AN EVALUATION OF THE USE OF BY-PRODUCT PHOSPHOGYPSUM AS A PAVEMENT MATERIAL FOR ROADS

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1. INTRODUCTION

Although the construction of new roads and rehabilitation of older roads in South Africa is currently being hampered by the prevailing economic climate, there is no doubt that upgrading and development of the road network in the short term is essential. The availability of conventional construction materials is simultaneously decreasing and their delivery is becoming increasingly costly, it is therefore essential to evaluate alternative materials for possible use in road construction.

Urbanisation and industrialisation have resulted in a serious depletion of high quality construction materials in developed areas, but they have resulted in large accumulations of waste materials and industrial residues. Typical examples of these are mine waste rock and slimes, domestic refuse, slags and ashes and industrial by-products such as phosphogypsum from the fertiliser industry. Work carried out overseas has shown that many of these materials have considerable potential as road construction materials and can be very cost-effective.

This paper summarises the background and road building properties of by-product phosphogypsum and discusses the preliminary results of a laboratory investigation of the product and a number of field trials using phosphogypsum in the Lethabong Metropolitan Local Council (MLC) area.

2. CONVENTIONAL ROAD CONSTRUCTION MATERIALS

Over the last 80 years or so, the art of using unprocessed and processed natural materials with or without chemical or bituminous stabilisers has been developed to a high degree in South Africa. This has resulted in a great deal of experience with the construction of roads using these materials and a comprehensive system of specifications and pavement designs has been developed. These designs and specifications allow roads to be constructed with a high degree of confidence for the environmental and traffic conditions expected. The experience gained over the years by contractors has also resulted in very competitive tendering, as contractors understand and know these materials well.

Traditional specifications make use of the material strength but over the years proxies for the strength in terms of plasticity index and particle size distribution parameters, e.g. grading modulus, have evolved to simplify and reduce the cost of material testing and construction control. As a result of this, engineers are often reluctant to make use of materials with unusual particle size distributions or plasticity properties, despite the materials having a California Bearing Ratio (CBR) or, in the case of stabilised materials, an Unconfined Compressive Strength (UCS) comparable with that of traditionally specified materials.

More stringent environmental concerns over the last decade have resulted in legislation requiring Environmental Management Project Reports (EMPR) for any borrow pit or quarry established for the provision of road construction materials. This, together with the rapidly escalating value of property and hence expropriation costs for borrow pits, has resulted in an increase in the cost of providing natural materials for road construction. As materials probably make up about 70 per cent of the cost of a typical rural road[1], significant benefits can be achieved by using materials that are already Aprocessed@ and stockpiled.

3. POSSIBLE ALTERNATIVE MATERIALS

Much of the development that will take place in the next decade will be associated with the expansion of existing urban areas and their adjacent peri-urban areas. As the urban areas develop the inter-urban communication routes will also require upgrading. It is in these developing areas and corridors that natural construction materials are being depleted and stockpiles of waste and by-product materials are increasing. A potentially valuable resource is waiting to be utilised.

Large stockpiles of industrial and mine discard occur in South Africa, many of them well within economic haul distance for road construction in urban areas. These stockpiles sterilise large areas of property that is urgently needed to assist with the provision of housing and have significant environmental implications, frequently resulting in air, water and soil pollution.

Materials such as mine dump rock and slimes, steel slags, power station and industrial ash, flyash and old rubber tyres have already proved to be useful in road construction in South Africa while materials such as broken glass, sulphur produced from the oil and petrochemical industry, crushed concrete rubble, shredded plastics and recycled asphalt paving (RAP) have been used for road construction in other countries.

Research into potential uses of other waste/by-product materials (not necessarily only as road construction materials) is currently being undertaken in South Africa but a concerted effort should be made to evaluate a wider range of materials. The Institute for Recyclable Materials (IRM) has been established in a cooperative agreement between CSIR and University of Pretoria to facilitate this process.

4. BY-PRODUCT PHOSPHOGYPSUM (BPG)

4.1 Background

The production of phosphate fertilisers from phosphate bearing rock by reaction with sulphuric acid results in a residue of acidic calcium sulphate (phosphogypsum). This is a finely grained material, which is pumped to dams where it is stockpiled. With time, the material dries out and the acidic nature becomes reduced. Dihydrate calcium sulphate ($CaSO_4.2H_2O$) makes up about 98 per cent of typical BPG deposits.

Large stockpiles of phosphogypsum are located at the now non-operative Chloorkop plant of AECI (2 million tonnes) as well as at the Potchefstroom plant (5 million tonnes increasing by 240 000 tonnes per annum). Both of these sources are within economic haul distance for road projects in Gauteng Province as well as other areas in North West Province and Mpumalanga. Other deposits in South Africa could be economically viable for use in growth centres in KwaZulu Natal and in the Western Cape Province.

Phosphogypsum is a major by-product generated in the United States with significant production in Texas, Florida and Louisiana. Major research studies have been carried out in all of these States and in all cases, BPG was found to be a potentially useful substitute for traditional road construction materials[2]. The USA researchers have not been able to extend their testing programme much beyond experimentation because of factors unique within the USA. Numerous experimental sections have, however, been constructed in Texas and monitored over extended periods with very good results.

4.2 Laboratory testing

Transportek, CSIR at the request of AECI (Ltd), has recently carried out a preliminary evaluation of the material available at Chloorkop. The investigation included a study of the variability of the stockpile, the basic engineering properties of the material and more detailed investigations into how the material could best be used in road construction in the area.

For the variability study, ten samples of BPG were collected from various parts of the Chloorkop dump and laboratory testing to determine the range of selected test results was carried out. The results are summarised in Table 1.

Table 1: Results of variability testing of BPG from Chloorkop (10 samples)

Property	Mean	Standard deviation	Minimum	Maximum	Coefficient of variation
Moisture content (%)	24.28	8.70	18.70	48.20	0.357
Apparent relative Density	2.42	0.013	2.39	2.44	0.005
Bulk relative Density	2.28	0.015	2.26	2.30	0.007
PH	6.01	0.30	5.30	6.40	0.050
Volatiles (%)	34.77	2.90	31.80	41.80	0.082
$CaSO_4$ (%)	91.07	1.50	87.90	92.90	0.016
Ca^{++}	1.57	0.40	1.00	2.40	0.245
% < 0.075	67.05	12.10	51.00	91.40	0.180
% < 0.053	64.42	10.60	51.00	81.20	0.164
% < 0.038	61.97	10.80	46.50	77.50	0.175

It was clear from this investigation that the variability of the material was very low. The pH of the material, however, showed significant variation with depth. Complete exposure and leaching of the material increases the pH to a value of about 6.4. There are some differences in the grading but these are considered to be insignificant in terms of the overall particle size distribution and the potential uses of the material for roads.

It is important to note that the two water molecules in the BPG are an integral part of the crystalline structure of gypsum and this needs to be taken into account when determining the moisture content of the material. Moisture contents in soil analysis are usually determined as the moisture loss after drying to constant mass at 105-110°C. When drying BPG this would result in a transformation of the gypsum, by losing three quarters of the water of crystallisation, to hemihydrite ($CaSO_4 . 2 H_2O$). It is thus necessary to determine the moisture content of BPG by drying to Aconstant mass@ at 45-50°C. This does make the testing of BPG samples a very slow process and the so called constant mass is never really achieved - there is a continuous loss of mass but it does slow down considerably and it is quite easy to decide at which point to determine the moisture content.

Following the variability study, an evaluation of the three materials with the highest variability was carried out. Laboratory tests to evaluate the traditional road building properties of the three samples were carried out and the results are summarised in Table 2.

Table 2: Classification test results of Chloorkop BPG

Property\Sample No	**KCH1**	**KCH2**	**KCH5**
Liquid Limit	32.8	NP	NP
Plastic Limit	33.4	NP	NP
Plasticity Index (PI)	0	0	0
Bar linear shrinkage	0	0	0
Percent passing:			
2.0 mm	99.4	100	100
0.425 mm	98.8	100	100
0.075 mm	78.4	90.8	74.2
Maximum dry density (kg/m^3)	1450	1345	1322
Optimum moisture content (%)	19.5	21.3	21.9

The strength of the material compacted dynamically (CBR) and statically (UCS) at various moisture contents and densities and under different curing conditions was then determined (Tables 3 and 4).

Table 3: Strength of compacted BPG (dynamic compaction)

Moisture content (%)	**Compaction (% Mod AASHTO)**	**Curing (days)**	**CBR (%)**		
			KCH1	**KCH2**	**KCH5**
Soaked	98	0	19	13	4
	95	0	17	12	5
	93	0	15	11	12
Optimum	98	0	14	17	14
	95	0	11	16	13
	93	0	10	15	13
Optimum	98	7	14	20	19
	95	7	12	18	18
	93	7	11	17	17
Air dried	98	0	92	96	99
	95	0	87	90	93
	93	0	81	85	89
Oven dried	98	0	140	110	120
	95	0	135	100	112
	93	0	130	95	107

Table 4: Strength of compacted BPG (static compaction)

Moisture content (%)	**Compaction (% Mod AASHTO)**	**Curing (days)**	**UCS(kPa)**		
			KCH1	**KCH2**	**KCH5**
Optimum	98	0	86	89	59
(100 x 50 mm		7	119	109	56
specimens)	105	0	141	168	14
		7	185	168	41
	110	0	200	171	31
		7	234	200	58

It is clear from the results that BPG differs considerably from traditional road construction materials in terms of its grading, low density and high optimum moisture content. The material is non-plastic, and in its natural state at optimum and soaked moisture contents has a low CBR. When air- or oven-dried, the strength increases dramatically.

As the prime use identified for BPG was a substitute for traditional road layerworks materials and the natural properties of the material essentially precluded this, a study into the stabilisation of the material was carried out. This included testing the material in combination with various soils, with flyash and with cement. Standard test methods were employed as far as possible and the appropriate strengths after treatment and normal curing were determined. A limited durability testing programme was also carried out. The results of the stabilisation testing are summarised in Tables 5 to 7.

Table 5: Summary of stabilisation test results

Sample		**KCH1**	**KCH5**
Stabiliser	Content (%)	Strength (kPa)	Strength (kPa)
OPC	4	424	370
	6	685	534
	8	1066	847
	10	1186	1079
Lime /Slagment	4	< 50	290
	6	340	360
	8	350	360
	10	370	395
Lime/flyash	4	< 50	< 50
	6	< 50	280
	8	110	230
	10	205	290

Table 6: Effect of addition of different soils on strength of BPG

Sample		KCH1	KCH5
Additive	Content (%)	CBR @100 (and 95) % Mod AASHTO (%)	
Gravel PI < 4	0	19 (15)	4 (12)
	15	16 (13)	36 (30)
	30	14 (11)	30 (24)
	45	14 (11)	28 (21)
	60	13 (13)	21 (16)
Gravel PI > 10	0	19 (15)	4 (12)
	15	23 (19)	27 (22)
	30	21 (16)	25 (20)
	45	19 (16)	20 (15)
	60	16 (12)	13 (9)

Table 7:Additional stabilisation and durability testing

Test	KCH1	KCH5
Standard UCS (soaked) (kPa)		
3 % cement	195	
6 % cement	473	534
9 % cement	909	
Optimum cement content (%)	7.5	
Tensile strength (kPa)*		
7 % cement	261	
Wet/dry brushing test loss (%)	16.2	19.2
Carbonated UCS (kPa)	487	341
Reduction of UCS on carbonation (%)	44	36

* Three point beam test

The results showed that BPG stabilised with 6 to 8 per cent cement would provide a typical C4 material, which is typically specified for base course for lightly trafficked roads and subbase or selected layers for most other roads. The residual UCS and wet/dry brushing test results show some reduction but as the cement/gypsum reaction differs from the traditional cement hydration reaction this is considered to be acceptable. It has been speculated that the cementation reaction with BPG results in dehydration of the gypsum to form hemihydrite.

Blight[3] evaluated the effect of adding up to 10 per cent BPG to a soil with a Plasticity Index (PI) of 8 and found that after 14 days, a strength increase of over 300 per cent was obtained (no actual strengths were provided in the paper). In this work, a low PI gravel (soaked CBR 140 %) and a gravel with a PI greater than 10 (soaked CBR 48%) were added to the BPG in various proportions in an attempt to increase the soaked CBR of the BPG. Neither gravel had any significant effect on the strength of BPG sample KCH1. Both gravels, however, caused a significant increase in strength on BPG sample KCH5.

No evaluation was made of the effect of small quantities of BPG on the gravel strength as investigated by Blight[3].

4.3 Field trials

On the basis of the test results obtained, Lethabong MLC in collaboration with Transportek, CSIR and AECI Ltd decided to construct a number of trial sections using BPG as a stabilised base course and stabilised subbase. Suitable sections of road were identified in Edenvale and Tembisa. The Edenvale section was constructed by Lethabong MLC and consists of two experimental sections, a stabilised BPG base and subbase, a stabilised BPG subbase with crushed stone base and a stabilised natural gravel subbase with crushed stone base control section. All layers were designed to be 150 mm thick. The Tembisa sections were let to Contract and consisted of three stabilised BPG subbases on subgrades of various qualities with 125 mm of crushed stone bases. All sections were paved with fine TPA asphalt, 30 mm thick on the Edenvale section and 20 mm thick in Tembisa.

The BPG was stabilised with 7 per cent (by mass) of Ordinary Portland Cement (OPC). Although this stabiliser content appears high, the low density of the BPG results in an effective stabiliser content of about 5 per cent by volume. Investigations in the United States have shown that the notorious cement-sulphate reaction, which usually produces the undesirable mineral Ettringite, with a large volume expansion and disastrous results on the stabilised material, is not a significant problem with BPG if low alumina cement is utilised. Discussions with local cement producers have indicated that South African OPC is generally a low alumina material. The test results obtained have supported this information. The other problem frequently encountered with high cement contents is shrinkage and thermal cracking. Laboratory and field studies both locally and overseas have indicated that this does not appear to be a problem, possibly also as a result of the unusual hydration reaction of BPG.

4.4 Construction aspects

After construction of the trials, a workshop was held during which various aspects of the projects were discussed. It was generally concluded that the construction process was not affected by using the BPG although the following points were recorded:

- a pad foot roller gave more effective compaction requiring 6 to 8 passes to obtain the required density;
- a moisture content higher than optimum was necessary. This probably results from dehydration of the gypsum by the cement;
- priming of the base was cheap and easy (it broomed easily);
- mixing of the BPG and cement was done with a disc harrow and was very effective achieving a homogeneous mix;
- the cost of the stabilised BPG subbase (R69/m^3) was between that of stabilising the in situ material (R57/m^3) and stabilising an imported subbase material (R86/m^3).

4.5 Monitoring

Various in situ testing was carried out during construction and this indicated that the required densities were easily obtained, many being in excess of 100 per cent Mod AASHTO. Samples of the stabilised material were removed and compacted in the laboratory for UCS testing. 7 Day soaked strengths of between 740 and 1 304 kPa were obtained.

Six months after construction (December 1998), Transportek monitored the performance of the roads. Monitoring consisted of Dynamic Cone Penetrometer (DCP) profiles, deflection measurements, visual evaluation and the extraction of cores. All sections were performing as well if not better than the control sections although isolated problems, not necessarily associated with the BPG were observed. Limited non traffic-associated cracking of the asphalt was evident on the Edenvale sections immediately after construction and this increased with time.

Deflections on the stabilised base and subbase section in Edenvale were higher than would normally be expected from a stabilised base but the in situ strengths of the base were generally in the range of 2 to 2.5 MPa based on DCP penetration rates. The subbase UCS=s varied from 400 to 1800 kPa with an average of 762 kPa. The strength of the stabilised subbase in the control section varied from 211 to 390 kPa.

Similar results were found on the Tembisa sections although the deflections were lower. The base course in most cases overrides the contribution of the subbase to the pavement structure but with continued service and regular monitoring, the influence of the BPG subbase on the pavement structure will be identified.

A second monitoring exercise was carried out 19 months after construction by an independent consultant. No significant visual changes had occurred although one area on Aitken Road had been reconstructed over a short length (this area was inundated with water from a broken pipe during construction), a small patch had been placed on the stabilised BPG subbase and a large section of the adjacent control section had been rebuilt. The reasons for failure in all cases were considered to be non-traffic related.

Rutting showed no pattern and no significant changes. In all cases, the average rut depths were less than 6 mm, most of this being determined during the first monitoring and probably being related to construction (the roads all carry low traffic volumes) and not the traffic.

DCP testing was repeated approximately 2 metres away from the previous DCP test points. The average CBR and UCS of the BPG base were essentially unchanged over the 1998 measurements (253 and 252 per cent and 1926 and 1944 kPa for 1998 and 2000 respectively). The stabilised subbase CBR (and UCS) increased from 61 per cent (551 kPa) to 93 per cent (798 kPa) between 1998 and 2000. This was unexpected as the 1998 testing was carried out during December and the 2000 testing during January, following a particularly wet December. Although a time lag is normally evident between rain and the road wetting up, a general decrease in the DSN_{800} values of both the experimental sections and the control section indicates that the subgrade has become wetter. It can thus be concluded that the strength of the stabilised BPG has continued to increase over time.

The roads in Tembisa showed similar trends with respect to the stabilised subbases. Although the DSN_{800} of all the roads increased, the strength of the stabilised BPG subbase increased by between 86 and 121 per cent, but the strengths of the stabilised natural gravel control subbases increased by between only 30 and 50 per cent.

5. A PARADIGM SHIFT IS NECESSARY

Those involved with road design and construction have developed a Afeel@ for materials traditionally used and have a good understanding of their performance. The use of different technologies or materials is conventionally met with resistance but gains acceptance slowly as experience with the technology or material is gained. This process has been found in the authors= experience to typically cover a time-span of up to 10 years. The use of modified binders, fly-ash extended cement, impact compaction and many similar examples of innovative technologies has generally taken up to 10 years before being accepted and implemented on a wide scale.

The use of a construction material that looks more like a stabilising agent, with no aggregate giving body to it, has typically met the same resistance up to now. Laboratory testing has shown that a material comparable in strength and durability with any C4 type material can be obtained cost-effectively. A C4 material would normally be used where appropriate in a road structure without questioning the properties of the parent soil or gravel, purely on the basis that it provides the required strength and durability. Because BPG looks different and has an unusual composition, should it be treated differently?

Construction experience has shown that the material can be worked effectively using conventional plant. On this basis, there should be no reason why the material is not utilised, even if only for light pavement structures initially. Its properties can, and should, be verified for each specific project using conventional test methods.

6. CONCLUSIONS

In order to ensure sustainable delivery of roads, alternative construction materials will need to be exploited. By-product phosphogypsum, despite having properties significantly different from conventional natural materials, has been shown in overseas studies to be a potentially useful road construction material, particularly when stabilised with cement. Local research has supported the overseas findings, and has enabled a number of trial sections to be constructed with adequate confidence. Monitoring of the sections over a period of 18 months has indicated that the materials are performing well and they have been shown to be cost-effective compared to conventional materials.

As the cost of natural construction materials increases and their availability decreases, the relative cost of by-product and waste materials will decrease making these materials increasingly cost-effective. To maintain and even increase the delivery of the road infrastructure in line with the expected increasing demand, greater use is going to have to be made of such materials in future. A change in engineering thinking will, however, be necessary.

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ABBREVIATED CURRICULUM VITAE
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Philip started work at the then National Institute of Transport and Road Research, CSIR in 1976 after graduating from the University of Natal with an MSc in Engineering Geology. He has been at the CSIR since then, apart from two years on secondment in the Sultanate of Oman (1974 to 1976).

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