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MODELO CONCEPTUAL DE COMPORTAMIENTO DE FIRMES RECICLADOS IN SITU CON CEMENTO Y ADITIVOS BITUMINOSOS.

CONCEPTUAL PERFORMANCE MODEL FOR DEEP IN SITU RECYCLED PAVEMENTS WITH CEMENT AND BITUMEN ADDITIVES.

Steyn, WJvdM.
CSIR Transportek
PO Box 395
Pretoria 0001
South Africa
Tel +27 12 841 2634
Fax +27 12 841 2690
E-mail wsteyn@csir.co.za
Sadzik, E.
Gauteng Department of Transport and Public Works
E-mail elzbietas@gpg.gov.za
Semmelink C.J.
CSIR Transportek
E-mail csemmelink@csir.co.za

RESUMEN

El objetivo de esta comunicación es proveer información a cerca de un modelo conceptual de comportamiento de firmes sometidos al reciclado profundo in situ, en los cuales cemento y betún espumado, o cemento y emulsión bituminosa, han sido agregados a la mezcla. Transportek (CSIR) y el Departamento de Transportes y Obras Públicas de Gauteng están realizando ensayos acelerados a escala natural sobre varias secciones de firmes que han sido rehabilitadas con cemento y betún espumado, o cemento y emulsión bituminosa. Durante estos ensayos, el comportamiento de la estructura del firme es registrado como asi también ciertos parámetros medioambientales. Basado en esta información y los datos correspondientes a los ensayos de laboratorio, un modelo conceptual de comportamiento de firmes reciclados está siendo desarrollado. El modelo actual se basa en los resultados obtenidos de ensayos realizados con cargas de neumáticos relativamente altas. Datos de construcción e información visual del comportamiento ayudan para un mejor entendimiento y una mejor conceptualización del modelo. A pesar que los ensayos acelerados a escala natural de varias de las estructuras de firme todavía continúa, los resultados iniciales indican aspectos de comportamiento muy distintos a firmes convencionales. La descripción de las estructuras de los firmes, su construcción y su medioambiente son presentados en esta comunicación. También, se discuten y se muestran los resultados iniciales de los ensayos acelerados y de los ensayos de laboratorio. Finalmente, se propone un modelo conceptual de comportamiento basado en los resultados disponibles hasta este momento.

ABSTRACT

The purpose of this paper is to provide information regarding a conceptual performance model for Deep In Situ Recycled (DISR) pavements where both cement and either foamed bitumen or bitumen emulsion have been added to the mix. CSIR Transportek and the Gauteng Department of Transport and Public Works, are conducting Accelerated Pavement Testing (APT) on test sections that have been rehabilitated in situ with cement and either foamed bitumen or bitumen emulsion. During APT the behaviour of the pavement structure is monitored together with environmental parameters. Based on this information, and associated laboratory testing data, a model for the performance of these pavements is currently being developed. The model is currently based on the results of APT testing under relatively high tyre loads. Construction data and visual behaviour data add to a better understanding and definition of the model. Although the APT evaluation is destined to continue for some time, the initial results indicate very distinct performance-related issues. In the paper a description of the pavements, their construction and their environment are provided. The initial APT and laboratory testing results are shown and discussed. A conceptual performance model based on the available results is proposed.

PALABRAS CLAVE

ensayo acelerado de firmes a escala natural, reciclado profundo in situ, grava tratada con betún espumado, grava tratada con emulsión bituminosa, cemento, modelo conceptual de comportamiento.

KEY WORDS

Accelerated pavement testing, deep in situ recycling, foamed treated gravel, emulsion treated gravel, cement, conceptual performance model.

1. INTRODUCTION

Deep In Situ Recycling (DISR) is a process used to rehabilitate existing pavements. Selected existing layers in a pavement are recycled together with additives to make up a new pavement layer. The process often negates the need to import additional material (from borrow pits), and is therefore friendly towards the environment. It is also a cost-effective process as the recycling process is relatively fast and disruptions to traffic are normally minimised.

DISR has been used in South Africa since 1972 using conventional equipment and since 1989 using deep in situ recyclers. The process was generally well received, although no specific guidelines exist for the design of DISR pavement materials. Currently, road authorities experience difficulties in evaluating designs where DISR is offered as an alternative design as relatively little experience exists regarding the final product’s long-term performance and ultimate failure model.

The Gauteng Department of Transport and Public Works (Gautrans) embarked on a research process through which specific aspects of DISR are addressed. CSIR Transportek joined them in this research effort. This paper focuses on this major research process into DISR in South Africa. The main objectives of the process are to determine failure mechanisms and performance models for different DISR pavements, as typically used in South Africa. This should ultimately lead to a better understanding and guidelines for the use of DISR during rehabilitation of existing pavements.

In South Africa DISR is used in different forms. The major difference between the different versions of the process is the amount and combination of additives used. Four main products can be identified. These four products are shown in Table 1. In Table 1 a preliminary expectation of the typical failure model for each of the four products is also indicated. These expectations need to be confirmed through research. The research process described in this paper focussed on the evaluation of both field sections and laboratory samples with a material that can be termed ‘cemented’ under the terminology of Table 1.

Table 1: Four main products possible from DISR (1).

	Granular	Cemented	Visco-elastic	High Stiffness
% Cement	_ 1,0	> 1,0	< 1,5	_ 1,5
% Bitumen	< 3,5	< 2,0	> 3,5	> 3,5
Cement: Bitumen	< 1:1	> 1:1	< 1:3	-
Typical failure model	Deformation	Brittle fatigue	Deformation	

fatigue

Fatigue

The research process consisted essentially of Accelerated Pavement Tests (APT) and a laboratory component. Long-Term Pavement Performance (LTPP) sections were also constructed, but no results from their monitoring are included in this paper. In the APT component, Heavy Vehicle Simulator (HVS) tests were (and are still being) conducted on test sections constructed in the field. The main aim of these APT tests was to evaluate the performance (including a failure model and damage factor) of the pavement structures under normal and overloaded conditions in a full pavement structure configuration. The aim of the laboratory tests were to evaluate certain engineering and material properties of the stabilised materials used in the recycling process, and to determine the effects of different combinations of additives on the engineering properties of the materials. Ultimately, design models for these materials have to be developed based on the available research results.

In this paper the focus is on the results from the first phase of the APT and laboratory testing programmes. Both the APT and the laboratory programmes are currently continuing, focussing on further aspects of the bigger DISR performance picture.

2. BACKGROUND TO THE TESTING PROGRAMME

2.1 Background and preparations

Chronologically, the test programme started with the evaluation of appropriate pavement sections to select locations for construction of DISR test sections. Once these pavement structures were identified, a surface deflection survey and a Dynamic Cone Penetrometer (DCP) survey were conducted on the selected pavement sections to evaluate the current condition and homogeneity of the pavement. Material samples were collected to evaluate the standard engineering properties of the materials. The existing pavement consisted of a multiple seal (20 mm thick) over a lightly cemented ferricrete base layer. This was supported by a natural gravel subbase layer and in situ subgrade. The pavement was approximately 20 years old and carried traffic in excess of 10 000 standard axles per year when the recycling started. Sections of the pavement showed traffic load induced fatigue cracks.

A preliminary design for the pavement was based on this information. It was decided to opt for a ‘cemented’ type of material (using 2 per cent ordinary Portland cement) and both a foamed asphalt and an emulsion as the viscous additive (both added at a rate of 1,8 per cent residual bitumen). This resulted in two test sections. The first test section was constructed using the foamed bitumen treatment, resulting in a foam treated gravel (FTG) base layer while the second test section was constructed using the bitumen emulsion process, resulting in an emulsion treated gravel (ETG) base layer. Both the test sections were 100 m long and 3,6 m wide. The recycling process included the upper 250 mm of the existing lightly cemented base layer and thin (20 mm) surfacing seal. The pavement was finally surfaced using a 30 mm asphalt surfacing. The nominal pavement structure is shown in Figure 1.

Before commencement of the HVS testing, the pavement structure was evaluated using existing knowledge of the material types and the typical failure mechanisms and performance models for similar materials. These mechanistic calculations

indicated an expected life for the pavement structure ranging between 1 and 3 million standard axles (80 kN).

Figure 1: Nominal pavement structure after recycling.

2.2 Accelerated Pavement Testing Phase

As it was expected that the pavement would provide good resistance to loading, the HVS trafficking started with a relatively high wheel load of 80 kN. This load is applied on a set of dual truck tyres inflated to 820 kPa, and translates to a single axle load of 160 kN. The load represents severe overloading and the intention was to obtain a quick evaluation of the possible bearing capacity and failure model of the pavement structure, before longer term testing at standard load conditions (40 kN, 620 kPa). The test was to be conducted in the nominally dry condition, indicating that no water would be allowed to enter the pavement structure during initial testing.

After approximately 350 000 of the 80 kN load applications, the loading was continued on one half of the original test section and the other half of a new test section at a load level of 100 kN (inflation pressure 850 kPa). This continued for another 150 000 load applications before water was allowed to penetrate the pavement structure from the surface. The reason for increasing the load level and for allowing water ingress was the very good resistance against loading experienced by the pavement structures. In section 4 of this paper the results of the measurements on the test sections are shown and discussed. Ultimately, Moisture Accelerated Distress (MAD) occurred and the tests were abandoned.

The process described above was used both on the FTG and the ETG test section. Recently the second phase of APT has started with a wheel load of 40 kN (620 kPa tyre inflation pressure). These data are not reported in this paper.

20 mm multiple
surfacing seal
250 mm Foam /
Emulsion and
cement treated base
250 mm natural
gravel subbase
In situ subbase

2.2 Laboratory Testing

The initial laboratory testing phase consisted mainly of an evaluation of the engineering properties of the materials used for the construction of the pavement structure. The effects of different combinations of additives on these properties were investigated. In situ material was milled using the recycling machine, and this material, which was identical to that treated on the road, was used for preparation of samples in the laboratory. The engineering properties of the original untreated milled ferricrete are shown in Table 2.

The material was initially tested in four different configurations. These configurations are shown in Table 3. Subsequently, as part of phase 2 testing, different percentages of bituminous material were also evaluated in the laboratory, as well as samples with cement as the only additive.

Table 2: Material Properties of Ferricrete

Test Material Property Value
Optimum moisture content (%) 11,2
Maximum dry density, Mod AASHTO
(kg/m^3)
2013
Apparent relative density (kg/m^3) 2777
Density results
Bulk relative density (kg/m^3) 2436
Liquid limit (LL) 26,8
Plastic limit (PL) 19,8
Plasticity index (PI) 7,0
Atterberg limits
Bar linear shrinkage (BLS) 2,6
Swell (%) 0,6
CBR at 98% compaction 56,0
CBR at 95% compaction 23,0
CBR at 93% compaction 17,5
California Bearing
Ratio (CBR)
CBR at 90% compaction 5,8
Water absorption (%) 5

835

Table 3: Materials used for laboratory testing.

Untreated
Cement
Treated
Gravel (CTG)
Foam Treated
Gravel (FTG)
Emulsion
Treated
Gravel (ETG)
% cement 0,0 2,0 2,0 2,0
% residual
bitumen
0,0 0,0 1,8 1,8

The following laboratory tests were conducted (2, 3,4):

- Unconfined Compressive Strength (UCS);
- Indirect Tensile Strength (ITS);
- Flexural beam fatigue;
- K-mould tests;
- Static triaxial tests, and
- Dynamic triaxial tests.

These tests were conducted on samples that were prepared at different density and saturation levels. A range of confining pressures was also used for the triaxial tests. The results from the laboratory tests are shown and discussed in section 3 of this paper.

3. LABORATORY TEST RESULTS

A summary of the results from the laboratory tests is provided in this section (Table 4). The full data set is given in (2).

Table 4: Summary of results from laboratory testing.

	Cement Treated Gravel (CTG)	Foam Treated Gravel (FTG)	Emulsion Treated Gravel (ETG)
UCS [kPa]	3 015 to 3 564	1 096 to 1 864	1 645 to 2 467
ITS [kPa]	339 to 493	230 to 329	181 to 395

UCS and ITS results

The CTG had the highest UCS and ITS values. Addition of a bituminous binder reduced both the UCS and ITS values, with the highest binder content having the smallest values and the ETG having higher UCS values than the FTG. The ITS values of the FTG were higher than those of the ETG. The results indicate that the addition of the viscous binders to the CTG reduced both the compressive and tensile strengths. The addition of the binder possibly interferes with the cementitious bonds, thereby lowering the strength of the material.

Flexural beam fatigue results

The flexural beam fatigue test is described in (5). In this test the strain-at-break is measured, and is equal to the strain at the point of crack initiation. This parameter represents the flexibility of the material. A higher strain-at-break value indicates a more flexible material. The strain-at-break results were similar for the CTG and ETG / FTG samples evaluated at the lower bituminous binder contents (1,8 per cent binder) (149 to 174 microstrain). However, at the higher bituminous binder content (3 per cent) a marked increase in strain-at-break (214 to 353 microstrain) was noted for the ETG and FTG samples.

Static shear strength

The static shear strength of the materials was determined from static triaxial tests. The theory behind the determination of the parameters, i.e. the cohesion and friction angle, from the laboratory test is discussed in detail in (5).

Both the friction angle and the cohesion of the CTG were not sensitive to the degree of saturation. This is reasonable because the shear strength is dependent more on the chemical bonds provided by the cement, which are not sensitive to the moisture content in the material than on suction generated by negative pore water pressure in unbound materials.

A decrease in the degree of saturation caused increases in the cohesion for the untreated ferricrete, while the cohesion for the bitumen treated materials were decreased. An increase in relative density increased the cohesion of the untreated ferricrete, but decreased the cohesion of the ETG and FTG samples.

A decrease in the degree of saturation caused an increase in the friction angle of the ETG and FTG samples. Increases in the relative density had a negligible effect on the friction angle of the untreated ferricrete, but caused increases in the friction angle of the ETG and FTG samples.

The cohesion values were significantly higher for the treated materials than for the untreated ferricrete. The friction angles were also generally higher for the treated materials than for the untreated ferricrete, except for the combinations of low density and high saturation. This demonstrates that the addition of the cement and/or the binder increases the cohesiveness and the friction angle of the material, which should make the treated materials more resistant to deformation. Increases in the degree of saturation and the relative density had a larger effect on the cohesion and friction angles of the FTG samples than the ETG samples. The cohesion of the CTG was in approximately the same ranges as the FTG, and the lower levels of saturation of the ETG.

Permanent deformation

Dynamic triaxial tests were performed to assess the permanent deformation behaviour of the untreated and treated ferricrete. The theory behind the use of the dynamic triaxial test is discussed in (5). For the untreated ferricrete an increase in relative density caused an increase in the number of repetitions to reach a certain level of plastic strain, whereas an increase in the stress ratio (vertical stress divided by horizontal stress) resulted in a decrease in the number of repetitions. The degree of saturation did not have a large influence on the number of repetitions. For the CTG the influence of the relative density and saturation on the bearing capacity was not apparent, whereas an increase in the stress ratio clearly decreased the bearing capacity of the material. For the ETG the permanent deformation behaviour was within a small range and no strong trends were observed, although it appeared as if the decreasing stress ratio caused decreases in the bearing capacity. For the FTG there was no clear trend for the permanent deformation behaviour as a function of the relative density or the degree of saturation. On the whole, the CTG was the most resistant to permanent deformation. The behaviour of the untreated, FTG and ETG materials were very similar, except at the high plastic strain and low saturation level.

The results from the K-mould (6) tests indicated that the predicted permanent deformation for the samples changed dramatically after addition of the cement and bituminous additives. The untreated ferricrete sample had a permanent deformation of almost ten times the permanent deformation of the treated samples when tested at approximately optimum moisture content. The differences between the CTG, FTG and ETG samples were negligible.

These results appear to show that the addition of the cement and binders to the untreated ferricrete somewhat reduces the dependence of the permanent deformation behaviour on the degree of saturation. The addition of the cement only improves the permanent deformation resistance at the higher saturation levels. However, the inclusion of the bituminous binders with the cement did not improve the permanent deformation resistance of the ferricrete. At higher binder contents this conclusion may not be valid. These results should not be considered alone, without taking the benefits of the binder treatments to the field construction, workability, and the resistance to shrinkage cracking of the material. The minimum time before the road may be opened to traffic may also possibly be reduced with the bituminous binder treatment.

4. ACCELERATED PAVEMENT TESTING RESULTS

The standard measurements performed on an HVS test section include permanent deformation, elastic deflection, visual evaluation and moisture contents. These measurements are performed at predetermined intervals during the trafficking of the test section. In this paper only selected data are shown, the complete database is available in (7).

In Figure 2 the results of the permanent surface deformation measurements on both the FTG and the ETG sections are shown. It is evident that the permanent surface deformation was very small during trafficking with the severely overloaded conditions (80 kN and 100 kN dual wheel loads). Permanent surface deformation only increased when water was allowed to penetrate the base layer of the test section.

In Figure 3 the elastic surface deflections measured on the test sections are shown. It is again evident that the response from the pavements under the different loading conditions did not differ significantly, except for the 80 kN ETG test where lower elastic surface deflections were observed. Similar trends were, however, observed for all the tests.

Figure 2: Permanent surface deformation on both FTG and ETG test sections under 80 kN and 100 kN dual wheel loads.

Figure 3: Elastic surface deflection response from pavement structures.

After further investigation, it was evident that the elastic deflection bowls measured on the various test section did start to show a change in shape after a number of load applications. In Figure 4, the typical elastic deflection bowls for one of the test sections are shown at the start of the test, after a certain number of load applications and at the end of the test. It is evident that the shape of the deflection bowls changed, indicating a change in the structure of the material. The position of the change in the deflection bowl (relatively close to the maximum) indicates that the major change in the material occurred near the surface of the pavement structure.

0.0
2.0
4.0
6.0
8.0
0 50,000 100,000 150,000 200,000 250,000 300,000 350,000
Number of load applications
Permanent surface
deformation [mm]
FTG 80kN FTG 100kN ETG 80kN ETG 100kN
Water added
0.0
100.0
200.0
300.0
400.0
500.0
600.0
700.0
800.0

900.0
0 50,000 100,000 150,000 200,000 250,000 300,000 350,000
Load applications
Elastic surface deflection
- 40 kN 800 kPa
FTG 80kN FTG 100kN ETG 80kN ETG 100kN

Figure 4: Typical elastic deflection bowls during HVS test.

The remaining observations from the HVS test sections (visual observations, densities, temperatures and moisture contents measured) are not specifically discussed in this paper, as they do not directly contribute to the topic discussed. The data from those measurements did not contradict that which was found from the specific data shown in this paper.

In summary the HVS data indicated that the FTG and ETG materials were both highly resistant to permanent deformation, but that a point occurs during traffic loading where a drastic change in the shape of the elastic deflection bowl occurs. This is most probably caused by the deterioration of the cemented bonds in the FTG / ETG layer.

5. DEVELOPMENT OF CONCEPTUAL PERFORMANCE MODEL

One of the major objectives of the APT phase of the DISR test programme is development of a performance model for these types of pavements. Evaluation of the data obtained from the early HVS tests started to guide thoughts to a typical lightly cemented material performance model. The lightly cemented materials used extensively in South Africa (8) have a distinct performance model (8). This model describes the deterioration of a lightly cemented layer as starting in an effectively bound condition, and breaking down to an effective granular condition early during its life. However, the performance of the material in this equivalent granular state is superior to the performance of the original untreated material (8,9). The performance model for lightly cemented materials is shown schematically in Figure 5.

The HVS data indicated similar low permanent deformation values during the extent of the dry testing (Figure 2), and similar trends in the elastic surface deflection behaviour (Figure 3). A large decrease in effective elastic modulus was also observed once the elastic surface deflection increased, after which the moduli were relatively constant during the remainder of the test.

-100
0
100
200
300
400
500
600
700
0 500 1000 1500 2000 2500 3000
Distance [mm]
Elastic surface deflection [micron]
10 1000 35000 229100
Number of load applications

Investigation of the laboratory results indicated that the typical Unconfined Compressive Strengths (UCS) of the ETG and FTG materials (as used in this study) were similar to those reported (TRH14) for lightly cemented materials. The reported values range between 1 500 kPa and 3 500 kPa, compared to the CTG, FTG and ETG values measured at between 1 000 kPa and 3 500 kPa. The flexural beam tests indicated that the strain-at-break results for the ETG and FTG materials were slightly higher (between 149 and 174 micro strain) than those typically found for the lightly cemented materials (125 to 145 micro strain) (10).

Figure 5: Typical lightly cemented material performance model (8).

A further difference between the behaviour of the lightly cemented and the ETG / FTG materials, concerns the response of the materials to water ingress. The typical lightly cemented materials deteriorated (*11*) considerably under water ingress, with material weakening and undergoing extensive permanent deformation (8,9). The FTG/ETG materials, however, did not deteriorate to the same extent under the action of water ingress, but rather showed erosion of the fine materials at the surfacing / base layer interface. This was similar to erosion failure observed by De Beer (*12*) on a finely grained cementitious material. It is strongly suggested to introduce a durability test during the material design of DISR process. Tentative

PRE-CRACKED
PHASE 1
POST - CRACKED
EQUIVALENT GRANULAR
(DE BEER,1990)
N ef
PHASE 2 PHASE 3
SHRINKAGE
CRACKING
INTACT TRAFFIC ASSOCIATED CRACKING
PERMANENT DEFORMATION
SCHEMATIC CRACK DEVELOPMENT
TIME/TRAFFIC
POOR QUALITY
MATERIAL
WATER REMOVED
WATER ADDED
GOOD QUALITY
MATERIAL

erosion criteria developed in 1989 could be used as a starting point to alleviate this problem (*11*). These tentative guidelines are shown in Table 5.

Table 5: Proposed tentative erodibility criteria for lightly cementitious materials (*11*).

Layer	Traffic class [80 kN axle load, 520 kPa tyre inflation pressure repetitions]	Erosion Index L [mm]
Base	< $0,2x10^6$ to $50x10^6$	_ 1
Subbase	< $0,2x10^6$ to $3x10^6$	_ 5
Subbase	$3x10^6$ to $50x10^6$	_ 3

This migration of fines caused a build-up of fine material on the sides of the HVS section with coarse material left under the central wheel area (Figure 6). It appears as if the presence of the bituminous additives contributes to decreasing the permeability of the material, thereby causing less deterioration and weakening under water ingress than the lightly cemented materials. Further laboratory testing of this phenomenon is currently underway.

It appeared from both the APT and laboratory test results that the ETG sections / material performed better than the FTG section / material. Although the support for the ETG was better in the field than for the FTG, this should not have played a role in the laboratory test data. The second phase of laboratory testing is also looking into this phenomenon.

Figure 6: Erosion of fine material from test section to untrafficked sides of test section after water ingress.

6. FURTHER WORK

As indicated in the beginning, this paper is based on the first phase of the investigation into the performance of DISR pavement structures incorporating cement and bituminous binders. As such, only the high wheel load HVS tests and the initial laboratory tests are described, as the remainder of the tests were still continuing at the time of writing this paper.

Based on the information from the first phase of testing, it is clear that a number of specific issues need further investigation. These issues are:

- The response of the pavement structures to different tyre loads;
- The effect of different amounts of cement and bituminous binder, and also different ratios on the performance of the DISR structures, and
- The effect of bituminous binder content on the permeability and erodibility of the FTG and ETG materials.

A number of these tests are currently conducted and these results will be reported at a later date as part of a more complete performance model for DISR pavement structures.

7. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are drawn based on the information provided in this paper:

- The DISR technique can provide a pavement structure with a high bearing capacity and good resistance against permanent deformation for the materials tested;
- It appears as if the selected material type behaved in a typical lightly cemented performance model – which is to be expected if the material properties are compared with a typical lightly cemented materials;
- The DISR materials investigated were still water susceptible, although erosion of the fine material occurred rather than weakening and deformation of the base material. This could be addressed by introducing suitable erodibility (durability) criteria for DISR materials, and
- The combination of both laboratory data and APT data to determine the performance model for the DISR materials is recognised.

It is recommended that the current research programme into the performance of different DISR materials and pavement structures be continued, to provide a more complete performance model and failure mechanism definition for these materials.

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