CONCRETE BLOCK PAVEMENTS IN THE PORT OF ROTTERDAM

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SUMMARY

Concrete block pavements (CBPs) have been applied in a huge volume (10-15 million square meters) in the port of Rotterdam at heavy duty industrial areas, like container terminals. CBPs at the container terminals exhibit a satisfactorily performance in terms of bearing capacity under dynamic and static loading, flexibility against settlements, ease of maintenance and low investment costs. Additionally, concrete blocks are resistant to oil spillage.

This paper presents the experiences with concrete block pavement structures in relation to the axle or wheel loads and the number of movements of transport vehicles. Construction and maintenance costs (life-cycle costs) were assessed and compared to those of other types of pavement structures. However, for some loading areas CBPs are no longer applied, even though there are still opportunities for application of CBPs. Some improvements are suggested in order to accomplish a better performance.

1. INTRODUCTION

This paper describes the experiences with concrete blocks at container terminals in the port of Rotterdam and relates the different loading regimes of the transport vehicles to the required maintenance. For a comparison with other type of pavement structures the construction and maintenance costs (life-cycle costs) have been assessed.

CBPs are used at several container terminals in the port of Rotterdam since the construction of the first terminal in 1967. The container terminals have been built at reclaimed area from the sea. In the beginning, container handling was primarily performed by trailers and tractors and straddle carriers, but since the construction of terminals at the Maasvlakte (peninsula at the entrance to the port of Rotterdam) in the nineties, container handling has become mainly automated. Concrete block pavements (CBPs) on a base layer of sand cement placed on a sand subsoil have proved to be suitable for different types of dynamic (Straddle Carriers, Reach Stackers, Multi-Trailer systems, etc) and static loading.

However, at the automated container terminals containers are transported by Automated Guided Vehicles (AGV's) and Automatic Stacking Cranes. At the land side Straddle Carriers still are used. The CBPs at the sea side have been replaced by semi-flexible pavements, because rutting occurred in the fixed driving lines of the AGV's. This resulted in problems for the navigation software and mechanical wear of the AGV's. Maintenance frequencies became too high leading to operational stagnation in the container handling.



Straddle Carrier in operation



Twin Carry AGV in operation

Figure 1. Equipment container transport

2. DEVELOPMENTS IN CONCRETE BLOCK PAVEMENT STRUCTURES

Nowadays, more or less the following structure is used at terminals in the port of Rotterdam. Obviously, it is clear that the sand cement stabilization layer plays a major role in the bearing capacity of the whole pavement structure.

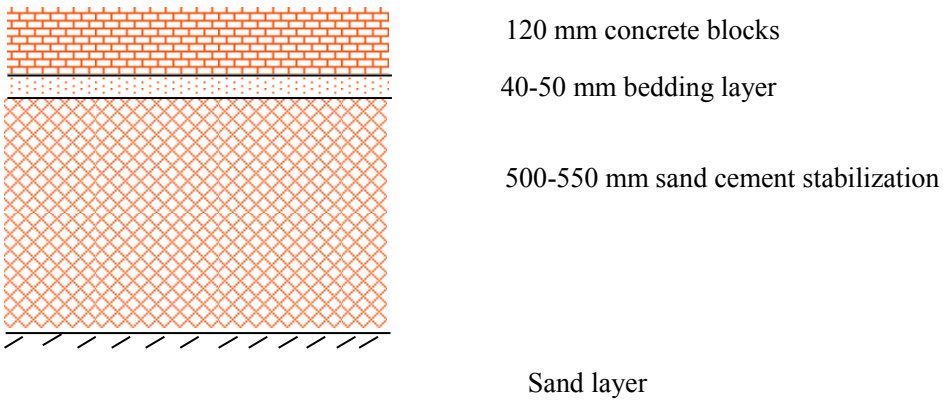


Figure 2. Pavement structure terminals - Port of Rotterdam

The application of sand cement stabilization as the base layer is strongly encouraged by the large nearby availability of sand from the sea bed. The mix composition and construction methods of the sand cement have been optimized with time.

The first generation terminal in the port of Rotterdam was built on a sand layer from the sea bed, placed on a layer of harbour silt, resting on a peat/clay subsoil (Luidens and van Hees, 1996). The pavement structure of the first terminals consisted of concrete blocks laid on a bedding layer and a base layer of sand cement stabilization. Consequently, the deeper weak subgrade layers were subject to large settlements of 1 to 1.5 m in the first 10 years (van Leeuwen, 1980). The terminals built at the Maasvlakte in later years, were constructed on a better subgrade resulting in less settlement.

2.1 Concrete blocks

The concrete blocks that were applied complied with the NEN 7000 (Dutch) standard. Average block dimensions are 220 mm long, 110 mm wide and 120 mm thick; the shape is rectangular. The bending tensile strength of the blocks is 5.9 MPa. The choice for 120 mm thick blocks instead of 100 mm thick blocks was mainly subject to the susceptibility of the thinner blocks to overturning if subjected to torsional loads (van Leeuwen, 1980). The blocks are laid in a herringbone bond at the whole terminal. When there is insufficient space an elbow bond is applied.
However, some adjustments have been made during the years to improve performance of the concrete block pavements:

- Mechanical laying was introduced in the 1980's due the restriction of manual laying of blocks heavier than 6 kg. By mechanical laying, the blocks are laid in batches of one square metre at a time (Luidens and van Hees, 1996).
- Due to mechanical laying, the blocks were placed very close together causing damage in the upper edges of the blocks. Another problem was the splintering of the upper edges when loaded by heavy torsional loads. The heavy torsional loads are caused by the small turning radius and the high wheel loads of the transport equipment. Therefore, block shapes were modified by introducing "spacers" to ensure sufficient joint width (Luidens and van Hees, 1996).
- During the years just the tolerance of the measurements has been shifted from 10 mm to 15 mm. This change of tolerance requires more quality control, because the specific bond for mechanical laying during storing, transport and construction of blocks is more sensitive and can get disturbed. During construction, these disturbances in bond will lead to inferior quality.

2.2 Bedding layer

The bedding layer is mostly applied in a minimum layer thickness of 40 mm. Application of smaller or larger layer thicknesses are not preferred. A layer thickness of 30 mm is not sufficient for profiling the unevenness in the upper part of the sand cement stabilization, because of the risk of "flapping" of the blocks. The bedding layer (0/8 gradation) consists of the following mix composition:

Table 1. Mix composition of bedding layer

On sieve	**Mass percentage retained [%]**	
	Minimum	Maximum
C 8 mm	0	10
C 5.6 mm	20	40
2 mm	60	80
63 µm	90	100

The bedding layer is spread and compacted by an asphalt paving machine to achieve the optimum evenness and compaction.

2.3 Joint sand

After laying the concrete blocks the sand for the joint fill is swept and the blocks are vibratory loaded to accomplish optimal interlocking effect of the blocks. The joint sand consists of the following mix composition:

Table 2. Mix composition of joint sand

On sieve	Mass percentage retained [%]	
	Minimum	Maximum
C 4 mm	0	10
1 mm	10	45
63 µm	90	100

2.4 Sand cement

The sand cement stabilization has been applied ever since the construction of the first terminals in Rotterdam. Application of sand cement base has always been preferred because of the large availability of sand in the port, easiness in construction ("mix-in-place"), low costs and good performance for heavy duty areas. It was first applied in a layer thickness of 330 mm in the days that container transport was performed by tractors and trailers and Straddle Carriers, and wheel loads varied from 125 to 170 kN (Luidens and van Hees, 1996). Nowadays the wheel loads and especially the number of transport movements have become much higher. The maximum wheel load of the Automated Guided Vehicle was recently raised to 205 kN (twin-carry AGV) and the maximum wheel load of the Straddle Carriers (8 wheels) is approximately 132 kN.

The AGV drives in fixed lines (highways), without any lateral wander, using a pattern (2x2 m) of navigation points embedded in the surfacing. Consequently, the same line in the pavement is continuously subjected to repetitive loading of the wheel loads of the AGV's. The damage at the AGV-area is more extensive than at the areas where the Straddle Carriers and Trailers are used. These vehicles do not drive in fixed lanes and wander laterally over the pavement. For that reason, the sand cement base layer at the heaviest trafficked area (AGV-area) is applied in a layer thickness of 550 mm. This is the maximum layer thickness which can be laid in one pass. For areas loaded by Straddle Carriers and Multi-Trailer systems, the sand cement is applied in a layer thickness of 500 mm.

The sand cement the strength requirements are as follows:

- Average laboratory compressive strength after 28 days of at least 5 MPa
- Average field compressive strength after 28 days of at least 2 MPa
- Rejection if the individual field compressive strength is 1.5 MPa or less after 28 days

The cement content varies between 140 and 180 kg/m^3 depending on the particle size gradation of the sand and the mechanical properties. Adequate drainage system is absolutely required to prevent saturation of the bedding layer when subjected to loading of heavy loaded vehicles and a large number of movements. Drainage holes are drilled in the sand cement at the AGV-area in the direction perpendicular to the quay side at 1/3 of the length. This is important in the first years of operation, because the joints between the concrete blocks are not optimally filled and water can penetrate into the bedding layer and the upper part of the sand cement.

Experiencing that the AGV had a more pronounced damaging effect on the pavement structure, the upper part of the sand cement was improved in terms of strength (resistance against deformation) and wear (Luidens and van Hees, 1996). Research showed that it was necessary to mix a 50% coarse fraction, consisting of crushed concrete and 50% sand together with cement in order to obtain more strength and wear resistance. This composite base layer was applied in a layer thickness of 200 mm

upon a sand cement layer of 400 mm. The mix of crushed concrete and sand is termed "modified sand cement" layer. This layer was applied at the Delta Dedicated East (DDE) and Delta Dedicated West (DDW) terminal.

As already mentioned, the AGV drives in highways use navigation points embedded in the surfacing. At the DDE and DDW terminal the navigation cables were placed in the upper part of the sand cement, by sawing notches in the sand cement. The navigation cables were put in protection pipes ("grids") which were placed in the notches. The notches were covered with a cementitious material. In a later stadium this system was replaced by transponders, installed in the concrete blocks.

Unfortunately, within a few years extreme rutting occurred, mainly at the locations of grids. Rutting increased sharply in extent and severity due to penetration of water in the sand cement. This caused the top of the base to disintegrate. Numerous repairs gave little to no improvement. This resulted in problems for the navigation software and mechanical wear of the AGV's. The frequency of unpredicted, premature maintenance led to operational stagnation in the container handling. Therefore, the CBPs at the sea side of the DDE and DDW terminals were replaced by semi-flexible pavements (Luidens and van Hees, 2000; Moenielal and A. Boekee, 2000).

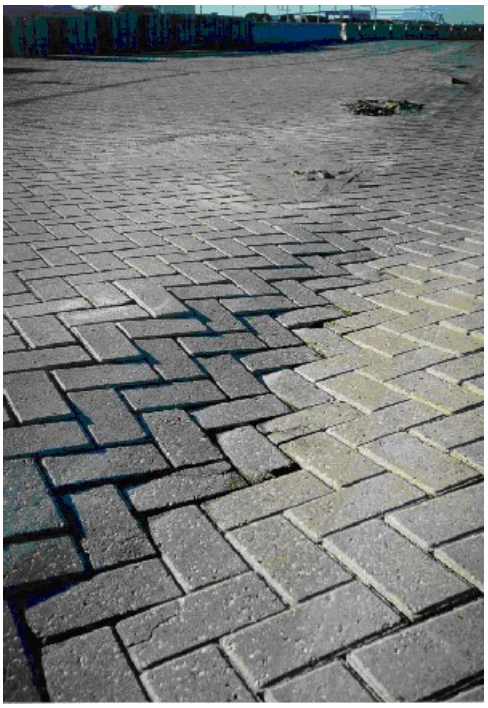


Figure 3 shows an example of the extreme rutting (rut depths of 10 cm were observed) as occurred on the DDE and DDW Terminal.

Research showed that is possible to identify the key factors that cause the (non-reversible) rutting in the CBP. A number of possible reasons are suggested:

1. large number of repetitive axle loads of AGV and driving without any lateral wander
2. insufficient drainage of water leading to saturation of bedding layer. This leads to "pumping effects" resulting into fine parts squeezed from the bedding layer to the surface
3. crushing and pulverization of aggregate of bedding layer due to heavy wheel loads of AGV and continuously loading at the same traffic line
4. crushing of material of the bedding layer in the upper part of sand cement with low wear resistance
5. crushing of aggregate of the bedding layer and upper part of the sand cement layer

Figure 3. Rutting at DDE and DDW terminal

6. aspects regarding to construction
    - inhomogeneous mixing of sand cement over the whole layer thickness
    - drying out of upper part of sand cement during construction
    - loose material in the upper part of the sand cement (sods/scrapings) when re-profiling the sand cement

The mechanism that possible causes the rutting under loading of an AGV wheel pass is illustrated in Figure 4. The numbers 1 to 5 correspond with the above mentioned items.

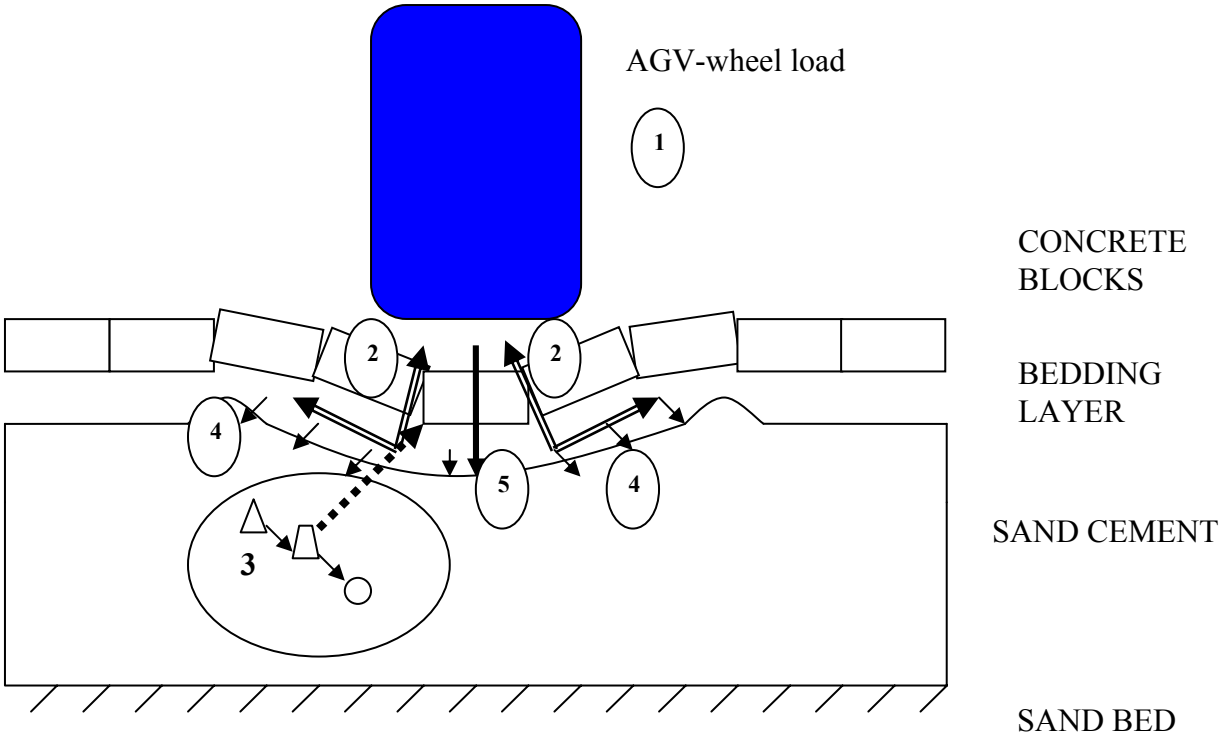


Figure 4. Mechanism rutting under loading of AGV

When looking at the current situation with twin-carry AGV's (handling of two 20-ft containers simultaneously) in operation, the sensitivity for water penetration into the base layer, and the speed of maintenance semi-flexible pavements were expected to be more advantageous. It was questioned if the conventional concrete blocks pavement on sand cement stabilization was able to withstand the higher dynamic and torsional loads of the twin-carry AGV's.

3. MAINTENANCE IN LOADING AREAS

3.1 General

At the new automated terminals the pavement structure can be divided as follows:

- 50% lava (unbound granular base layer) on container stacks
- 40% concrete blocks at driving lanes used by Straddle Carriers and Multi-Trailer systems
- 10% semi-flexible pavements at AGV-area

It is remarkable that the major part of the automated container terminals contains a lava base layer. For the container stacking area 150 mm lava 0/40 is used, covered by 50 mm lava 0/20.

3.2 Straddle Carriers and Multi-Trailer systems

Concrete blocks have always been used for the driving lanes of Straddle Carriers and Multi-Trailer-systems. Because of the high number of loaded wheels of the Carriers (8x) and the Trailers many repetitive wheel loads are exerted onto the pavement. The loading characteristics of the Straddle Carrier can be described as follows:

- maximum wheel load 125 kN
- tire pressure 0.7 MPa

- highest number of movements at a single line per hour 4 (mix 20/40 ft containers)
- highest number of wheel load passes at a single line 16
- highest number of wheel load passes at a single line in one year 1.38×10^5

The loading characteristics of the Multi-Trailer systems are:

- axle load 300 kN (4 wheels)
- maximum wheel load 75 kN
- tire pressure 0.7 MPa
- highest number of movements at a single line per hour 4 (mix 20/40 ft containers)

The main damage occurs near the container stacking area, where there is not much space available for the transport vehicles. This results in concentrated wheel load passes and sharp turns leading to deformations and rutting of the pavement. The first maintenance action is needed when rut depths of 20-30 mm occur, usually in year 7-8, followed by regular maintenance every 6-7 years. However, it has to be noticed that repair is limited to patches smaller than 5% of the total area used by the Straddle Carriers and Multi-Trailer systems.

The repair consists of the following activities:

- removing concrete blocks and bedding layer
- inspection upper part of sand cement (holes)
- refilling upper part sand cement, reuse and re-compaction of bedding layer
- reuse and vibratory compaction of concrete blocks

The next figures present pictures of the bedding layer and upper part of the sand cement during maintenance at the Straddle Carrier area.



Inspection after removing blocks



Crack in upper part sand cement



Crushed material bedding layer and sand cement

Figure 5. View of upper part of sand cement during maintenance

3.3 Automated Guided Vehicle (AGV)

The AGV is strongly characterized by driving in the highways, without any lateral wander, and the heavy wheel loads. Consequently, the same line in the pavement is subjected to continuously repetitive loading of the wheel loads of the AGVs.

As already mentioned, the system of the grids has recently been replaced by transponders installed in the concrete blocks. The wheels of the AGVs are sprung (in beginning unsprung) and the AGV is equipped with large Carrier type tires. The AGV consists of hydraulic driving and braking systems. The loading characteristics for the AGV (front/back axle 2 wheels) are described below:

- axle load 410 kN (2 wheels)
- maximum wheel load 205 kN
- tire pressure 0.7 MPa
- number of movements at a single line per hour 9 (mix 20/40 ft containers)
- number of axle load passes of 240 kN at a single line 500 per year (as reference)
- number of axle load passes of 240 kN at a single line 2.01×10^4 (as reference)



Figure 6. AGV highways between stacks and quay crane

The twin-carry AGV's have recently been taken in operation. In the past, the maximum wheel load of the AGV used to be 160 kN. It is assumed that movements of the twin-carry AGV's will be approximately 10% of the total number of movements and the conventional AGV will form 90% of the total number of movements.

Concrete blocks are currently only used at the AGV-area of the Delta Dedicated North (DDN) terminal. At this terminal the navigation cables were not installed in grids and no notches were used. Conventional sand cement stabilization is applied in a layer thickness of 500-550 mm, upon which the bedding layer (40-50 mm) and the concrete blocks (120 mm) have been laid. In fact, the navigation cables are directly placed in the bedding layer. Rutting (30-40 mm) may be observed at some locations



Rutting AGV-highway



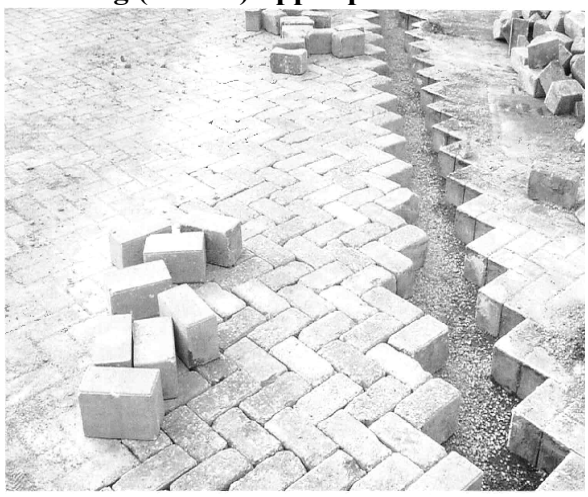
Rutting and deformation in curves



Crushing (30 mm) upper part sand cement



Damage in upper part sand cement



Repair with old concrete blocks



View surface after repair

Figure 7. Observations during maintenance

of this terminal, but not as severe as visible at the DDE and DDW Terminal. Maintenance is mainly required at parts where the most frequent loaded highways cross each other and where the blocks are subjected to torsional loads of the AGV (sharp curves). Maintenance is scheduled when rut depths of 30-40 mm are observed. From experience it is known that regular maintenance has to be performed every year on 2-3% of the total area.

The repair consists of the following activities:

- removing concrete blocks and bedding layer
- inspection upper part of sand cement (holes)
- refilling upper part sand cement with (un)bound granular material
- reuse and re-compaction bedding layer
- reuse (75%) and vibratory compaction of concrete blocks

Reuse of the concrete blocks is limited. After three maintenance cycles the old concrete blocks are replaced by new blocks. The following figures display rutting and the maintenance activities. The displayed rutting is primarily generated by crushing of the bedding layer into the upper part of the sand cement due to the repeatedly loading of the AGV at a single line of trafficking.

4. MONITORING RUT DEPTH BY ARAN

Rut depth at the DDN Terminal was measured in the longitudinal direction of the AGV-highways by means of the Automatic Road Analyzer (ARAN). The ARAN is a vehicle which enables to measure different surface characteristics like rut depth and longitudinal unevenness while driving at high speed. The rut depth is deduced from the transverse profile measured by ultrasonic sensors mounted each 0.10 m on an instrument bar mounted at the front of the ARAN. The width of the beam can be varied; at the DDN Terminal the maximum width of 3.50 m was used.

For every 5 m length a full transverse profile was measured and stored. The rut depth was determined for a software modeled straightedge of 1.2 m over the cross section. The rut depth measurements were carried out in 2004 and 2006. The DDN was taken into operation in 1994. The numerical results for the most frequent loaded AGV-highways (4 highways under the quay crane) are presented in the next table.

Table 3. Rut depth AGV-highways under quay crane (QC)

Number AGV-highway	Average Left Wheel track [mm]	Standard deviation [mm]	Average Right Wheel track [mm]	Standard deviation [mm]
1	10.5	5.2	10.8	4.5
2	10.7	4.4	11.3	4.0
3	12.2	4.3	13.0	3.8
4	12.1	5.6	10.1	4.6

For example, the results regarding AGV-highway 1 (parallel to quay wall) under the quay crane are plotted in the next figure.

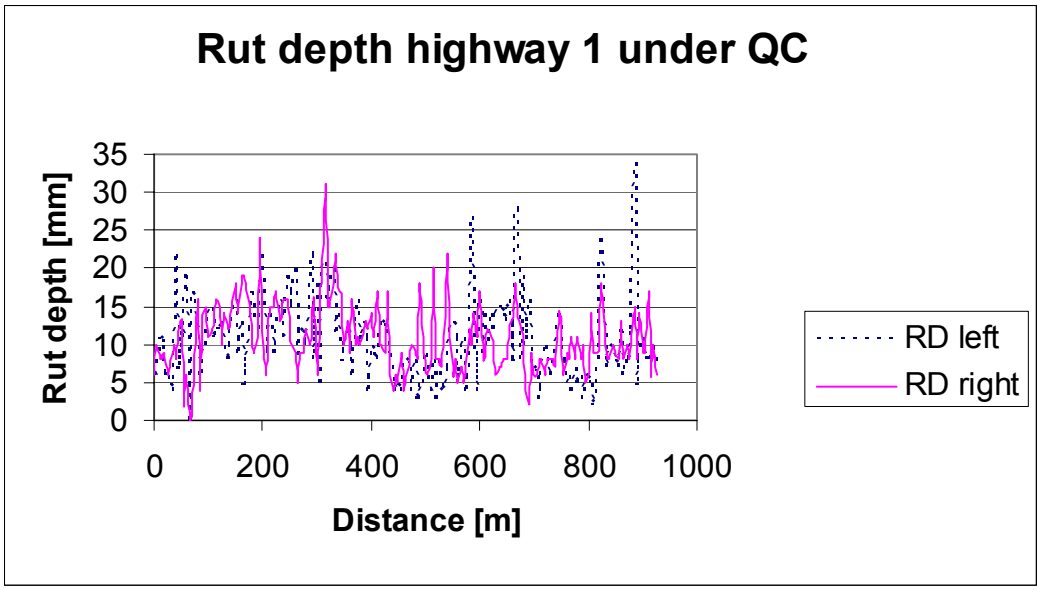


Figure 8. Rut depth AGV-Highway (parallel to quay wall)

When comparing the results of 2004 to those of 2006, the following rut depth distributions for both wheel tracks were determined. The AGV-highways are divided here in two groups:

- The most frequent loaded highways (4x) located under the quay crane (QC)
- The highways (7x) located between the automatic stacking crane (ASC) of the stacking areas and the quay crane (QC)

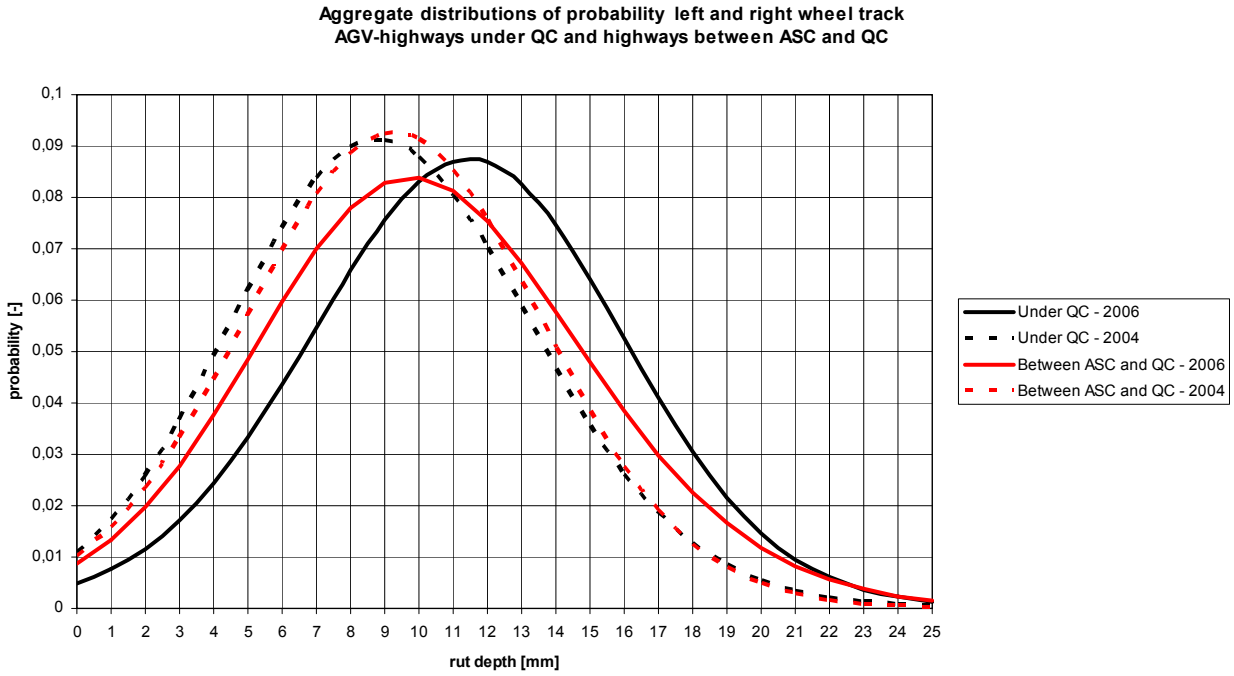


Figure 9. Comparison rut depths AGV-Highways

A comparison has been made by breaking down the rut depths into three categories. The results are shown in the table below:

Table 4. Categories of rut depth (RD) of AGV-highways in September 2004 and May 2006

Category	Average Left and Right wheel track 2004 [%]	Average Left and Right wheel track 2006 [%]	Increase of rut depth 2004- 2006 [%]
RD < 20 mm	97	94.1	-2.9
20≤ RD ≤ 30 mm	2	4.5	+2.5
RD ≥ 30 mm	0.1	0.5	+0.4

The following conclusions may be drawn:

1. The test results of 2006 show that the rut depth for the major part (94%) is less than 20 mm. It can be seen that 5% of the test results is larger than 20 mm and 0.5% of the test results is above 30 mm.
2. There are no specific locations to be found where the rut depth is larger than 20 mm. The large rut depths occur at different locations. In every highway 1 or 2 two test points can be observed that have rut depths larger than 30 mm. The maximum rut depth is 39 mm.
3. Looking to the results of 2004 and 2006 there is an increase to be observed for almost 3% of the test points.
4. For the most frequent loaded highways under the quay crane the rut depth has been increased with 2.5-3 mm in the period between September 2004 and May 2006. For the highways between the automatic stacking crane and the quay crane an increase of 1 mm can be observed.

In summary it can be concluded that the annual increase of rut depth varies between 1 mm and 3 mm depending on the trafficking line. This is in line with rut depth development at pavement structures at public roads.

5. CONSTRUCTION AND MAINTENANCE COSTS

For the Straddle Carrier and MTS area the life-cycle costs for the concrete blocks are very low. The block pavements show a good performance under dynamic and static loading and have a low maintenance frequency. For the AGV-area, however, semi-flexible pavements are preferred nowadays by the owners of the container terminals in Rotterdam. The first semi-flexible pavements were built in 1999. Because some damage (wear of top layer) can be observed now due to oil spillage, regular cleaning is necessary at slippery patches. Thus, it seems that semi-flexible pavements have their disadvantages too. While the experience with semi-flexible pavements is growing, it can be concluded that there is still opportunity for other type of pavement constructions. A feasibility study (Moenielal and Gaarkeuken, 2004) has been performed for the Euromax Terminal for determining the most optimal pavements constructions at the AGV-area. The Euromax is a new container terminal currently under construction. In the study for Euromax application of concrete blocks, semi-flexible pavements and unreinforced concrete have been investigated.

For the comparison of construction and maintenance costs for the different constructions the net present value method has been used under the following assumptions:

- 10 hectares AGV-area (long 1250 m and wide 80 m)
- Interest rate of 6.5%
- Regular maintenance including:

  - semi-flexible pavement: cleaning slippery patches and repair cracks every year and replacing 40% of the wearing course in 10th year
  - concrete blocks: repaving 2% of area every year
  - unreinforced concrete slabs: replacing joint filling every 7 years and replacing new slabs at 1% of area in 10th year
- Reconstruction at end of structural life (20 years)
  - semi-flexible pavement: 70% of area
  - concrete blocks: 50% of concrete blocks, 35% of lean concrete base
  - unreinforced concrete slabs: 25% of slabs

The determined net present values for periods of 20 and 30 years are shown in Figure 10.

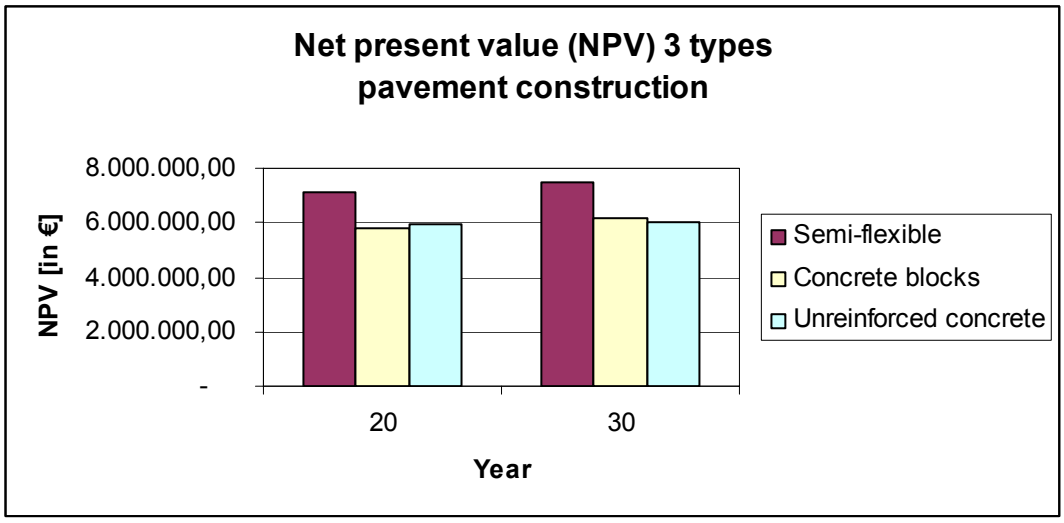


Figure 10. Comparison of pavement constructions by net present value

The concrete blocks and concrete slabs look more cost-effective than semi-flexible pavements. For the Euromax terminal also the duration of operational stagnation due to maintenance was an important issue. That issue was not included in Figure 10. Evaluation of the proposals of the contractors tendering for the Euromax terminal revealed that the semi-flexible pavements appeared to be more cost-effective than alternatives with concrete blocks and unreinforced concrete slabs. Therefore, Euromax Terminal chose for semi-flexible pavements at the AGV-area, while concrete blocks will be applied at the other loading areas. A Design-Build-Maintain contract was used for the tender of the construction of the pavements at the Euromax Terminal. This involves the contractor being responsible for all the maintenance performed on the pavement in the first 10 years of operation. If more maintenance is required than stated in the contract documents, the contractor will have to pay a fee according to the duration of the operational stagnation.

6. CONCLUSIONS AND RECOMMENDATIONS

The concrete blocks have proven to be suitable (technical aspects and cost-effectiveness) for the areas loaded by Straddle Carriers and Multi-Trailer systems. However, for the AGV-area some improvements have to be made to the pavement structure. The key factor for good performance of the concrete blocks is the strength and wear resistance of the upper part of the sand cement. The behaviour and performance can be improved by adjustments, like:

- Application of lean concrete (C15-strength) as described in the British Port Manual. The lean concrete can be applied in layer thicknesses of 250-300 mm on a subbase layer of sand cement stabilization
- Sufficient time for hardening of the cement bound layers. Due to tight time schedules the sand cement is sometimes loaded too early by trucks and equipment of the contractor. This leads to premature damage especially of the upper part of the sand cement
- application of sand cement mix-in-plant instead of mix-in-place

7. ACKNOWLEDGEMENTS

The author expresses his thanks to Mr. Daan Quak and Mr. Hans Heijstek (ECT) and Mr. Jan van Hees (Euromax) for providing information and their co-operation in the preparation of this paper. Mr. Christ van Gurp (KOAC•NPC) is cordially acknowledged for his interest and his comments.

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