PERMEABLE PAVING FOR A NEW CONTAINER HANDLING AREA AT SANTOS CONTAINER PORT, BRAZIL

JOHN KNAPTON, PROFESSOR OF STRUCTURAL ENGINEERING, UNIVERSITY OF NEWCASTLE UPON TYNE, UK. TEL: +44 191 222 6407 FAX: (44) 191 222 6502
e-mail: john.knapton@ncl.ac.uk web page: www.staff.ncl.ac.uk/john.knapton/
IAN D. COOK, TECHNICAL MANAGER, BLOCKLEYS BRICK PLC, TELFORD, UK. TEL: (44) 1952 251933. FAX: (44) 1952 641900. E-mail: tech.info@blockleys.com web page: www.blockleys.com

ABSTRACT

This Paper describes the solution process to the design of a 132,000m^2 container handling facility at Santos, Brazil in which the surface was engineered to allow the percolation of water. There are exceptional factors which led to some unusual aspects of the design solution and these are described in the Paper. The underlying clay is soft and is predicted to undergo consolidation settlement under the loads imposed upon the pavement during the container handling operations. A surcharge load was applied for 2 years to counter the consolidation settlement which would have occurred otherwise in the soft clay. The surcharge load was selected to achieve a level of pre-consolidation equal to that which would otherwise be induced by the self weight of the pavement. The other principal special factor in this project is the heavy loading regime applied by the container handling equipment and by the containers themselves. Equivalent wheel loads exceeding 50,000kg operate and the client wished to have the freedom to deploy such plant at any location in the pavement. Other special factors include tying the new pavement to an existing adjacent area which is surfaced with concrete raft units of plan dimensions 2.4m x 2.4m. In much of the existing facility, the raft units had suffered deterioration and had settled by approximately 400mm. Also, it was necessary to tie the new pavement into a new quay structure which was piled and which will not settle. This Paper shows how design solutions were developed. It shows how the adoption of the design was based upon an analysis of technical requirements, initial cost, maintenance cost and weather conditions.

1. PORT OF SANTOS GROUND CONDITIONS

The site has 40m thickness of 7000 years old soft clay, overlying 6m of silty sand overlying silty sandy clays. The water table is at the surface of the clay. Standard Penetration Tests were carried out and the clay was found to be very soft. In some places near the surface, the clay moved under the weight of the test apparatus and no readings were possible. The cone penetrometer showed clay to have a strength of 0.5N/mm^2 near the surface, increasing to 1.0N/mm^2 at a depth of 22m. In some boreholes, the vertical strength of the clay was a little less than 0.5N/mm^2 near the surface.

12m surcharge was placed of which 10.5m was removed prior to construction of the pavement so 1.5m of the sand remained. Vertical drains on a 1.4m to 2m grid were installed in the surcharge material to accelerate the preconsolidation settlement. The sand used for surcharge was fine single size material which permits the flow of water. There was never standing water on the surcharge sand. The water table was at the sand/soft clay interface. The surcharge sand was compacted such that after the surcharge settlement, the 1.5m thickness remaining sand was well compacted

2. PAVEMENT LOADING

At Santos, containers are handled by transtainers and by Front Lift Trucks. The deadweight of transtainers is 120t and they have a payload of 40t so that each wheel load is 29.3t for an 8-wheel vehicle or 57t for a 4 wheel vehicle. The wheel proximity factor was calculated to be 1.35 using the British Ports Association Heavy Pavement Design Manual (2m wheel spacing, 3000mm effective depth). Therefore the effective wheel load is 40.5t in the case of the 8 wheeled machine which was the preferred solution. With dynamics, this should be 44t. Such a load cannot be carried directly by unbound material such as crushed rock. If crushed rock were to be used as the general pavement construction material, a special beam would have been needed to support the transtainers. This would constrain the transtainers to run in pre-defined positions which would be contrary to the flexibility of operation which the client preferred.

3. ALTERNATIVE PAVEMENT DESIGN SOLUTIONS

Evidence from the adjacent site indicated that settlements in the new pavement could be sufficient to reverse drainage falls. This could lead to flooding and water entering stored containers - see Figure 1. For this reason, the design processed took as one of its objectives the percolation of water through the pavers. Three permeable pavement solutions were considered - all involving rectangular pavers as the preferred surfacing material:

(1) Crushed rock throughout the terminal with steel fibre reinforced concrete runway beams beneath the rubber tyred transtainer wheels.
(2) Cement stabilized surcharge sand with 50mm diameter holes drilled on a 2m grid, allowing operational flexibility.
(3) Cement stabilized no-fines gravel which had a permeability of 0.1 cm/sec without any holes drilled, also allowing operational flexibility.

The cost of gravel was \$30/m^3 and the cost of concrete was \$60/m^3. Therefore, providing 50cm of cement stabilized gravel had a similar cost to providing 1m thickness of gravel. Preliminary design studies indicated that alternatives (1) and (3) would be the preferred solutions in terms of operational flexibility, technical performance, initial cost and maintenance cost. For this solution, the British Ports Association design chart indicated that the pavement base should be 500mm thick to accommodate 1.5m passes of an equivalent single load of 44kN. For containers stored in blocks 4 high, the thickness required was 550m. Following preliminary cost comparisons for the above three solutions, the following design section was developed for alternative (3):

80mm	pavers
50mm	bedding material (6mm grit)
500mm	cement stabilized gravel
1500+ mm	sand (according to pre-compaction settlement)

4. MAINTENANCE COSTS

By the time maintenance was being evaluated, alternative (2) was eliminated on initial cost and technical grounds. The maintenance costs are based upon assessing the likelihood of various defects developing and making assumptions regarding the sizes of areas which will require reconstruction. These assumptions are based upon predictions of settlement over a period of 30 years and upon experience of European paved areas in similar situations. It is assumed that the area to be paved is 132,000m^2 and that containers will be handled principally by rubber tyred gantry cranes (transtainers) operating in the same location throughout the life of the pavement.

The principal reason for maintenance is settlement. When settlement has reached 600mm, it is assumed that the pavers will be lifted, additional crushed rock will be installed and the pavers will be cleaned and relaid. It is assumed that 20% of the pavers will be renewed at each repair. (The cost of installing new pavers is approximately 25% greater than that of cleaning and relaying, so the 20% figure is not particularly sensitive). The maintenance schedule set out assumes that the client requires a fully operational pavement with a significant residual life at the end of 30 years. If this is not the case, then some of the maintenance during the last ten years can be reduced.

In order to reduce the cost of maintenance to present day cost, a discount figure of 7% is used. This figure represents the value by which future maintenance is reduced when expressed in value at the time of construction. Based upon the above, life cycle costs were calculated for the no-fines concrete base solution (the adopted solution) and for the crushed rock with reinforced concrete beams solution. The results are shown in Table 1.

Table 1. Life cycle cost comparison - using discounting.

YEAR	AREA (m^2)	Alternative (3) No-fines base solution	Alternative (1) Crushed rock base with embedded reinforced concrete beams
0	132,000	$5,280,000	$4,224,000
5	4,000	$164,182	$222,620
10	8,000	$228,439	$309,748
15	8,000	$158,922	$215,488
20	8,000	$110,560	$149,913
25	12,000	$115,373	$155,753
30	12,000	$80,264	$108,356
TOTAL	52,000	$857,740	$1,161,878
		DIFFERENCE	**$304,138**

5. PERMEABLE PAVER DETAILS

The dimensions of the rectangular concrete pavers were determined based upon a module of 200mm x 100mm and large 6mm radius spacers. The allowable variation in modular length is 198mm to 202mm and the allowable variation in width is 98mm to 102mm. The spacers were located with their centres 18mm from each corner, working anti-clockwise with an additional spacer on each of the two longer sides located with its centre 18mm from the centre of each longer side - see Figure 2.

6. SPECIFICATION FOR BEDDING AND JOINTING MATERIAL

The bedding and the jointing material comprised naturally occurring coarse grit with no crushed fraction - see Figures 3 & 4. The particle size distribution fell within the envelope defined by Table 2.

Table 2. Grading envelope for jointing and bedding material.

Nominal aperture of sieve size(mm)	Percentage by mass passing through sieve(%)
10	100
5	50-80
2.36	20-50
1.18	0-30
600 microns	0-15
300 microns	0-5
150 microns	0-3
75 microns	0-3

7. CEMENT STABILISED CRUSHED ROCK BASE

The following specification was developed, taking into account the following:

(1) Material to be equivalent to that used in the British Ports Association design chart used in design.
(2) Material must permit the percolation of water.
(3) Material must prevent the loss of paver bedding sand.

The specification was:

(a) Cement to be Portland cement in accordance with relevant Brazilian standards.
(b) Cement content shall be approximately 130kg/m^3 but to be sufficient to ensure a characteristic 28 days compressive strength of 10Mpa.
(c) Water to be clean and free from any material which would detract from the properties of the concrete.
(d) Aggregates to be naturally occurring crushed rock material with an absorption value not greater than 2%. The materials to retain all of their strength when saturated and the grading to fall within the envelope shown in Table 3.

Table 3. Range of permitted gradings for base material.

Sieve size (mm)	Percent by mass passing
37.5	100
20	50 - 80
10	405 - 805
5	5 - 0
600 micron	0

8. PERMEABILITY OF UNDERLYING SAND

Calculations showed that the permeability of the sand was 36mm in one hour. The hydrological data showed that peak rainfall considering a 1 in 20 years return period is 40mm in 12 minutes. In 6 hours the 20 years return period rainfall is 80mm. This means that the sand cannot accommodate intense short storms but it can absorb protracted heavy rain. The voids in the pavement were calculated to be equivalent to 150mm total void. This means that an intense storm plus 6 hour rainfall can be detained in the pavement reservoir. Whilst it was clear that the surcharge sand would permit the vertical percolation of rainwater, it may be that the material would have insufficient horizontal permeability. As a result of this, a system of horizontal drains immediately below the base was developed.

9. MAINTENANCE

The principal reason for maintenance is settlement. When settlement has reached 600mm, it is assumed that the pavers will be lifted, additional crushed rock will be installed and the pavers will be cleaned and relaid. It is assumed that 20% of the pavers will be renewed at each repair. The maintenance schedule set out in Table 4 assumes that the client requires a fully operational pavement with a significant residual life at the end of 30 years. If this is not the case, then some of the maintenance during the last ten years can be reduced and the 30 years repair can be eliminated.

Table 4. Predicted maintenance schedule - area to be repaired.

Year	Area (m^2)
5	4,000
10	8,000
15	8,000
20	8,000
25	12,000
30	12,000
TOTAL	52,000

(The total area is 132,000m^2)

There is also the possibility that jointing material will be displaced by moving vehicles and plant during periods of flooding. Either the joints can be treated initially with a solvent based polymer, as previously discussed or alternatively, the displaced sand can be replaced as required. Because of the coarse grading of the sand, it is expected that removal in this way will be minimal and this is the preferred option. Occasional manual brushing may be required.

There may be areas of block breakage where containers are stacked roughly. It is common for pavers to break in the vicinity of regularly stacked containers in locations close to corner castings. In such areas, there is sometimes local settlement which will not exceed the amount by which corner castings protrude beneath the floor of containers. Once this level of settlement has occurred, the containers will rest uniformly on their undersides such that pavement point loads will be minimised. Many port authorities are prepared to accept this in container stacking areas, partly because it does not deteriorate progressively once the initial settlement has occurred and partly because it is in the main invisible. If necessary, it can be remedied by raising the pavers and providing additional bedding sand.

There may be differential settlement at the perimeter of the pavers and between pavers and structures supported by piles e.g. quay. In such areas, the pavers will rotate relative to their neighbours and large gaps will develop. It may be necessary to re-sand such areas at say 6 monthly intervals, depending upon the amount of traffic passing over the zones. Of course, in most of the development, there will be no traffic crossing the paved area perimeter.

There may be isolated areas of paver breakage because of damage caused by impact or by occasionally understrength pavers which have passed through the quality control systems. In such cases, it will be necessary to replace the pavers only if breakage results in paver disintegration. It is common for a number of broken pavers to be left in place in heavy duty pavements.

Other than the above, there should be no maintenance needed to the pavement. Pavers are known to have particularly low maintenance costs compared with either rigid or bituminous pavements. The principle reason for maintenance in this area is the predicted settlements of the underlying soils. Experience at Europe Container Terminus, Rotterdam suggests that predicted settlement values tend to be an upper bound and assume containers are all heavy. This is rarely the case and it can be the case that settlements are less than half of those predicted. This can be appreciated by comparing the predicted settlements with the actual settlements of the adjacent raft pavement area which has undergone settlements of approximately 300mm or less in 15 years.

10. CONCLUSIONS

The preferred solution at Santos comprised 80mm thick concrete block pavers bedded in a single sized grit laid over a no-fines cement stabilized crushed rock of thickness 550mm. The pavers had 6mm radius spacers to provide a 6mm gap to allow the free flow of water into the bedding material and then through the open textured base and into the surcharge sand. Whilst this system will not permit the immediate percolation of rainwater in the most severe storms, it will ensure that standing water percolates quickly. Other solutions would have resulted in deep water standing for long periods to a depth which would cause intrusion into containers.

Permeable paving is becoming widely available and is perceived to have many environmental and cost advantages. If permeable paving is used in heavily loaded conditions, a great deal of care is needed in the design and specification of pavement construction materials. No material whose strength will reduce should be specified and care must be undertaken to endure that the underlying subgrade can absorb the water percolating through the pavement.



Figure 1. Ponding on adjacent paving as a result of long term consolidation settlement.



Figure 2. Permeable paver employs spacers to form 6mm joint around each paver.



Figure 3. Pavers installed over coarse grit.

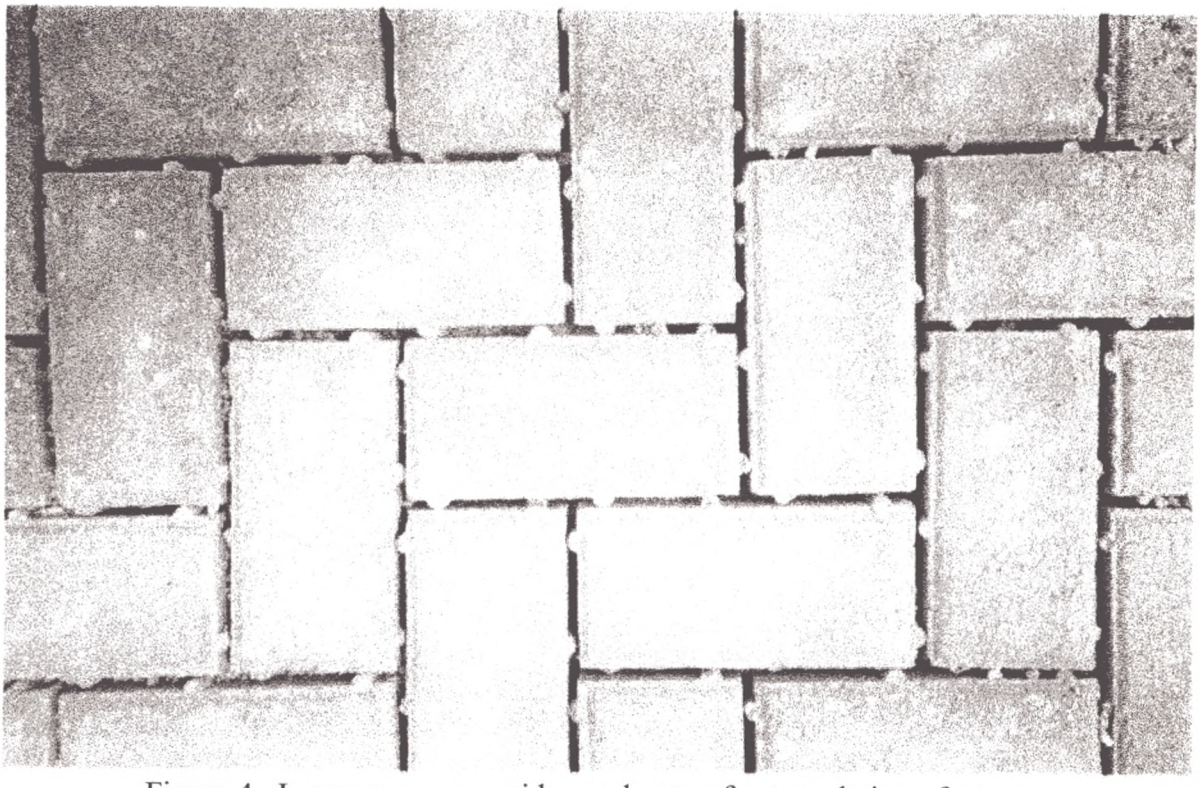

Figure 4. Large spacers provide ample gaps for percolation of water.