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PRELIMINARY DEVELOPMENT OF SLAG AS A STABILISED MATERIAL FOR LABOUR INTENSIVE CONSTRUCTION OF ROADS -.

M.R. Lieuw Kie Song
Research Centre for Employment Creation in Construction, University of the Witwatersrand, Johannesburg, South Africa

S. Emery
Department of Civil Engineering, University of the Witwatersrand, Johannesburg, South Africa
Department of Civil Engineering,

Abstract

Stabilisation of natural pavement materials to make road pavements is widespread in South Africa, using cement and lime as cementitious binders. The rapid speed of the cementing reaction limits these to plant based construction. Some hydraulic binders have the potential to be developed for Labour Intensive Construction stabilisation technology because their slow hydration reaction allows time to work with the material and place it by hand without loss of quality. The mixture of LD slag and GBFS has such a potential, and there has been limited use of it as a road building material elsewhere. However because its properties vary widely, it needs to be investigated individually for each plant.

The potential employment benefits of using a mixture of slag as a road basecourse were calculated, assuming that it was hauled from a locally based central mixing plant, spread, shaped, compacted and cured using labour intensive methods. The percentage of the costs that went to labour compared well with other labour intensive technologies such as waterbound macadam.

The laboratory investigation covered the reactivity of the mixture, the use of gypsum as an accelerator, the stockpile life of the mixture, and the strength gain upon hydration. The results obtained so far show that the Witwatersrand LD slag activates Vanderbijlpark GBFS. This slag mixture hydrates to become a bound (cemented) material suitable for road pavement use. A suitable mixture including a small amount of Milled GBFS has been shown to provide a material which, although variable, is close to the South African C3/C4 stabilised road material classification.

Keywords: Labour-intensive construction, LD- slag, Granulated Blast Furnace Slag, Stabilisation

1. Introduction

Stabilisation of natural pavement materials for use in roads is widespread in South Africa, since many uncrushed natural materials are too weak to be used in the upper pavement layers. Cement, lime and bitumen are the stabilisers commonly used. The rapid speed of reaction of cement and lime means that only plant based construction is fast enough to mix the stabiliser into the natural material, spread out the material and compact it before the stabilisation process is too far advanced. The plant based technologies needed with cement and lime stabilisers, and the widespread use of such stabilisation, means that Labour Intensive Construction (LIC) has been excluded from a significant section of the road construction industry.

Some hydraulic binders, such as ground blast furnace slag (GBFS), have a much slower speed of stabilisation reaction, and this has the potential to develop as a LIC stabilisation technology. The slow hydration reaction of this material allows ample time to work with the material and place it by hand without loss of quality. Blast furnace slag has been used as a stabiliser with success in parts of Europe and recently in Tanzania. In South Africa, several slags are available but are treated almost as a waste material. Some have particular properties, which have rendered them unsuitable for use as a road building material in their pure form. The research programme then was to develop a suitable slag mixture, which would perform as a stabilised material, and concomitantly develop the technology to use the slag mixture in LIC.

Previous research (Lieuw Kie Song, 1999) has shown that the stabilisation reaction does occur with South African slag materials, and that there are employment benefits. This paper describes further research into refining the type and mix of slag to obtain a suitable stabilised mixture, with the ability to stockpile the material for use in LIC. Firstly though, the potential employment intensity of the use of this material is compared with that of other road building materials serving the same function.

2. Potential Employment Intensity

The normal cementitious stabilisation process in roads consists of thoroughly mixing 1-5% of cement or lime with a natural gravel or sand, spreading the stabilised material along the road, adjusting the moisture content to the desired compaction moisture content (typically by adding water), and compacting and shaping the material to form a pavement layer. For a single pavement layer (such as the basecourse) in a kilometre of two-lane road, this typically means 3,500 tonnes of natural material and up to 200 tonnes of stabiliser to be mixed.

For a mixture of slag forming a suitable stabilised mixture, the construction process and volumes are very similar. In adapting the process to LIC, it was recognised that the large volumes involved are difficult to mix thoroughly by hand. The need for efficiency and quality suggested mixing the materials in a central mixing plant. If the plant is located well away from the construction site, transport is probably better by plant. However close in haul, and the spreading and compaction of the slag mixture does lend itself to LIC on all roads which can be constructed at a more leisurely pace. These would include roads in developing areas, sub-divisional roads, and many light traffic roads.

Thus the slag mixture could be stockpiled along the road a day or so prior to the construction of the road layers. At construction, water would be added to adjust the moisture content to the optimum for compaction, as well as to kick start the hydration process. A workforce of 100 labourers could typically lay and compact a kilometre in 4-5 days (for a 150mm thick layer, 8 metres wide, with stockpiles of slag mixture along the road), with a few labourers needed for the subsequent curing.

The potential employment benefits of using a mixture of slag as a basecourse (Lieuw Kie Song 1999) have been calculated for the central mixing plant and hand laying technology. This assumed that it was hauled from a locally based central mixing plant, spread, shaped, compacted and cured using labour intensive methods. It was found that even if this combination of equipment and labour was used, the percentage of the costs that went to labour compared well with other labour intensive technologies. The various base course technologies are compared and presented in Table 1.

Table 1 Employment intensity for various base course materials

Construction type	Relative rating of total costs	Cost of plant and equipment	Labour component	Material component	Production rate	Dominant features
Crushed stone	1	35-45%	7-12%	40-45%	Fast	Low employment
Slag stabilised base course	*0.7-1.5*	*15-24%*	*13-29%*	*56-63%*	*Slow*	*High material costs*
Waterbound macadam	1-1.10	35-45%	20-30%	20-30%	Medium	High plant costs
Slurry-bound Macadam	1-1.20	25-30%	25-35%	30-40%	Medium	Low equipment costs
Foam gravel	0.9-1.15	40-45%	10-15%	35-45%	Fast	Fast construction
Emulsion treated bases	0.7-1.2	30-40%	30-35%	20-30%	Slow	Low maintenance costs

Source: Labour-intensive construction guidelines for Macadam pavements, a design manual, Potgieter et al. 1998 (For the non GBFS stabilized bases)

This analysis and the comparison with other base course materials shows that this basecourse material has similar percentages of cost going to labour, as other basecourses whose construction process is also considered to be labour-intensive. The high variation in cost is the variable transport cost depending on the proximity of the source of slag. The economics of using a slag mixture as a pavement layer will be largely determined by the distance to the slag source.

3. Slag materials

The two main types of slag investigated in this research are steel or Linz-Donawitz slag from steel mills, and Granulated Blast Furnace Slag from blast furnaces making raw iron. Both have been previously considered as road construction materials in their own right (Sherwood, 1995), but with only limited success.

3.1 Steel (LD) slag

Steel or Linz-Donawitz (LD) slag, is produced in the conversion of raw iron into steel using the Linz-Donawitz process. It is also referred to as Blast Oxygen Furnace Slag (BOF) slag. After the slag, which comes out of the steel furnace molten, is air-cooled it resembles grey sandy gravel. Large quantities of lime (CaO) are used in this refining process and, although most of it exists in bound crystalline form with the other constituents, LD slag can also contain free lime and magnesia. Belgium research found that the free lime content in the LD slag can vary between 0 and 5% (Choquet 1984).

The free lime present in the slag can react with water to form hydrated lime according to the reaction below:

$$CaO + H_2O \rightarrow Ca\,(OH)_2 + \text{heat}$$

In this reaction heat is released and the lime expands making the LD slag volumetrically unstable. If used in a pavement layer, the material will hydrate and the layer will swell, heave and crack unacceptably. The chemical composition of LD slag is represented in Table 2. It should be noted that not all the CaO in the material exists as free lime, but most of it exists in bound crystallised form with the other constituents.

Table 2: Most important constituents of LD slag produced at Iscor in Vanderbijlpark, SA

Constituent	Percentage
SiO_2	12.5
Al_2O_3	4.1
CaO	36.4
MgO	8.9
Fe_2O_3	15.3
FeO	12.1
Fe	3.9
MnO	4.8

Source: Suprachem specifications

LD slag is produced in all the steel producing regions in South Africa, the most important of which are the Witwatersrand area, Newcastle in KwaZulu Natal and the Saldhana region in the Western Cape. The annual production in the Vanderbijlpark area alone is 430,000 tons, which is sufficient for the construction of roughly 170 km of 15 cm thick basecourse for two lane roads.

Previous experience in South Africa with LD slag in road construction has not been satisfactory. LD slag was used as a base course material on some roads in the Vanderbijlpark area, but these roads deteriorated rapidly after construction and had to be reconstructed using other materials. The most likely reason for this poor performance are, as discussed earlier, that the free lime in the LD slag hydrated and caused the material to swell. However no detailed studies of these road sections and the reasons for deterioration have been done yet. After these experiences the use of LD slag as a road building material was discontinued in this area.

3.2 Granulated Blast Furnace Slag

The other slag used in this research is Granulated Blast Furnace Slag (GBFS) which is produced in the refining of iron-ore into raw iron. GBFS is formed when the molten slag is rapidly cooled to a temperature below 800°C. It has similar chemical constituents as ordinary Portland cement and also has cementitious properties. Because of these properties, it is milled and mixed with Ordinary Portland cement (OPC) to produce what is commonly known as Blast Furnace cement. This has been used as a cement to make cement stabilised road materials. In its raw form, GBFS resembles sand with a 0-2mm grain size.

GBFS and OPC are chemically similar in that they contain CaO, MgO, SiO_2 and Al_2O_3. These do not occur as compounds however, but exist as part of such complicated chemical structures that the composition of these materials is often expressed as if these compounds existed separately within the material. The ways in which these constituents are combined are different in OPC and GBFS and this is one of the important differences. The ratios in which these four constituents occur are also different between OPC and GBFS. Table 3 provides an overview of the different constituents of GBFS from various sources in RSA and of typical OPC. The composition and the structure of the slag are the two main factors influencing the reactivity of GBFS.

Table 3: Typical Analysis of Ordinary Portland Cement and South African GBFS. (in % by mass)

		Slag Source (SA)	
Constituent	**Portland cement**	**Vanderbijlpark**	**Newcastle**
SiO_2	22	32.4	35.7
Al_2O_3	5	16.8	12.9
CaO	66	32.0	34.9
MgO	1.6	10.5	9.9
SO_3	1.0	1.6	1.0
Fe_2O_3	3.1	0.74	0.89
Mn_2O_3	0.1	1.0	0.98
P_2O_5	0.2	0.01	0.02
Na_2O	0.3	0.2	0.1
K_2O	1.0	1.03	0.81

Sources: Cement Chemistry, HFW Taylor p 105
Slagment specifications

The main consequence of this is that, unlike OPC, GBFS does not exhibit continued hydration if placed in water unless it is activated (by adding an alkali). Surface analysis by X-ray photoelectron spectrometry showed however that the slag surface was modified as soon as it came into contact with water. The most widely accepted theory as to why no apparent hydration occurs is that this modified layer formed around the particles is protective and thus prevents further hydration when they come in contact with water. This layer is currently believed to consist of an incongruent dissolution and a C-S-H hydrated layer but with very low Ca^{2+} concentration (Regourd et. al.1983).

It could thus be argued that the protective layer effectively inhibits the further hydration of the slag until it is activated by placing in a high pH environment. The exact mechanism by which the alkali attacks the protective layer and activates the reaction is very complicated and is still subject of research, but various mechanisms have been proposed. What is known is that lime is a very effective activator of GBFS. Thus in construction, the GBFS is activated with lime, and then water is added to enable the hydration to proceed, eventually leading to a cementitiously bound material. The rate of hydration is much slower than with OPC.

3.3 Mixture of steel slag (LD) and GBFS

Based on the activation mechanism described above and the properties of the steel (LD) slag and the GBFS, the attraction of using the two together as a road material becomes more apparent. The free lime present in the LD slag can act as the activator for GBFS, allowing the stabilisation reaction upon hydration, and an increase in strength. Furthermore if the lime is consumed in this stabilisation reaction, less of it will be available for reacting with water to produce hydrated lime, the reaction that is responsible for the expansion, and the potential swelling will decrease. As such, LD slag that might have unacceptable volumetric instability by itself, might be sufficiently stable when the free lime is used to activated the GBFS. However if a combination of the two types of slag that has acceptable properties can be formulated, the initial critical properties of both types of slag would need to be identified and specified.

In The Netherlands such a mix is being sold commercially as “Duomix”. It consists of 85% LD slag and 15 % GBFS. The strength improvement of this mix in the Netherlands is not very high. One example is a strength increase from a CBR of 50% for the unstabilised material to a minimum CBR of 125% after stabilisation and 28 days of curing (Pelt & Hooykaas, 2000). However because the properties of the constituent materials vary by plant, specific mixture must be developed individually.

The mix of LD and GBFS slag would be used as the pavement layer material itself, to be used in similar applications as cementitiously stabilised materials. As with all bound materials, there are always possible cracking problems and care will need to be taken to minimize these so that they remain acceptable. Furthermore the potential of swelling caused by the free lime in the LD slag that does not react with the GBFS also needs to be investigated. If the cracking and/or swelling can be predicted and controlled however, this material could be a very attractive road building material.

3.4 Slag as a cementitious binder in road construction

Slag has been used as a cementitious binder in road construction, although this lies outside the scope of this research. The properties of blast-furnace slags have been developed in France under the title gravè-laitier (gravel-slag) to stabilise gravel and sands for sub-base and base construction. Gravè-laitier is the most widely used road base material in France and it is estimated that 65% of French roads have a pavement layer composed of gravè-laitier. An extension of the process is to use air-cooled crushed slag as the coarse component of the mixture when, to use French terminology, the ‘gravè’ is replaced by slag and the product is known as ‘gravè-laitier tout laitier’.

A similar technique to the ‘gravè-laitier’ process is used in South Africa where ground granulated blast furnace slag (GGBFS) is known, somewhat confusingly, as milled granulated blast furnace slag (MGBS), and sold commercially as “Slagment”. South African specifications give a ratio of four parts of MGBS to one of hydrated lime as the optimum proportions, but suggest that equal parts of MGBS and lime are often used since this is a convenient ratio in practice even though more lime may be used than is needed.

4. Laboratory testing of slag mixtures

The laboratory testing programme so far has mostly focused on the strength development of the slag mixtures. The primary objective of this initial testing was to establish whether the free lime in the LD slag made in South Africa would indeed activate the South African GBFS, and that subsequently hydration would take place if these materials were mixed and compacted with water added.

4.1 Grading

Figure 1 shows the gradation of the steel slag (LD or Basic Oxygen Furnace slag), the GBFS and the LD-GBFS mix. There is an improvement in the grading of the mixture, and it lies closer to the Fuller maximum density curve. From basic soils principles, this alone will give better mechanical properties for the mixture than the individual slags alone.

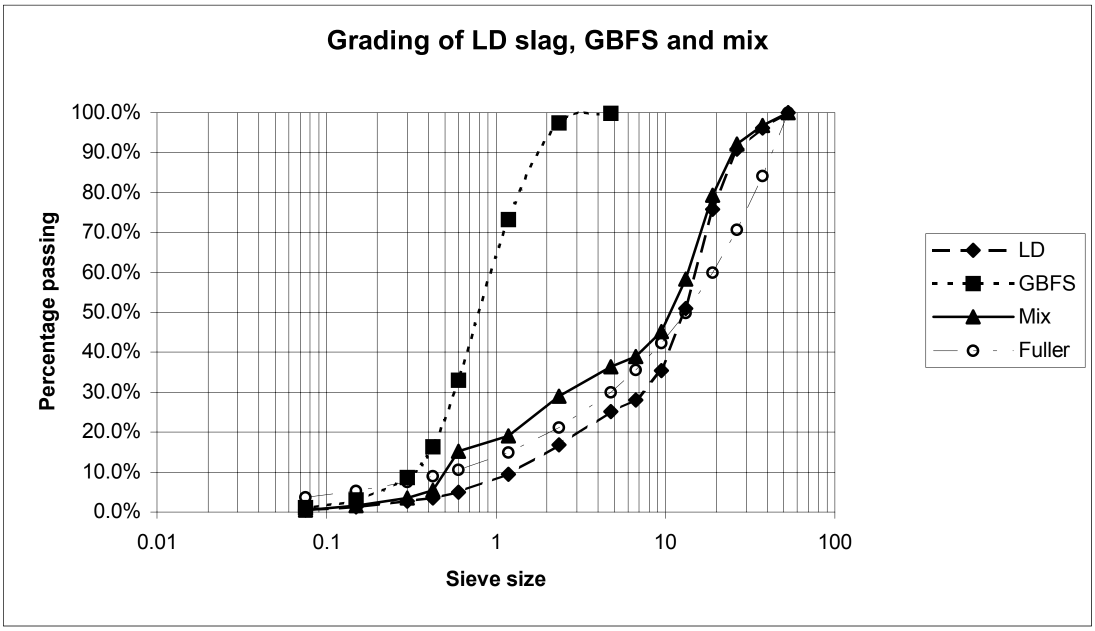

Fig. 1: Gradation of LD slag, GBFS and LD-GBFS mix

4.2 Strength

Strength testing of the mixtures was undertaken using the road industry standard unconfined compressive strength (UCS) of stabilised soils test (TMH 1, Test method A14 in CSRA, 1986). The laboratory strength of the cemented material is compared to Table 4 to determine the classification of the cemented material for design purposes; C3 and C4 are the most commonly used classes for light traffic roads.

The reactivity of slag varies between works, and is measured by a so-called alpha (α) coefficient, which is defined as:

$$\alpha = S \times P \times 10^{-3}$$

where S is the Blaine specific surface (cm^2/g) of the natural fines of the granulated slag (<80μm); and P is the friability property determined by milling the slag. Because of low reactivity (low α) of the GBFS produced at the Vanderbijlpark works, it was decided to include some milled GBFS (known commercially as “Slagment”) in the mixture to increase the reactivity.

Table 4 Design strength for cemented materials (TRH 14 from CSRA, 1985)

Property	C1		C2		C3*		C4*	
	min	max	min	max	min	max	min	max
UCS (7 days) @ 100% Mod AASHTO density (MPa)	6	12	3	6	1.5	3	0.75	1.5
UCS (7 days) @ 97% Mod. AASHTO density (MPa)	4	8	2	4	1	2	0.5	1

Notes * maximum strength given as a guide only

The composition of the samples was as follows:

85% Witwatersrand LD slag
13.2% Raw Vanderbijlpark GBFS
1.8 % Milled GBFS (Slagment)

Gypsum ($CaSO_4$) was trialled as an accelerator for the hydration of GBFS (Talling and Brandstetr 1989). Two samples were prepared by adding 1 percent of calcium sulphate to the standard mixture. The optimum moisture content of this mix was found to be 7.5%. After mixing the samples, water as added to bring the samples to this moisture content, and they were compacted. After compaction they were cured for 28 days in a plastic bucket. The test results are presented in Table 5.

Table 5: UCS strengths of initial set of samples

Sample	UCS strength (MPa)
Without $CaSO_4$	8.6
	4.7
With $CaSO_4$ accelerator	11.3
	4.8

Despite the spread of these results, they were still encouraging because of the high strengths obtained. The samples with the lowest strength still had a 28-day strength of 4.8 MPa which compares very well with other cemented materials used in road construction. Because cemented road building materials are tested after 7 days in South Africa, a direct comparison is difficult with these results. All samples were compacted to 100% of the Mod. AASHTO density.

4.3 Additional testing

Given the (almost too) high strength, and the variability of the initial results, additional testing was undertaken and new variables were included in this round of testing. The effect of different curing times was investigated and samples were tested after 7, 28 and 90days of curing. To assess the suitability for stockpiling which is an essential component of LIC using this material, The effect of delays in between mixing and compaction of the materials was also investigated and materials were stockpiled for 1 and 3 days before being compacted. The effect of adding the accelerator, anhydrous $CaSO_4$, was also tested again. The results of these tests are presented in Figure 2.

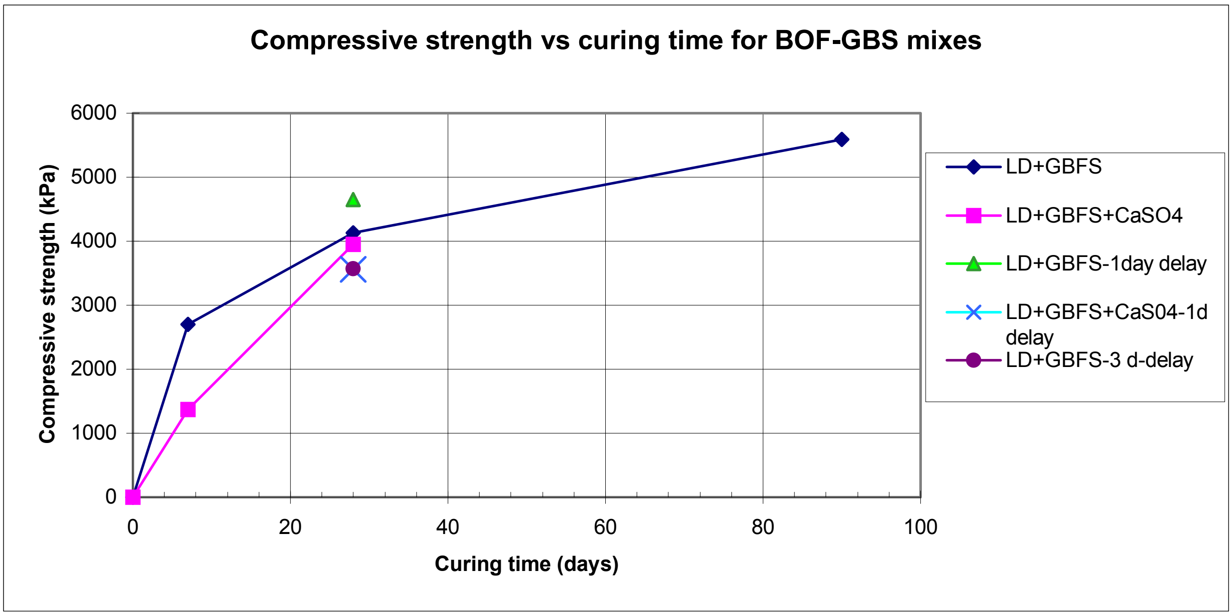

Fig. 2: UCS strengths of various slag mixtures.

The results will first be discussed with respect to the individual variables that were investigated. The first to be discussed will be the effect of adding the accelerator, Anhydrous calcium sulphate ($CaSO_4$).

4.3.1 Effect of adding $CaSO_4$

In the first strength tests, it was unclear as to the effect of $CaSO_4$ on the speed of strength development. The results from the additional tests showed no clear difference between the 28-day strength of samples with $CaSO_4$ added and those without. The samples with $CaSO_4$ have a lower 7-day strength which suggests that the $CaSO_4$ only affects early strength. The most likely conclusion however is that the CaSO4 has no effect on the strength development. As such it was concluded not to investigate the addition of this chemical any further.

4.3.2 Effect of curing time

The strength increase with increased curing time was as expected. Because most of the GBFS was unmilled, and thus had a smaller specific surface area and a lower □ reactivity, one would expect a slower and more prolonged hydration and this was the case as well with the materials that were cured for 90 days. The 90-day strength was 35% higher than the 28 day strength and the slope of the strength vs. time graph indicates that even after 90 days significant continued strength increases can be expected.

The materials tested after 7 days met the minimum strength requirement of the C4 material only. The mix without $CaSO_4$ also meet the requirements for a C3 material. Too short a curing period is disadvantageous for these slag mixes because it limits the time for working by labour. The longer time of strength gain also has the advantage of a lower heat of hydration and less cracking of the subsequent stabilised material. The results show that although the 7-day strength of the slag mixture might be lower than cement stabilised materials, with its continued strength development, the 28-day and longer-term strengths will compare favourably. The use of slag mixture would probably require a revision to the TRH 14 specification criteria to recognise this and to enable the slag mixture to be used within the normal design framework. This may include a lower 7 day (to give a rapid test result) and a comparable 28 day strength.

4.3.3 Effect of stockpiling on the material

The samples whose materials were stockpiled for one day before being compacted showed no significant difference from those compacted immediately. One set of samples showed a 12% higher strength. The samples that were stockpiled for three days showed a 14% lower strength. This is in proportion to the high variability of strength with this material. However more testing is necessary to find the maximum stockpiling time before strength reductions starts taking place. The addition of the milled GBFS will make the material more reactive, and samples without milled GBFS are expected to be less sensitive to stockpiling time but are also more likely to have lower initial strengths.

The considerable variability between samples is to be expected because of the variability of the amount of free lime in the LD slag. This is also related to the exposure to water after the slag has been produced. As slag is produced and stockpiled, and exposed to atmospheric water vapour or even rain, some of the free lime will start reacting with the water. The longer the material has been stockpiled, the more free lime will have been hydrated and the less reactive but more stable the material will become.

5. Further research

Given the high strength of the materials and the potential employment creation benefits the research on these materials is continuing. The testing is focused on the properties of the stabilised LD slag and not on the properties of the LD slag alone, and this includes:

- Volumetric stability of stabilised material
- Cracking behaviour
  Shrinkage cracking is a concern with all cemented materials, but given the slow reaction of the GBFS it is expected that this will be less of a concern as compared to more rapidly reacting stabilisers like OPC.
- Determination of optimal mix
  The initial mix ratios of LD slag, raw GBFS and milled GBFS were partially based on practice in the Netherlands and partially on experience with using GBFS produced in Vanderbijlpark as a stabiliser (Lieuw Kie Song 1999). More optimal combinations may exist.
- Influence of stockpiling/construction delays
  There appears to be no effect on the material when stockpiling for up to 3 days. More testing is necessary however to confirm this and to find after what time strength loss of the compacted materials starts to occur.
- Effect of using aged LD slag on strength development and volumetric stability

Because of the reactivity of LD slag changes as it ages, the aging of LD slag before its activation needs to be considered.

6 Conclusions

The mix of steel (LD) slag and Granulated Blast Furnace Slag (GBFS) has potential to be used as a road pavement layer material, in similar applications to traditional cement stabilised materials. The results obtained so far show that the LD slag activates the GBFS, and this slag mixture hydrates to become a bound (cemented) material. The slag mixture has a slow rate of development of strength, and appears to be able to be stockpiled before use.

Used in labour intensive construction, the slag would be mixed in a locally based central mixing plant, and then hauled, spread, shaped, compacted and cured using labour intensive methods. It was found that even using the combination of equipment and labour, the percentage of the costs that went to labour compared well with other labour intensive road construction technologies such as waterbound macadam.

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Contact details for Authors:
Maikel R. Lieuw Kie Song
Department of Civil Engineering
Private Bag 3, WITS 2050
Tel: +27 11 717 7137
Fax: +27 11 339 1762
E-mail: Maikel@civil.wits.ac.za