFS compared with the FBFS.

3.3. Physical and mechanical macro-characteristics

3.3.1. Bulk density, apparent density and water absorption of different particle sizes

The bulk density (BD) and apparent relative density (ARD) results are presented in Fig. 8. The general trend is a slight reduction in both BD and ARD with increased particle size. However, the 9.5–13.2 mm particle size range produced the highest BD and ARD results while the 19–26.5 mm particle size range yielded the lowest values. The observed reduction in density with increasing particle size are attributed to the presence of more voids in some of the larger slag aggregates, compared with lesser voids in the smaller particles.

A comparison of the two materials revealed that the FBFS exhibited higher BD and ARD values than the WBFS aggregates. The overall average BD for all the particle size ranges for WBFS was 2322 kg/m^3 which was 3% lower than the 2402 kg/m^3 for FBFS. The overall average ARD for all the particle size ranges for WBFS was 2506 kg/m^3 which was 2% lower than the 2555 kg/m^3 for FBFS.

The FBFS exhibited lower WA compared with WBFS (Fig. 9). The higher WA of WBFS compared with that of FBFS are in harmony with the observations of the SEM micrographs of the FBFS and WBFS in Figs. 4 and 6 where the micropores of WFBS were clearly observed indicating its high porosity, and therefore capable of absorbing more water than the FBFS. The overall average WA for all the particle size ranges for WBFS was 3.61% which was 46% higher than the 2.47% for the FBFS.

The bulk densinsities of conventional aggregates range between 1200 and 1800 kg/m^3 [33]. The aircooled blast furnace aggregates in this study can, in this regard, be classified as heavy aggregates. The water absorption of both the WBFS and FBFS are high in relation to Southern African quarried natural aggregates, which typically have WA values below 0,5%, although some aggregates can have significantly higher absorption values than this [34]. Generally, the water absorption of natural aggregates increases as the number of weathered particles in the aggregate increases.

The overall average FI for all the particle size ranges was 5.6% for WBFS which was 175% better than the 15.4% for FBFS (Fig. 10). The major reason for this big difference is that the FBFS aggregate was produced from a laboratory jaw crusher which generated very flaky particles. In contrast, the WBFS aggregate was produced from a commercial crusher plant where aggregate sizes reduction is systematically done. This resulted in angular and roughly cubical WBFS particles, especially for the bigger size fractions, that yielded good FI results. It is, however, noted that FI is a controllable property that can be manipulated by selecting appropriate crusher plant, reduction ratios, feed size and feed rate. This means that it is possible to produce FBFS aggregate sizes that can produce FI results similar to those obtained from the WBFS aggregates.

3.3.2. Aggregate crushing value (ACV) and 10% fines aggregate crushing test (10%FACT) value

Duplicate sample sets were tested for these characteristics. Average results are presented in Table 4. The WBFS aggregates yielded better ACV and 10% FACT results compared with the FBFS aggregates. The poor ACV results for FBFS aggregates are attributed to the poor FI results of this materials, which is known to have a marked influence on the crushing strength [33].

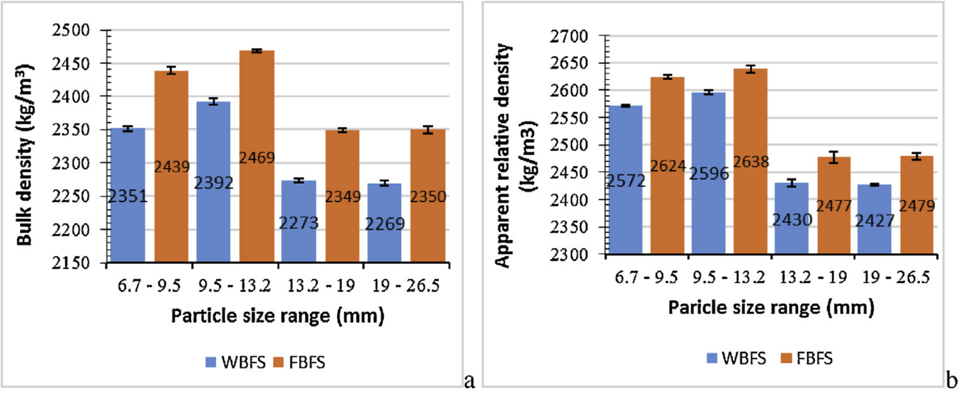

Fig. 8. Bulk density and apparent relative densities of different particle size ranges; a) Comparison of bulk densities of WBFS and FBFS; b) Comparison of apparent relative densities of WBFS and FBFS.

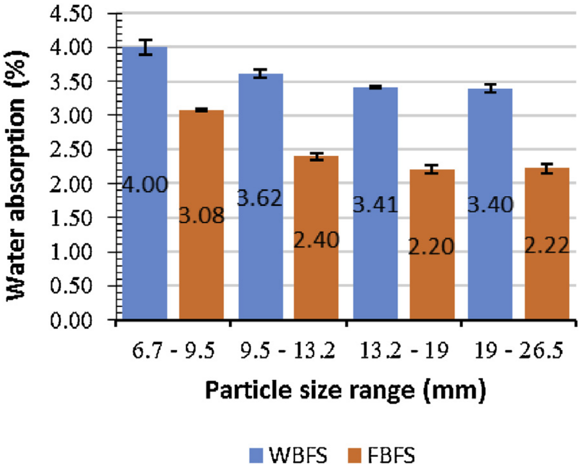

Fig. 9. Water absorption of different particle size ranges for WBFS and FBFS.

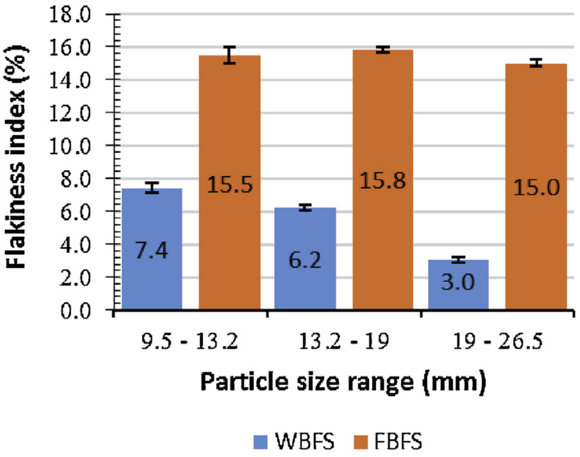

Fig. 10. Flakiness index of different particle size ranges for WBFS and FBFS.

Table 4
Dry and wet ACV and dry and wet 10% FACT values of slags.

Property	WBF slag	FBF slag
Dry ACV (%)	26	32
Wet ACV (%)	22	31
Dry 10% FACT (kN)	174	111
Wet 10% FACT (kN)	165	101
Wet/Dry Ratio of 10% FACT	94.8	90.9

3.3.3. Compaction and California bearing ratio (CBR) results

The samples used for compaction and subsequently for CBR tests were prepared in such a way that their particle size distribution (PSD) met the criteria of Fuller's maximum density grading curve, a PSD that ensures maximum density of compacted road aggregate material. These distribution curves are presented in Fig. 11.

An automatic compactor that applies a compaction energy of about 2.6 MJ/m^3 was used for compacting the slag materials with reconstituted Fuller particle size distribution grading. This compaction method is similar to the Mod AASHTO compaction procedure.

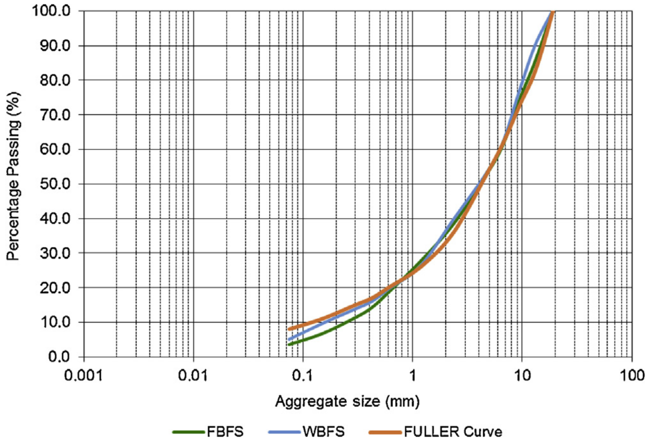

Fig. 11. Particle size distribution of FBFS and WBFS samples, and the Fuller grading curve.

The compaction curves of the two slag materials are shown in Fig. 12 while CBR results are reported in Table 5. The compaction experiments yielded maximum dry densities (MDDs) of 2056 and 2004 kg/m^3 and optimum moisture contents (OMCs) of 7.4% and 6.4% for FBFS and WBFS respectively. From the geotechnical engineering principles, a higher MDD is usually accompanied by a lower OMC. This, however, is not the case with compaction characteristics in this study where the material with the higher MDD had the higher OMC while the one with the lower MDD had the lower OMC. An explanation of this behaviour is that for these non-plastic slag materials, their aggregate shape and void space significantly affect their maximum achievable dry density. The flaky FBFS aggregate resulted in an aggregate specimen with high void space. Some crushing of these flaky particles which needed more wetting for better workability to fill up of the large void spaces could have led to a higher MDD of FBFS compared with that of WBFS.

The compaction results show that FBFS has a slightly (2.6%) higher maximum dry density (MDD) and a 15.6% higher optimum moisture content (OMC) compared with the MDD and OMC values for the WBFS for the same compaction effort.

The unsoaked CBR value of WBFS was 29% higher, while it's soaked CBR was 25% higher than that of FBFS. Many base course aggregate specifications require CBR values in excess of 80% whereas subbase specifications require minimum CBR values in the range of 20%–50% [35]. Both soaked and unsoaked CBR test procedures are, furthermore, recognised as indicators of road pavement performance and have been widely used as strength indicators in pavement structural design [36]. The unsoaked and soaked CBR results obtained for both FBFS and WBFS were more than 80% and therefore render the slags suitable for road base application.

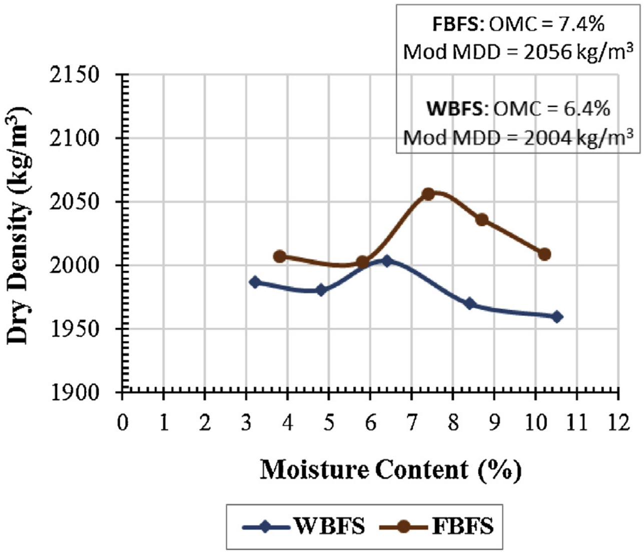

Fig. 12. Compaction curves of WBFS and FBFS.

Table 5
Comparison of physical and mechanical characteristics of blast furnace slags with the COLTO [44] specification for granular road bases.

	This study		Comparison with South African COLTO specification for aggregates in granular road bases	
Characteristic	WBFS	FBFS	COLTO Specification	Comparison
Dry ACV (%)	26	32	< 29% for siliceous cementing material[*]	WFBS was 3 % better than the limit and FBFS was 3% above the limit
Wet ACV (%)	22	31	–	Not itemised by COLTO specification
Dry 10% FACT (kN)	174	111	>110 kN for siliceous cementing material[*]	64 kN above the limit for WBFS and just about the specification for FBFS
Wet 10% FACT (kN)	165	101	–	Not itemised by COLTO specification
Wet/Dry Ratio of 10% FACT	94.8	90.9	>75%	19.8% above limit for WFBS and 15.9 % above limit for FBFS
Flakiness Index (%)	5.6	15.4	<35%	WBFS was 29.4% better than the limit and FBFS was 19.6 % better than the limit
Plasticity Index (for aggregates < 0.425 mm test sieve)	Non-plastic	Non-plastic	<5% for G1 <6% for G2 & G3	Non-plastic slag fines in both materials
Compaction (kg/m^3)	Mod MDD of 2004 kN/m^3, 80% of ARD and 86% of BD	Mod MDD of 2056 kN/m^3, 80% of ARD and 86% of BD	Minimum of 88% of ARD for G1 material; Minimum of 85% of BRD[§] for G2 material; 98% or 100% of modified AASHTO density for G3	Mod MDD for WBFS is 86% of its BD and Mod MDD for FBFS is 85% of its BD. The materials therefore qualify as class G2 aggregate
CBR (%)	169 (unsoaked), 153 (soaked)	140 (unsoaked), 128 (soaked)	–	Not itemised by COLTO specification

[*] Both FBFS and WBFS are considered to have siliceous cementing matrix in view of the considerable amount of SiO$_2$ obtained from XRF analysis.
[§] Bulk relative density.

3.3.4. Long-term expansion test characteristics

Some slag aggregates may contain expansive chemical compounds such as free lime (CaO) and/or free periclase (MgO). Hydration of these chemical compounds can cause significant expansion or swell and pop-outs and may lead to the disintegration of the aggregate. These reactions can negatively affect the performance of a structure made with such slags.

Expansion or swelling tests can either be conducted as short-term tests such as accelerated hot-water bath and autoclave expansion tests or as long-term swelling tests using compacted samples immersed in water tanks and maintained at room temperature. Long term swelling tests are considered as better simulators of the in-situ conditions and are known to provide more accurate swelling rate for unbound applications, compared with quickly done short-term accelerated swelling tests [25,37].

In the long-term swelling test experiments in this study, slag specimens, were compacted at their optimum moisture contents in the CBR moulds. After compaction, surcharges (soaking weights) equivalent to approximately 3 kPa were placed on the top of the compacted samples. These compacted sample assemblies were then soaked in water and the one-dimensional expansion of the compacted samples was monitored for a period of 111 days at room temperature.

A two-method swell measurement technique involving a dial gauge mounted on a CBR tripod and digital Vernier callipers were used in the experiment. Three reference points were marked on top of each of the CBR moulds for measuring the expansion using the depth rod of the Vernier callipers, from which an average was recorded. These measurements were checked against the measurements obtained from the conventional dial gauge method which is mounted on a CBR tripod. The two-method swell measurement technique was used to ensure accuracy in the expansion readings.

The swell readings were then used to evaluate the one-dimension volumetric expansion, ε, using the formula

$$\varepsilon = \frac{\Delta V}{V} * 100\% \quad (1)$$

Where: ΔV is the change in volume

V is the initial volume

The results of the long-term one-dimension volumetric expansion of the two slags after swell measurements over a period of 111 days are presented in Figure 14.

Following an initial expansion of 0.16% after the first four days, the FBFS steadily expanded until the 104th day after which it showed signs of stabilisation to a value of about 0.39%. For the WBFS, the steady increase after the 4th day stabilised to 0.32% on the 98th day Fig. 13.

The stabilising of the expansion values for the FBFS at 0.39% and WBFS at 0.32% after the 104th and 98th days, respectively, indicate insignificant amounts of expansive compounds such as free CaO and/ or free MgO in these slags. Moreover, these expansion values comply very favourably with expansion limits that are, for example, recommended for steel slags. The literature has shown that in Japan the acceptable expansion limit for steel slag meant for use in road pavement construction is 1.5% or less when assessed from the hot water bath expansion test [3]. The Chinese recommend a steel slag expansion limited to less than 2%, assessed from the steam expansion test [38,39]. The Brazilian specifications recommend an

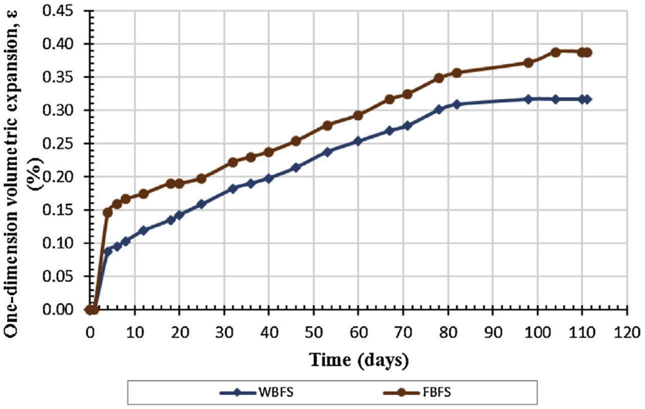

Fig. 13. Long term one-dimension volumetric expansion characteristics of the slags.

expansion limit of less than 3%, assessed from the hot water bath expansion test [40]. Furthermore, considering that a volume expansion of ≤2.5% from the water-soaking tests is satisfactory for aggregates for granular road base construction [41], the two blast furnace slags are excellent probable materials for use in granular road base construction as regards their expansion characteristics.

3.4. Compliance of slag aggregate properties with the COLTO specification

Assessment of the compliance of the physical and mechanical characteristics of the slag aggregates studied against the COLTO specifications (Committee of Land Transport Officials (COLTO), 1998) for granular road bases is presented in Table 5. The following are the assessment results:

a The WBFS aggregates complied with the dry ACV COLTO recommended maximum value of 29%. The FBFS yielded an ACV that was 3% above the specified limit.
b The WBFS aggregates complied with the dry 10% FACT COLTO specified minimum value of 110 kN. The FBFS was marginal with respect to the specified limit, but would suffice for low volume roads.
c Both slag aggregates complied with the COLTO requirements of the wet/dry ratio for the 10% FACT for durability specified at a minimum value of 75%, and the flakiness index maximum value of 35%.
d Both slag aggregates have non-plastic fines. The slag aggregate gradations, synthetically manipulated to form the Fuller PSDs, conform to the G2 aggregate compaction requirements and could, therefore be considered as G2 aggregate material.

It is noted that the FBFS aggregates marginally complied with the COLTO requirements (with regard to the ACV and 10% FACT) because they were products of a laboratory jaw crusher, which tends to produce flaky aggregates. Conventional aggregate crushing plants can optimize crushing procedures and produce FBFS aggregate particles that would be expected to yield better ACV and 10% FACT results than the ones recorded in this study. In this regard, both investigated slag aggregate types could be considered compliant with the COLTO requirements.

Table 6
Comparison of physical and mechanical characteristics of blast furnace slags with the ASTM D2940-03 and the UK Specification for Highway Works requirements.

This study			ASTM D2940-03 and the UK Specification for Highway Works comparisons		
Characteristic	**WBFS**	**FBFS**	**ASTM** D2940-03 (2003)	Manual of Contract Documents for Highway Works [43]**	**Comparison**
Water Absorption (WA) (%)	3.61	2.47	<10	<2	The slags' WA are above the limit for the UK specification. Okay for ASTM D2940-03 specification
Wet 10% FACT (kN)	165	101	>50	>50	Slags meet the requirements for UK and ASTM D2940-03 specifications
Flakiness Index (%)	5.6	15.4	<40	<35	ditto
Plasticity Index	Non-plastic	Non-plastic	–	Non-plastic	Slags meet the requirements for UK specification
CBR$_{soaked}$ (%)	153	128	–	–	Not specified in UK and ASTM D2940-03 specifications

-Not itemised in the respective specification.
** Requirements for Type 1 subbase materials that include crushed rock, crushed slag, crushed concrete or well burnt non-plastic shale.

3.5. Compliance of the investigated slag aggregate properties with other specifications

Further comparison of some slag aggregate properties with the American Standard specification for graded aggregate material for bases or subbases for highways or airports [42] and the United Kingdom (UK) Specification for Highway Works [43] is presented in Table 6. It is noted that apart from not meeting the requirement for water absorption under the UK Specification for Highway Works, the rest of the WBFS and the FBFS characteristics meet the requirements of the UK and ASTM D2940-03 specifications for road base and subbases.

4. Short-term environmental characteristics of the slags

The environmental characteristics were investigated using the TCLP experiments. The TCLP is a short term leaching procedure used to identify hazardous substances in waste and to classify it as either hazardous or non-hazardous.

The TCLP analysis results of the two slags are shown in Table 7. These results are compared with the South Africa National Norms and Standards for Assessment of Waste for Landfill Disposal, the Environmental Protection Agency (EPA) reference document on hazardous waste characteristics, the South Africa National Standards for Drinking Water and the World Health Organisation (WHO) Guidelines for Drinking Water Quality.

The results in Table 7 show that the studied slags do not exhibit toxic characteristics when evaluated against the EPA hazardous waste criteria. These materials may therefore be considered as non-hazardous solid wastes with regard to the EPA regulatory levels. Furthermore, almost all the elements, apart from Hg, Mn, Sb and Se, meet the criteria for classification as inert waste under the South African National Norms and Standards for the Assessment of Waste for Landfill Disposal. The materials may therefore be considered as low-risk solid waste.

However, the leached quantities of Al, Ca, Fe, Hg, Mn, Sb and Se are significantly more than the regulatory levels stipulated by the South Africa National Standards for Drinking Water and the WHO Guidelines for Drinking Water Quality. This implies that if these slags were subjected to acidic environments that could induce full leaching, there is a risk of toxic elements leaching from the material with a possibility of polluting the nearby ground and water sources.

It must be noted, nonetheless, that the acidic pH under which the TCLP test is done may not reflect the actual field pH conditions and therefore the leaching of toxic elements is very unlikely. It is further noted that in the leaching test, free leachant movement occurs removing all possible soluble leachate. In a road, the water reaches an equilibrium moisture content in the base and subbase and does not flow through the layers removing all of the possible leachate. In addition, the

Table 7
TCLP analysis results compared with SA, EPA and WHO regulatory levels for waste and drinking water.

	TCLP concentration of element in leachate (mg/l)		Regulatory limits in different standards/guidelines in mg/l				
Element analysed	Studied WBFS	Studied FBFS	SA Inert waste threshold[1]	SA Low-risk waste threshold[1]	EPA Regulatory level for solid waste[2]	SA Regulatory level for drinking water[3]	WHO Regulatory level for drinking water[4]
Ag	<0.01	<0.01	–	–	5.0	–	–
Al	3.99	7.84	–	–	–	0.3	0.2
As	<0.01	<0.01	0.01	0.5	5.0	0.01	0.01
B	0.46	0.34	0.5	25	–	2.4	2.4
Ba	0.29	0.33	0.7	35	100	0.7	1.3
Ca	468.9	253.1	–	–	–	300	–
Cd	<0.01	<0.01	0.003	0.15	1.0	0.003	0.003
Co	0.01	0.14	0.5	25	–	0.5	–
Cr(total)	<0.01	<0.01	0.1	5	5.0	0.05	0.05
Cu	<0.01	<0.01	2.0	100	–	2.0	2.0
Fe	25.5	42.3	–	–	–	2.0	–
Hg	0.05	0.05	0.006	0.3	0.2	0.006	0.006
Mg	65.4	43.4	–	–	–	70	–
Mn	47.8	41.4	0.5	25	–	0.4	0.4
Mo	<0.01	<0.01	0.07	3.5	–	–	0.07
Ni	<0.01	0.03	0.07	3.5	–	0.07	0.07
Pb	<0.01	<0.01	0.01	0.5	5.0	0.01	0.01
Sb	0.05	0.03	0.02	1.0	–	0.02	0.02
Se	0.74	0.66	0.01	0.5	1.0	0.04	0.04
V	<0.01	<0.01	0.2	10	–	0.2	–
Zn	<0.01	<0.01	5.0	250	–	5.0	–

- No regulatory level proposed.

[1] South Africa National Norms and Standards for Assesment of Waste for Landfill Disposal based on TCLP test results [46].

[2] Environmental Protection Agency (EPA) reference document on hazardous waste characteristics [47].

[3] South Africa (SA) National Standards on Drinking Water [45].

[4] World Health Organisation (WHO) Guidelines for Drinking Water Quality [48].

limited leachate removed is likely to be distributed over a large area and should have little or no impact on the environment outside the road reserve. The use of the slags in roads, therefore, provides a controlled environmental impact with limited leaching problems compared with the almost uncontrolled leaching in the areas around the slag dumps, especially the older ones established prior to environmental controls and requirements.

5. Conclusions

The chemical compositions of the FBFS and WBFS materials showed almost identical results. Both slags showed a strong CaO-SiO_2-MgO-Al_2O_3 chemical combination making up more than 93% of the total oxides. The major mineralogical phases identified were akermanite, gehlenite and monticelite for WBFS and akermanite and gehlenite for FBFS. These account for about 91% of the total mineralogical phases. Both XRF and XRD results point to a weak cementitious property in the slags. However, this property could still be potentially exploited to produce semi-bound base and subbase road layers with the addition of slaked lime or cement, thus increasing the load carrying capacity of a road pavement.

The microstructure of WBFS revealed clearly identifiable micropores on the slag particle, observed on the SEM image. This indicated higher porosity of the WBFS than the FBFS. The higher water absorption results of WBFS compared with those of the FBFS confirmed this SEM observations.

The ACV, 10% FACT, flakiness index, plasticity and compaction characteristics of both FBFS and WBFS complied with the South African COLTO specifications for crushed stone base and subbase aggregate materials. Furthermore, the slags' wet 10% FACT, flakiness index, plasticity index and CBR (soaked) properties met requirements of the American standard specification for graded aggregate material for bases or subbases for highways or airports and the United Kingdom (UK) Specification for Highway Works.

The good ACV, 10% FACT, flakiness index and CBR results obtained particularly from tests on WBFS point to the blast furnace slags' toughness, durability and high bearing strength properties that can be advatageously used to construct durable road base and subbase layers. Both WBFS and FBFS meet the generally accepted requirements of minimum 80% CBR for base and between 20 and 80% CBR value for subbase courses. In addition, the low long-term expansion property of the two slag materials make them suitable alternative materials for use in granular road base construction.

The studied slags have been classified as low-risk solid waste. Leaching of toxic elements from the slags may only occur if the slags were subjected to acidic environments, a situation which is very unlikely in many road bases.

The results from this study show that South African blast furnace slags can be used as valuable non-traditional substitutes for non-renewable natural gravels and aggregates in road construction. These materials have a potential for substantial environmental and sustainability benefits.

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