THE RESPONSE OF INTERLOCKING BLOCK PAVEMENTS UNDER ULTRAHEAVY LOADING

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ABSTRACT

Uncertainty has existed about the design parameters to be used in the design of interlocking paving in container terminals. Much of the material characterization is taken from tests conducted with normal highway loads, and there was little evidence about their applicability to ultraheavy loading conditions. An experiment at the Kaserne container terminal, consisting of amongst others two test panels with interlocking block paving, was designed and constructed to obtain design input under ultraheavy loading conditions. The aim of the paper is to present the response and performance of the test panels under loading of up to 100 ton axle loads. The main conclusions were that there was no indication of stress sensitivity of the unbound materials, and typical stiffness values used in road pavement design could be used. Limiting vertical compressive strains were as suggested by the South African Mechanistic Design Method for road pavements. The structural design of interlocking block pavements for ultraheavy loading may be performed using linear elastic layer analysis. Cost effective solutions include the use of dump rock instead of thick stabilized layers in the upper pavement to ensure load spreading and stress reduction in the subgrade.

1. INTRODUCTION

There has been widespread use of interlocking paving in container terminals. Remarkable successes in the form of good performance over a relatively long period of time have been found, but sometimes early severe deformation and distortion of the riding surface required excessive maintenance and also lead to client unhappiness about the inability of the terminal to function properly. Uncertainty existed about material characterization required for design purposes. Much of the material characterization is taken from tests conducted with normal highway loads, and there was little evidence about their applicability to ultraheavy loading conditions.

Eleven experimental test panels (each 5 m long and 6 m wide), which included interlocking paving as well as cast in-situ block paving [1][2][3], were constructed at the Kaserne container depot in Johannesburg, South Africa in March 1997. A range of layer thicknesses and material properties according to an experimental design were used. These panels were instrumented with multi-depth deflectometers (MDD) to obtain the structural response of the different layers under wheel loads up to ultraheavy loads. Measurements were also obtained under container stacks. The section was trafficked by trucks and Reachstackers during normal container distribution operations.

The aim of the paper is to present the response and performance of the interlocking paving panels under a range of loading and trafficking conditions, and to derive structural design parameters for container terminal pavements. Although the focus of the paper is on interlocking paving, the results obtained on the cast in-situ blocks are also presented as all the panels conform to an experimental design. Firstly the experimental design of the test panels is presented. The structural response and performance of the different panels and materials are presented next, and the structural design parameters are derived. Finally guidelines for the structural design of block paving pavements for container terminals are presented.

2. EXPERIMENTAL DESIGN

The aim of the experiment was to determine design parameters for block paving pavements. It was not the intention to only build test panels that would be strong enough to withstand all the loads. Consequently the test panels ranged from ultrathin structures to structures that would probably carry the loads satisfactorily, as shown in Figure 1.

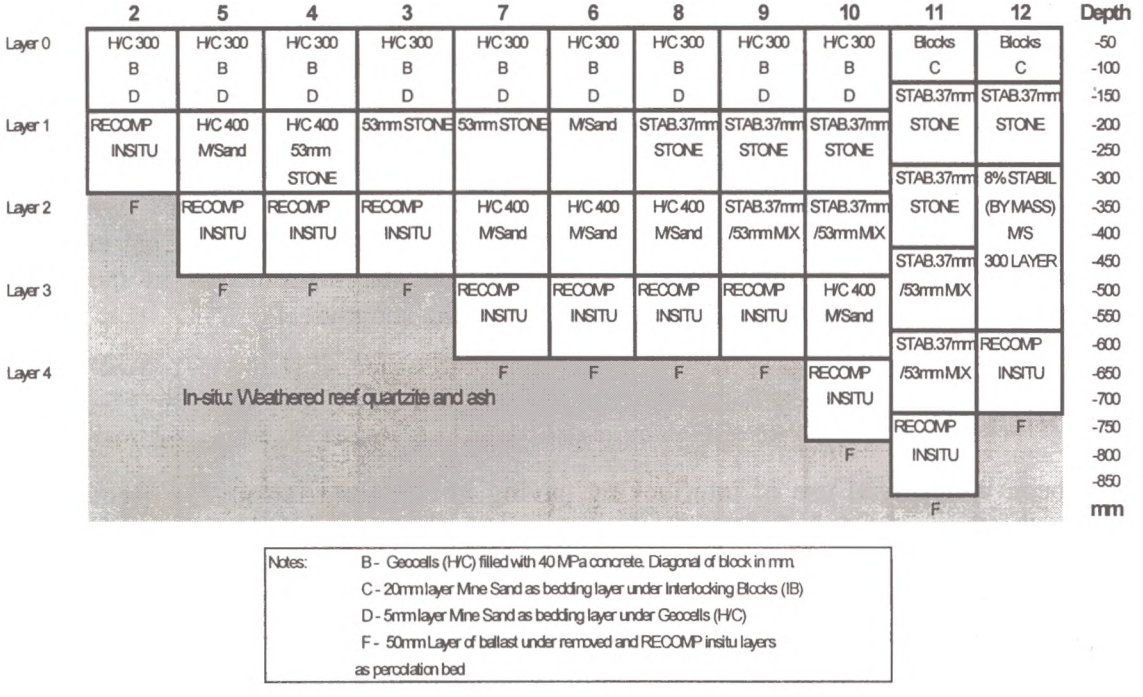


Figure 1. As-built structural composition of the test panels

The position of the test panels was selected between the maze of railway lines in an area where the in-situ reef quartzite rock layer was more than 1 m below the surface, and where the materials were relatively consistent as determined by a Dynamic Cone Penetrometer (DCP) survey. The layers were built 150 mm thick to facilitate construction.

The test section was excavated to a depth of 1 m and then backfilled in 150 mm layers and compacted to give a uniform subgrade. A 50 mm percolation layer was placed on the subgrade to facilitate future moisture ingress when the panels were to be tested in the wetted condition. This option was not exercised, as during construction there were two cloudbursts

that flooded the construction site. The material was thus in a fairly moist condition throughout the test programme.

The first six geocell panels were constructed on granular layers with mostly poor properties. The thickness of the structure was also shallow, and the expectation was that these panels would show the first signs of distress. Panels 8 to 12 had stabilised sublayers and a deeper structure. The ready-mixed concrete used in the geocells had a design strength of 40 MPa. The paving block panels were included as typical designs for this type of application [4]. Thus it was possible to evaluate a range of pavement structures.

3. INSTRUMENTATION

The main form of instrumentation was the multi-depth deflectometer (MDD) installed and monitored by the Spoornet Track Testing Centre's mobile laboratory team. MDD modules were installed at the interface of each pavement layer, and the core was anchored in the rock at a depth of about 1.9 m. By recording the relative movement between the layer interfaces the strains within each layer are determined, and from the applied stress the stiffness of the layer is calculated. Pressure transducers and strain gauges were also installed in some panels but erratic and inconsistent results lead to these measurements not being considered further.

4. TEST RESULTS

4.1 Field density

The densities achieved in the field after compaction with a Dynapac CA301D 12 ton compactor were generally satisfactory, as may be seen from the summary provided in Table 1. The only layer of concern was the mine sand with 8% cement, as the specification for subbase compaction is 95% of Mod AASHTO density, and the selected layers as 93% of Mod AASHTO density [5]. Sand should be compacted to at least 100% Mod AASHTO density.

Table 1. Summary of compaction results

Soil Layer	Mod Density (kg/m3)	Moisture content (%)	Relative field density (%)
Ash and quartzite subgrade	1518	11.7	98
Geocells 400 Mine Sand	1660	19.3	102
Geocells 400 53mm crushed stone	1764	-	-
53mm crushed stone	1703	-	-
Mine Sand	1591	19.3	98
53mm/37.5mm mix, stabilized, 4% cement	2348	6.8	95
53mm/37.5mm mix, stabilized, 2% cement	2365	6.9	97
Mine sand 8% cement	1523	19.3	85

4.2 Dynamic Cone Penetration tests

An indication of the consistency of the quality of the materials was obtained from DCP results. After construction the average CBR of each unstabilised layer was determined from the DCP penetration rate. A poor bearing capacity of some of the layers, particularly in the thinner pavements, was found. Under normal conditions such materials would not be used,

but in the experiment extreme conditions were sought to provide information outside the normal range.

4.3 Concrete quality

Concrete cubes were tested at 7 and 28 days, and the average strengths were respectively 45 MPa (18 cubes, σ=2.8 MPa) and 59 MPa (27 cubes, σ=3.3 MPa), significantly higher than the 40 MPa specified. These strengths were confirmed by drilling 100 mm cores, which gave a strength of 54 MPa at 16 days (4 cores, σ=3.7 MPa). Standard 80 mm interlocking blocks with a strength of 35 MPa were used.

4.4 Multi-depth deflectometer results

As the load is applied over the MDD, the interfaces between the layers move downward, and the elastic deflection is recorded relative to the anchor. It is assumed that the anchor does not move since it was embedded in the rock layer. A typical deflection profile with depth is shown in Figure 2 for section 12 under the Reachstacker with normal container load, which gave a wheel load of 210 kN at a tyre pressure of 980 kPa for each of the dual wheels.

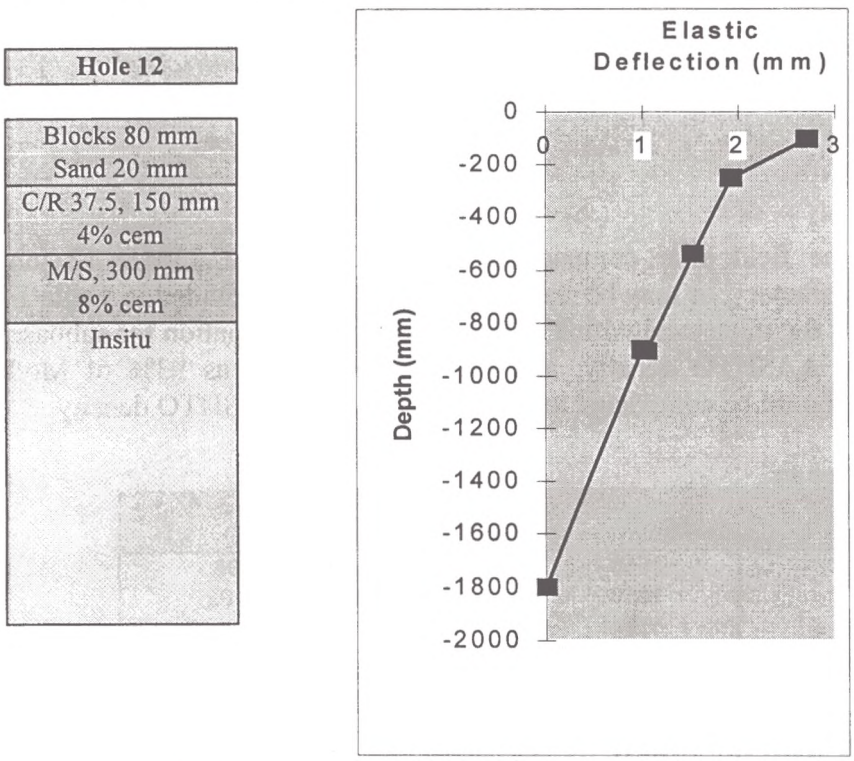


Figure 2. MDD depth deflections, section 12, under Reachstacker (210 kN wheel load)

Each MDD was subjected to a range of loading conditions, from the Kalmar 4160 R54 Reachstacker carrying a 27 ton container to an empty horse and trailer combination. For each loading condition the stiffness, or E-modulus was calculated as well as the associated stress condition. The ELSYM five-layer program was used for backcalculating the layer stiffnesses. By matching the deflections calculated for assumed stiffness values with deflections measured with depth to within 3% by iteration, the stiffness of the different layers was determined.

Figure 3 shows the range and average values of the stiffness calculated for each layer. Note that the loading tests were conducted about two months after construction and the cemented materials had had time to gain strength. There are several observations of general interest, namely:

(a) the typical design stiffness values for the different materials correspond with those suggested in the South African mechanistic design method [6], and for the block paving the stiffnesses suggested by Shackle [4] were confirmed by the structural response.

(b) the stiffness of the in-situ layer is relatively consistent considering that results were obtained on each panel independently. This provides confidence in the reliability of the measurements.

(c) the stiffness of the thinner layers in the weaker structures was low as was expected from the DCP results.

(d) no stress sensitivity was found in the unbound layers.

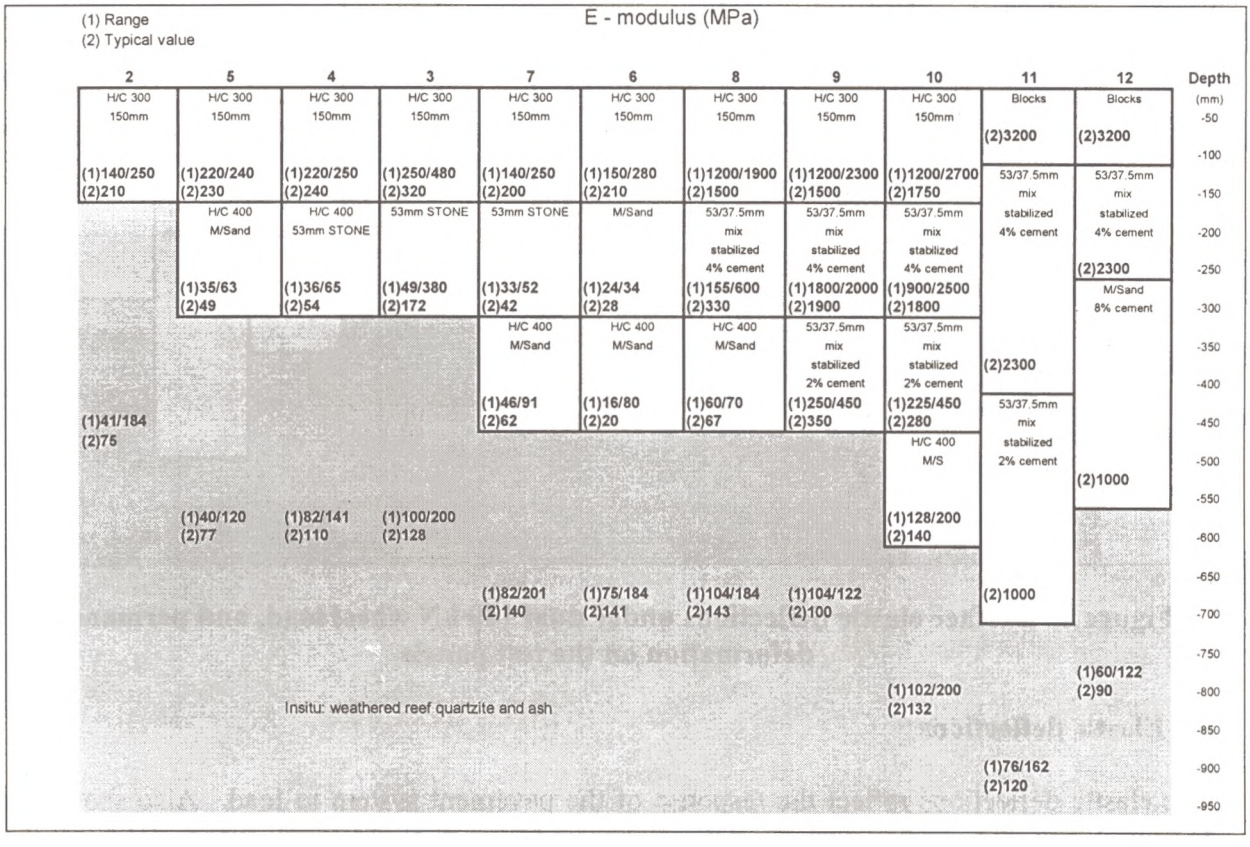


Figure 3. Range and representative stiffness values calculated from the MDD measurements

4.5 Permanent deformation

A laser level survey was done to measure the permanent deformation of the running surface. The surface of each test pad was surveyed at a fixed position transverse to the longitudinal axis of the test section prior to testing and after testing and 30 days of normal vehicle usage. The difference between the original level and the deformed level is the permanent

deformation averaged over the seven measuring points. These results are shown in Figure 4. As expected the weakest panels showed the greatest permanent deformation, up to 13 mm for section 6. The more substantial structures showed hardly any deformation. After 15 months in use no visible change in the performance of any panel was noticeable.

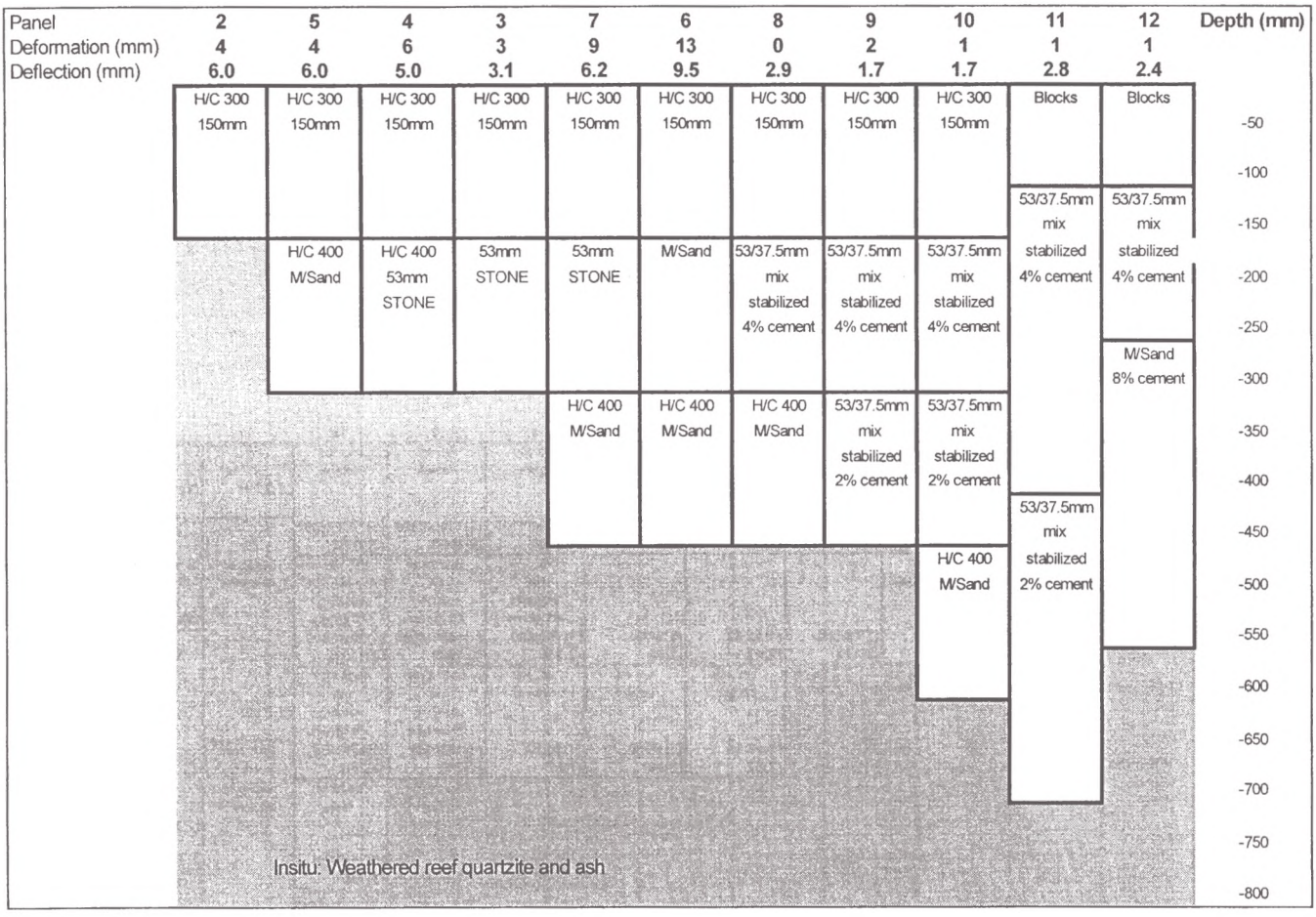


Figure 4. Surface elastic deflections under dual 140 kN wheel load, and permanent deformation on the test panels

4.6 Elastic deflections

The elastic deflections reflect the response of the pavement system to load. Also shown on Figure 4 are the elastic surface deflections under a dual 140 kN wheel load of the Reachstacker, measured with the MDD module immediately below the surface layer, and assuming that the concrete had negligible strains. Tyre pressure was 980 kPa. The weaker layers, particularly under the geocell concrete layer, contributed significantly to high deflections as may be seen for panel 6. Although high deflections could lead to spalling of the joints in the blocks, they usually result in high strains in the layers. High strains have been shown to severely restrict the ability of a pavement to provide the required service, as will be discussed in the next section.

4.7 Vertical compressive strains in the unstabilised materials

According to the South African mechanistic design method the vertical compressive strain on unstabilised layers and the in-situ material should be less than 2000 microstrain to ensure that rutting of less than 20 mm takes place after 10 000 load applications. Lower strains would result in the pavement being able to accommodate larger numbers of load applications. All the strain values exceeded the upper limit of 2000 microstrain, and the poor performance in terms of high permanent deformation and high deflections are thus corroborated. The substantial stabilised layers in panels 9 to 12 significantly reduced the vertical compressive strains in the in-situ material, and this finding gives a guide to the design of pavements for ultraheavy loads.

4.8 General observations during testing

Under the ultraheavy wheel loads of the laden Reachstacker it was found that there was upward seepage through the geocell layer from below the pavement. During construction 470 mm of rain fell, and the unstabilised layers were rather wet. This pore pressure dissipation is beneficial as excess pore pressures, and subsequent weakening of the material, is avoided.

During testing the laden Reachstacker wheel was turned on the interlocking block panels. The blocks moved and appeared loose after this wheel turning. This may be as a result of the jointing sand not having been completely compacted, although in operational container terminals this type of problem has been reported. Special care needs to be taken in the initial months after opening to have maintenance staff available to fill the joints with sand as movement is noticed. No surface abrasion as a result of the wheel action was evident on any of the panels.

On the interlocking block pavements punching of blocks into the underlying material occurred initially, and is attributed to the normal construction with a plate vibrator providing insufficient compaction for the highly concentrated container post loads. This type of problem has been reported at operational container terminals, but is minimised when trafficking with the Reachstacker has taken place.

No visible change in the performance was evident after 15 months of trafficking. Short term performance is thus an indicator of potential long term performance.

5. GUIDELINES FOR THE STRUCTURAL DESIGN OF CONTAINER TERMINALS

The structural design should provide a pavement structure such that none of the layers are overstressed. The criteria that are used in the mechanistic design are [6]:
(a) the vertical compressive strain in the unbound layers, specifically to limit rutting;
(b) the factor of safety in the crushed stone base layer.
In addition the deflection on the surface is considered, as high deflections create the perception that the structure is inadequate.

For the purpose of the evaluation of suitable designs, representative stiffness values derived in the experiment were used. The stiffness of the 80 mm blocks and 20 mm sand is 3200 MPa, and that of the crushed stone is 400 MPa. The in-situ material had a stiffness of 110 MPa.

From the research on mine haul roads [7] the stiffness of a dumprock layer with maximum size one-third of the layer thickness is 3000 MPa, which is equivalent to stabilised layers. In many areas dump rock is cheaper than stabilisation, and the construction is quicker. By trial and error appropriate structural designs for carrying the five high stacked containers and the 92 ton Reachstacker axles were evaluated. The structures are shown in Figure 5. The loading conditions are given in Table 2.

Table 2. Input parameters

Number	Loadcase	Gross load (ton)	Wheel load or Corner point load (kN)	Contact Pressure (MPa)	Radius of Contact area (mm)
1	Loaded Reachstacker (vehicle)	92	225	0.98	270
2	Container Stacking (5 - High)	150	370	22	75

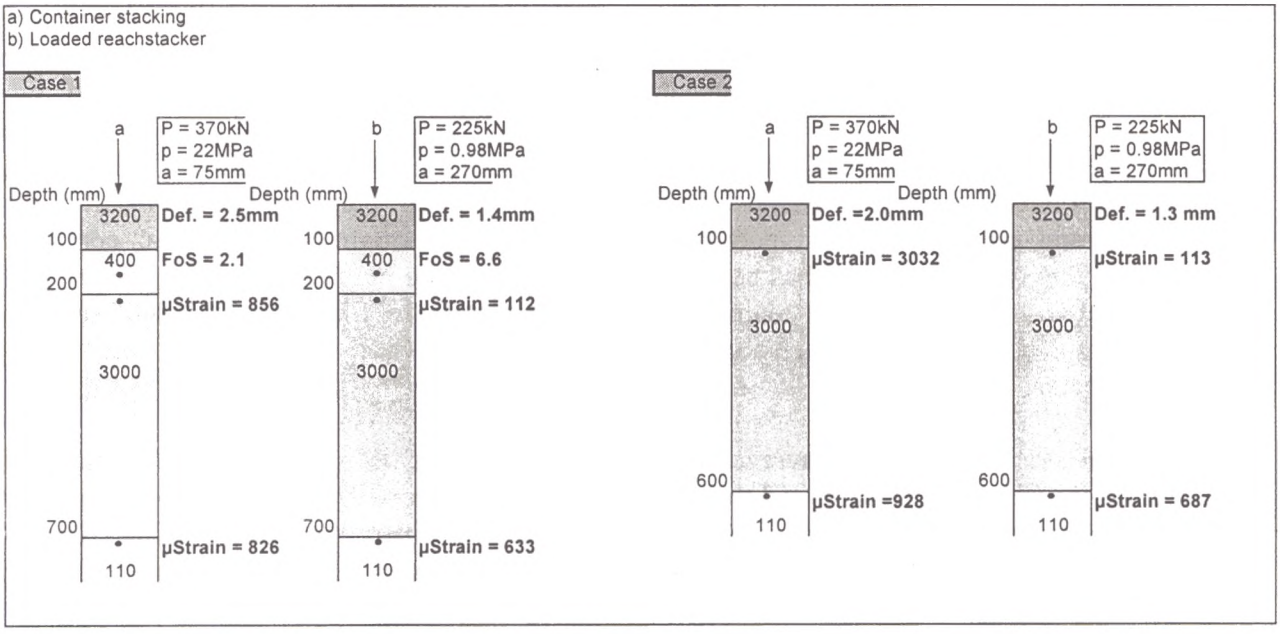


Figure 5. Results of structural analysis of block pavement for container terminal

The worst loading condition is the stacked containers. Under all the loading conditions the shear resistance of the crushed stone layer is adequate in terms of the factor of safety. Although the vertical compressive strain on the dumprock directly below the interlocking block layer is higher than the target value of about 800 microstrain, this pavement would not be a feasible option as the unevenness of the dumprock would not allow the blocks to be placed directly. A crushed stone levelling layer is required.

From Figure 5 the deflections of up to 2.5 mm reflect the flexible nature of the structure, and this should not cause any problems. Should this be a concern then the thickness of the dumprock layer could be increased, or an additional stabilised layer could be included on the dumprock.

6. CONCLUSIONS

The aim of the experiment was to obtain design input information of interlocking block pavements under ultraheavy loading conditions. The response and performance of 11 test panels constructed at Kaserne container terminal were presented. The following was concluded from the experiment:

- The DCP results obtained during construction showed that the weaker designs were in the range that would not normally be used, but these were invaluable in providing design information.
- The blocks showed no scuffing or deterioration during the 15 month evaluation period.
- Stiffness values for the different materials under ultraheavy loading corresponded with typical values used in road pavement design.
- The unbound materials showed no stress sensitivity over a range of loading, and confirms similar findings in open-cast mine haul road research.
- Permanent deformation and elastic deflections of the surface was related to the type of structure. This information provided confirmation that the allowable vertical compressive strains under ultraheavy loading that unstabilised layers could support was as suggested by the South African Mechanistic Design Method for road pavements.
- Initially the blocks were sensitive to the turning wheel of the Reachstacker and to the point loads of stacked containers. Maintenance crews should be available to restore this deterioration.
- The structural design of block pavements for ultraheavy loading may be performed using linear elastic layer analysis. Cost effective solutions include the use of dump rock in the upper pavement to ensure load spreading and stress reduction in the subgrade.

ACKNOWLEDGEMENTS

The execution of this experiment was truly a team effort. A special word of appreciation is due to Ms Sally Hall of Hyson-Cells who arranged for the construction, to Mr Stuart Morgan formerly of Spoornet for acting as construction manager, to Mr Richard Raven who assisted with the data collection and analysis as his final year research project, and the staff from the Spoornet Track Testing Centre, in particular Messrs Dries Herbst, Hannes Maree and Mike Thomas, for the support in the MDD installation and data collection. The construction was executed by Mr Des Kirwan of Rox Civils under difficult conditions.

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