Innovative design and construction of the Euromax Container Terminal Rotterdam

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ABSTRACT: The "Euromax Container Terminal Rotterdam" project was started in 2005 on the last available area of the Maasvlakte I in the port of Rotterdam, the Netherlands. At the terminal Automatic Guided Vehicles (AGV's) transport containers from vessel to stack over the so-called AGV-area. This AGV-area was tendered as a D&C(M) contract.

The composition of the pavement consists of a grouted macadam surface layer, applied on two layers (bind and base) of polymer modified asphalt concrete, on top of a Cement Treated Base (CTB).

The pavement structure was designed by means of amongst others the linear elastic multilayer program APSDS4 and the Finite Elements Modelling program CAPA-3D. The pavement structure specifications were set regarding rutting, evenness, drainage, skid resistance, bearing capacity, cracking and surface damage (ravelling, potholes, popouts, etc.). Laboratory testing of the sand subbase, CTB, asphalt concrete, tack coat and grouted macadam was performed to determine the optimum material properties for the design.

The design life of the pavement is 20 years during which a maximum of 4,000,000 AGV's will pass the normative location. The lateral wander of the AGV's is very limited because transponders, which are drilled into the surface layer, guide them automatically.

The final state-of-the-art pavement design was both competitive in costs and quality when compared to reinforced concrete or concrete brick pavements. During the design proces focus was on the use of locally available materials as much as possible, because of their economic and environmental benefits. Some interesting product and process innovations were applied.

The container terminal is operational for more than 5 years and no significant damage has been reported yet.

KEY WORDS: Innovative design, bearing capacity, polymer modified asphalt, container terminal, in-situ measurements

1 INTRODUCTION

As a result of the yearly growth in container handling, the obvious need for a new container terminal arose in the port of Rotterdam in the early years of this century. This new container terminal is called "Euromax Terminal Rotterdam" (ETR) and is located at the north-westerly corner of the "Maasvlakte I". The ETR is located at the last available location for container terminals at the Maasvlakte I. The Maasvlakte I was created in the 1960s by reclaiming land from the North Sea through dykes and dredged sand. Lately the port authorities have started the development of the "Maasvlakte II", at which the first container terminals should be operational in 2014.

The ETR-project consists of 3 phases: phase 1 started in 2005 and the first part of the terminal is operational from early 2008. The construction of phase 2 started directly after the completion of phase 1. Phase 1 and 2 together are fully operational from 2010 onwards and so far no significant damages have been reported. Phase 3 is a possible extension of the terminal towards the new land at Maasvlakte II. For the moment it is unknown when this extension shall take place. In Figure 1 the first part of phase 1 is visible. The quay is on the right.

Figure 1: Overview of a part of the Euromax Container Terminal Rotterdam

The ETR is a part of ECT and it is one of the most advanced and environment-friendly container terminals in the world. The handling of the containers from the vessel to the stacks is fully automated. The total area of phase 1 is 84 ha, the quay length is 1,500 m and the current water depth along the quay is 16.8 m. This means that today's very largest container ships can be handled at the ETR. In case the size of the container vessels should increase in future, the port basin can easily be further deepened to 19.6 m. The cranes at the ETR have a reach of 23 containers wide.

The construction of phase 1 of the ETR-project was awarded via a tender. Ooms Civiel won the project, together with BemoRail and Cofely. In the project BemoRail took care of the construction of the on-site rail terminal and Cofely took care of all electrical engineering. Afterwards the second phase of the project was awarded directly to the companies mentioned above.

This paper only describes the works performed by Ooms Civiel on Euromax, so the rail and electrical engineering works are outsight the scope of it. After a short summary of the total project, the focus will be on the design and construction of the AGV-Area, as this area was tendered as a "Design, Construct & Maintain" (DC&M) contract.

2 EUROMAX TERMINAL ROTTERDAM – TYPE OF CONTRACT AND FIGURES

The Port Authorities were the Client of the ETR project. ARCADIS managed the total project on behalf of the Client. The total costs of phase 1 and 2 together are about EUR 112,000,000. Apart from the AGV-area the project tender specifications were relatively simple, as the

Client´s consultant (ARCADIS) provided the complete Statement of Work and the bill of quantities and the competitors only had to price it.

As part of the tender the competitors had to make a proper design for the area from the quay to the stacks. There was also a penalty system in the contract concerning the (lack of) availability during the first 10 operational years of the AGV-area. Lastly the contractor had to offer a fixed price for the maintenance of the AGV-area during the first 10 operational years. After the completion of the container terminal the Client had to decide whether or not this maintenance contract would be commissioned to the winning contractor.

To give a good insight of the scale of the project the following figures are given. The total amount of earthmoving work was about 1 million m³. The total length of concrete sewers is about 21 km. The project contains some 16 km of PVC-pipes and the total length of ground drainage is about 37 km. The pavements contain about 260,000 m² in-situ cement stabilization, 600,000 m² polymer modified asphalt concrete, and 410,000 m² concrete bricks. These bricks had to be applied mechanically. In total 53,000 transponders were drilled into the pavement surface of the AGV-area to guide the AGV's automatically.

3 AGV-AREA PAVEMENT DESIGN PHASE

The Port Authorities set requirements for the pavement in the AGV-area regarding rutting, evenness, drainage, skid resistance, bearing capacity, cracking and surface damage (ravelling, potholes, popouts, etc.). Also the type of traffic and the number of traffic load repetitions during the design life of 20 years were given by the Client. A number of these aspects will be discussed below.

The Client did not prescribe the material of the surface layer of the pavement. This meant that other pavement structures than the well-known solutions with reinforced concrete or concrete bricks could be accepted. Ooms Civiel took this challenge and developed the alternative asphalt concrete pavement structure described in this paper, as they were convinced this could be a more suitable and cost-effective alternative.

3.1 Traffic load

Two types of AGV are present at the analysed area: the standard AGV (shown in Figure 2) that transports only one container and the twin-carry AGV that can transport two containers simultaneously. Given the standard container weight distribution and the AGV dead weight (22.5 kN), the maximum design traffic load is set to 82.5 kN. This load is distributed from the AGV to the pavement structure by 4 (big) wheels. The centre-to-centre distance of the wheels per axle is 2.45 m, while the centre-to-centre distance of the wheels in between the two axles is 8.8 m. The tire pressure is 1.0 MPa and the operational speed of the vehicles is 15 km/h. Altogether this means that the AGV-area is exposed to a much heavier design load than a regular motorway.

Traffic analyses learned that the design traffic consists of 4 million AGV's passages during the life of 20 years (50% of these traffic repetitions were said to be "empty": just an AGV without carrying a container). In Figure 3 the total traffic load distribution is displayed. The loading groups of an empty AGV and of an AGV carrying an empty container are left out to make the figure more readable.

Figure 2: Example of an Automatic Guide Vehicle

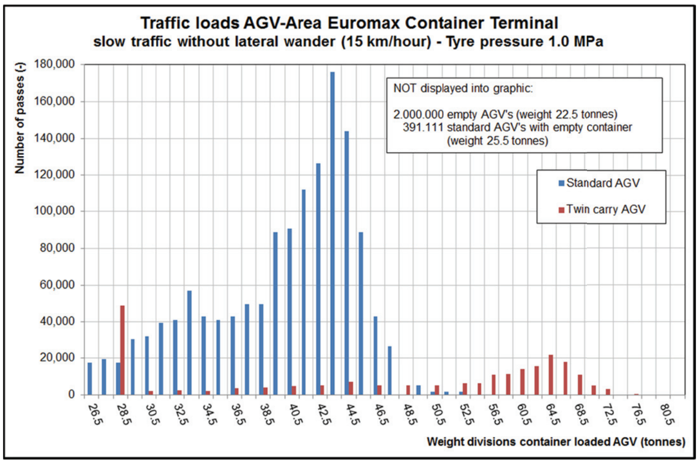

Figure 3: Design load distribution at the AGV-area of Euromax Terminal Rotterdam

3.2 Final pavement design

Ooms Civiel started to design and optimize the pavement structure given the traffic loading and the requirements mentioned earlier. Before doing any analysis, a pavement design concept was set up to determine some basic design directions that were thought to be key points to distinguish from the competitors. The main ideas consisted of:

- giving preference to the use of locally available products, especially in the base layers;
- the anticipation of the natural variation of the (local) material properties (not performing analysis on the mean values only, but also perform e.g. worst-case analyses);
- applying polymer modified asphalt concrete in all asphalt layers and not only in the surface layer;
- a thorough mechanistic analysis will contribute to the acceptance of the design by the Client;
- considering future maintenance as an important part of the pavement design;
- developing recommendations for preliminary laboratory testing.

The pavement design was performed by using amongst others the computer program "Airport Pavement Structural Design System" (APSDS 4.0) (Mincad Systems ltd., 2000). APSDS is a linear elastic multilayer program, which was originally developed for airports. Nowadays APSDS can be used to analyse all kind of heavy-duty pavements, including container terminals.

At the end of the analyses the most challenging pavement structure was determined to be:

50 mm grouted macadam (including Sealoflex® SFB 5-20 (JR) Bitumen)
50 mm polymer modified asphalt concrete (including Sealoflex® SFB 5-20 (JR) Bitumen)
60 mm polymer modified asphalt concrete (including Sealoflex® SFB 5-50 (HT) Bitumen)
550 mm Cement Treated Base (CTB), in-situ constructed (compacted) natural sand

In the next subsections the various pavement materials are treated separately.

3.3 (Compacted) Natural sand

The Maasvlakte I was created in the 1960s by reclaiming land from the North Sea through dykes and dredging sand. This means that huge amounts of sand were available (for free) at the location itself and therefore it was the most cost-effective to use this sand in the pavement design. Using locally available products also leads to environmental advantages for the whole project as for instance it highly reduces the total number of truck movements during the construction period. During 40 years the sand was more or less untouched and some natural compaction had occurred (dead weight).

It became however obvious that the differences of the amount of natural compaction over the AGV-area were high. Therefore the quality of the mechanical compaction of the sand was an important issue in the early start of the construction of the pavement design. The amount of compaction was tested frequently and a lack of compaction had to be compensated before going into the next phase of the construction. In the design analyses the Young's modulus of the sand was set to 100 MPa. As normative failure mechanism the natural sand was checked by the permanent deformation at its top interface.

During the construction at a number of locations some traces of clay leftovers from the dredging process were found in the natural sand while digging out trenches for drainage. A study was performed to analyse the effects of this clay on the risks of the pavement design. It appeared that the presence of clay in the CTB should have had very negative effects upon the quality of the CTB and any presence of clay in the first 100 mm underneath the CTB should also be avoided. These risks were minimized by removing all clay parts from the top 1 m of the natural sand.

3.4 Cement Treated Base (CTB)

The idea of applying a Cement Treated Base (CTB) in-situ as a base in the pavement structure was once again triggered by the huge amount of available sand at the location. Generally in the Netherlands there still is a lot of scepticism when applying CTB's in pavement structures. This is caused by some bad experiences in the 1970's on road stretches.

In the past CTB's already have been applied at several container terminals, without causing any problems. However, the traffic loads at these terminals were less huge than the traffic load that is to be expected on ETR. To get the CTB accepted by the Client, a lot of numerical analyses and lab testing has been performed. The results of the analyses and testing proved that the suggested solution should be able to perform as expected.

From the performed analyses it became clear that the absolute minimum long-term tensile strength at the bottom of the CTB was set to be 0.5 MPa. According to the formulas from the CEB-FIP MODEL CODE 1990 (applied to CTB's) this requirement could be transformed into a compressive strength after 28 days of 2.0 MPa. Statistical analyses of the field results of the compressive strength values of a huge number of CTB cores from earlier projects (Fugro Laboratorium, 1999) showed that to get this minimum compressive strength provided a mean compressive strength of 4.2 MPa. The accompanying percentage of cement has been determined in the laboratory given the actual available sand and the required mean compressive strength.

The CTB subbase should provide the main part of the bearing capacity of the pavement structure. For that reason the CTB has to be applied as thick as possible in one working passage. Given the available equipment to construct CTB's in the Netherlands that meant a thickness of 550 mm. The in-situ construction of the CTB is shown in Figure 4.

In the analyses the CTB has been checked for fatigue at its bottom and for the permanent deformation (crushing) at its top.

Figure 4: In-situ construction of
Cement Treated Base

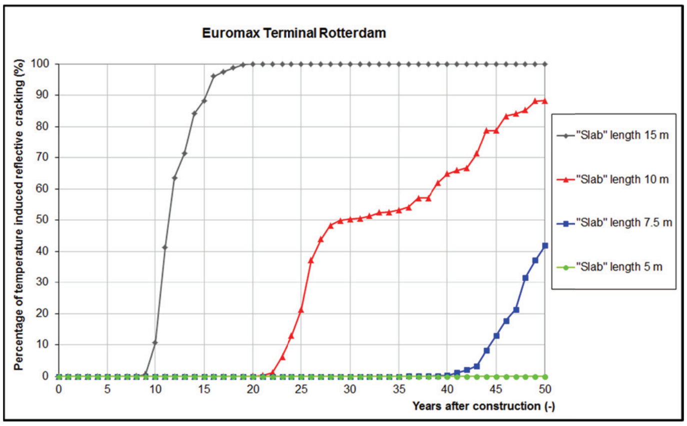

Figure 5: Prediction of temperature induced
reflective cracking vs. CTB “slab” length

During the lifetime of the pavement structure, temperature induced cracks will develop in the CTB. Without measures the distance between these cracks varies from 6 to 10 m, however this distance may locally be double and more. This results into large “slabs” and huge temperature induced slab movements that will initiate reflective cracking in the asphalt concrete directly on top of the CTB cracks.

Figure 5, which is derived from (de Bondt, 1999), shows that temperature induced reflective cracking is not expected for these project conditions, if the centre-to-centre distance of the cracks is 5 m or less. For that reason the CTB layer has been pre-cracked every 5 m over a depth of about 200 mm by a sharp blade. This procedure was optimised for the specific project conditions.

The effect of traffic loads on top of the created notches was analysed by means of the 3D finite element modelling software CAPA-3D (Scarpas and Karsbergen, 1999). The model contained 3,092 elements and 13,432 nodes, and is partly shown in Figure 6. The slab size in the model could change from 5 m (design slab size) into 2.5 m, representing a cracked slab.

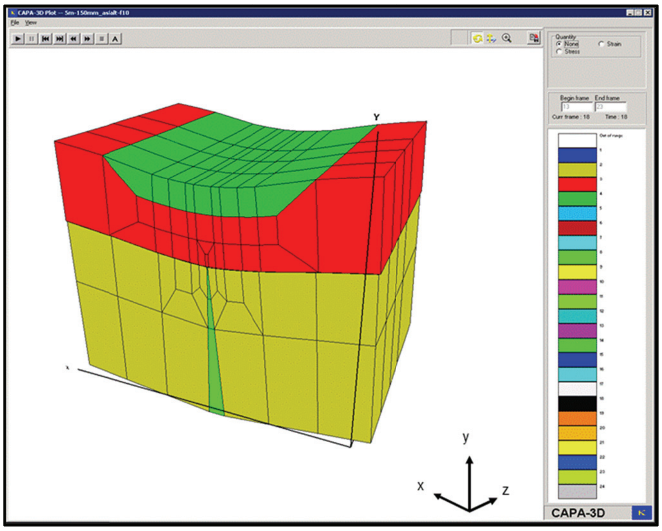

Figure 6: Pavement FEM-model to analyse traffic induced reflective cracking

The performed analyses showed that the maximum wheel load centred at the notch and the load positioned directly next to the notch led to the critical principal and horizontal stresses. The results of the analyses are shown in Figure 7 to Figure 10.

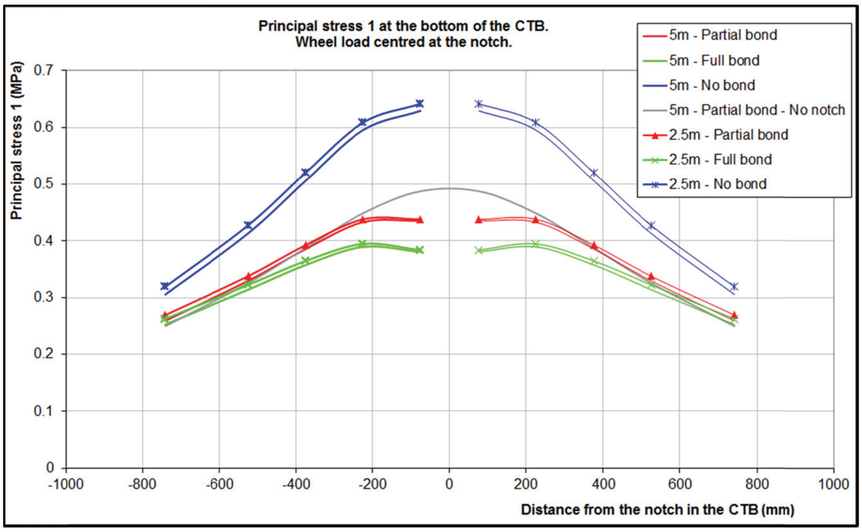

Figure 7: Principal stress in CTB, wheel load above notch

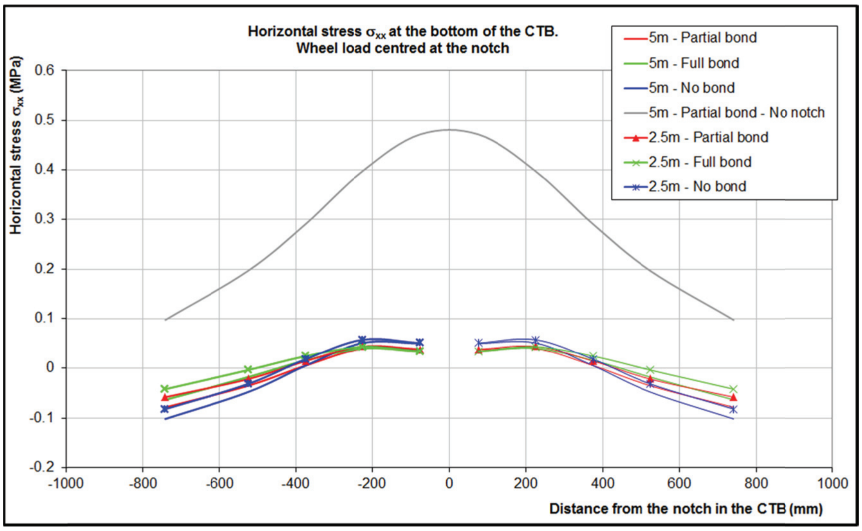

Figure 8: Horizontal stress in CTB, wheel load above notch

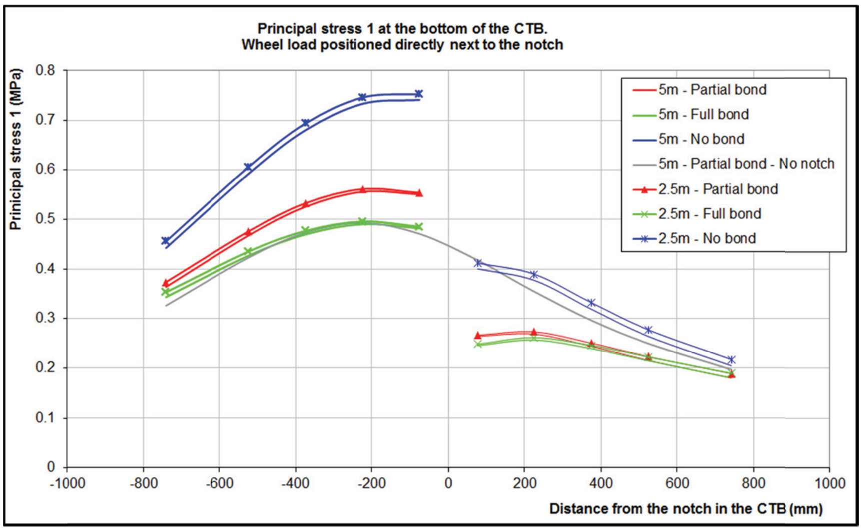

Figure 9: Principal stress in CTB, wheel load next to notch

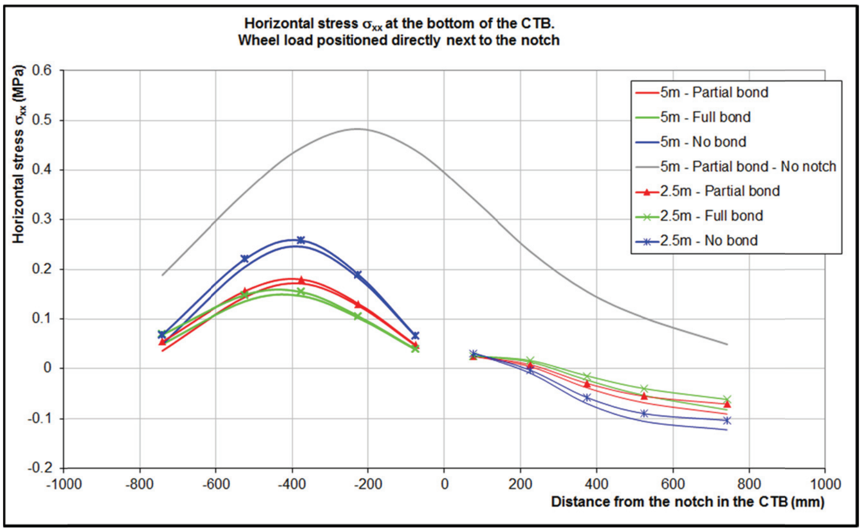

Figure 10: Horizontal stress in CTB, wheel load next to notch

The figures show that loading of the notch/edge does not result into additional cracking of the CTB as stress relaxation will occur around the notch. These findings also rule in case of a cracked slab (sized 2.5 m). In other words, there is no edge loading problem.

Lastly, the figures show the necessity of a normal (partial) bond between the CTB and the asphalt concrete, as a lack of bond (blue lines) results into unwanted high stresses. This finding has been verified and confirmed by the results of performed interface shear testing in the laboratory. This normal bond (friction at the layer interface) can be created by applying a regular bituminous tack coat emulsion on top of the CTB, just before applying the first layer of asphalt concrete.

3.5 Polymer modified asphalt concrete

In all asphalt concrete layers of the pavement structure the polymer modified Sealoflex® bitumen is used. This PMB provides the asphalt mixture a high durability and high resistance to ageing. It also provides a high creep resistance to prevent permanent deformation of the asphalt layer(s), especially at high temperatures. It also provides high tensile strength and toughness to prevent the development of (reflective) cracking. The PMB used in the surface layer and the binder layer differs a little from the PMB in the base layer. This results into higher chemical resistance to oils and fuels that may be present through spillage. To optimise the quality of the asphalt concrete, recycling of old asphalt concrete was not allowed. The fatigue resistance (ε_6) of the asphalt concrete base layer is 250 μm/m (4-point bending mode); the resistance to permanent deformation (f_c) is 0.05 μm/m/s and the healing factor is 6. All asphalt concrete layers are checked for fatigue.

The FEM-model reported in chapter 3.4 has also been used to analyse the principal stresses and strains that the notch causes throughout the asphalt concrete layers. For this, the maximum wheel load has been moved longitudinally over the notch in 69 steps (to simulate a passage): step 18 equals the centred load at the notch and step 23 equals the wheel load positioned directly next (adjacent) to the notch. The results from the analysis are presented in Figure 11 and Figure 12.

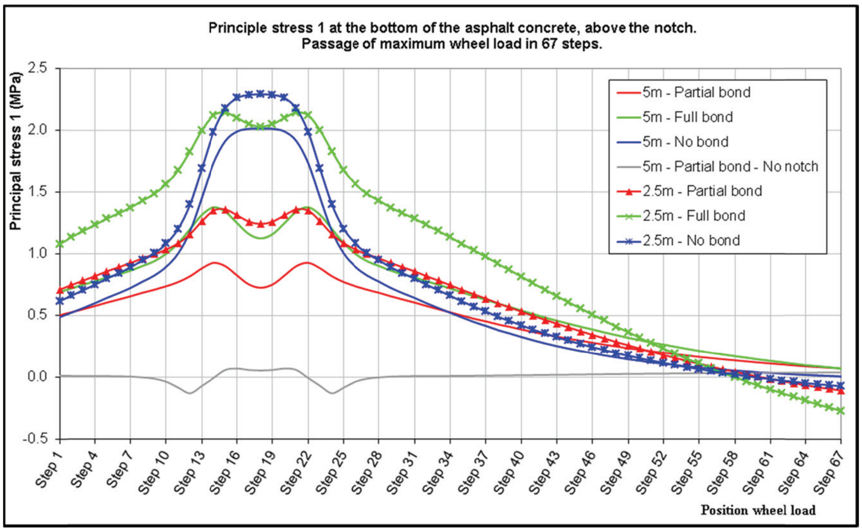

Figure 11: Principal stress at the bottom of the asphalt concrete above the notch

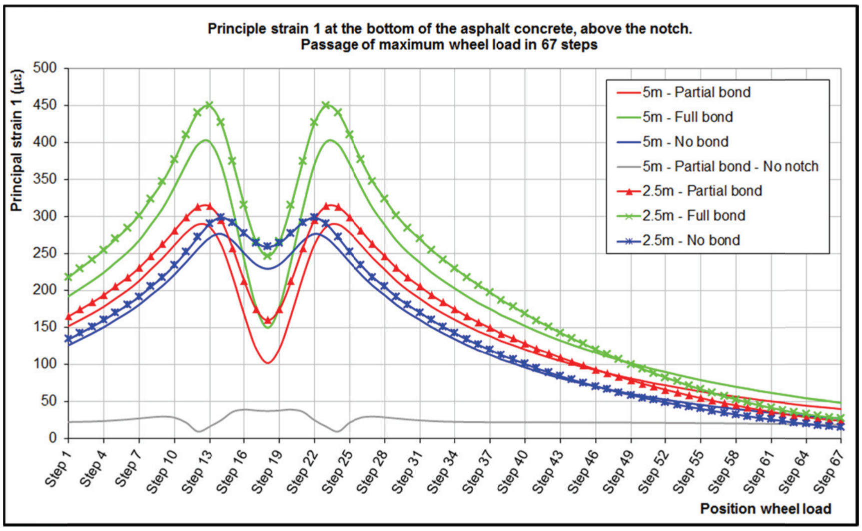

Figure 12: Principal strain at the bottom of the asphalt concrete above the notch

These figures clearly show the increase of the principal stresses and strains at the bottom of the asphalt concrete, due to the presence of the notch in the CTB. However, the values stay in between the material limits of the ductile asphalt mixtures and therefore it is not expected that traffic load induced reflective cracking will occur from the notches of the CTB upwards to the pavement surface during the pavement design life of 20 years.

3.6 Grouted macadam

The grouted macadam consists of porous asphalt concrete (containing polymer modified bitumen) that is filled with cement grout slurry. The polymer modified asphalt concrete provides the cracking resistance (ductility) of the surface layer. The cement slurry is necessary to obtain a rigid surface, also during the hot summer months. This stable surface is also necessary to keep the drilled transponders on the right positions, which is important for a correct guidance of the AGV's.

The master curve of the grouted macadam has been established in the laboratory and is shown in Figure 13. This master curve describes the relationship of the Young's modulus vs.

the temperature (and loading time). Also the flexural strength has been determined for the grouted macadam and it showed a temperature dependent component, caused by the asphalt concrete. Lastly, the fatigue relationship of the grouted macadam has been determined as well:

$$\log(N) = 9.47 - 9.47\,(\sigma / \sigma_f)$$

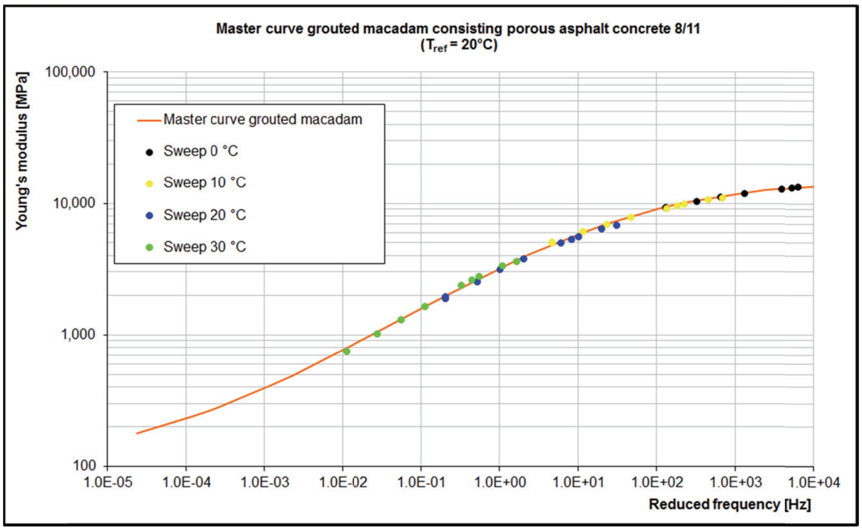

Figure 13: Master curve of grouted macadam (specimens from site)

The relationships were used to determine the minimum required flexural bending strength of the grouted macadam. For this, numerous analyses have been performed in which the temperature input during a year was split up into the 4 seasons and one extremely hot week in the summer. The analyses resulted into a minimum flexural strength requirement of 2.5 MPa.

4 AGV-AREA PAVEMENT CONSTRUCTION PHASE

Not only at the completion but already during the construction of the pavement structure of the Euromax Terminal Rotterdam many parameters have been monitored by in-situ measurements and lab testing. Via this the quality during the construction could be controlled and working procedures could be adapted if necessary. During construction amongst others the following tests were performed:

- determination of the flexural bending strength of (the drilled field cores from) the grouted macadam (see Figure 14);
- determination of the composition and the level of compaction of the asphalt concrete mixtures;
- the variation of the quality level of the polymer modified bitumen;
- the compressive strength of the Cement Treated Base (including statistical distributions) (see Figure 15);
- the thickness of all layers of the pavement structure (including statistical distributions) (see Figure 16 and Figure 17);
- the level of compaction of the sand subbase;
- heavy weight deflectometer measurements (200 kN) (see 4.1);
- analysing the achieved field bearing capacity by using input parameters from the earlier performed laboratory testing of in-situ specimens.

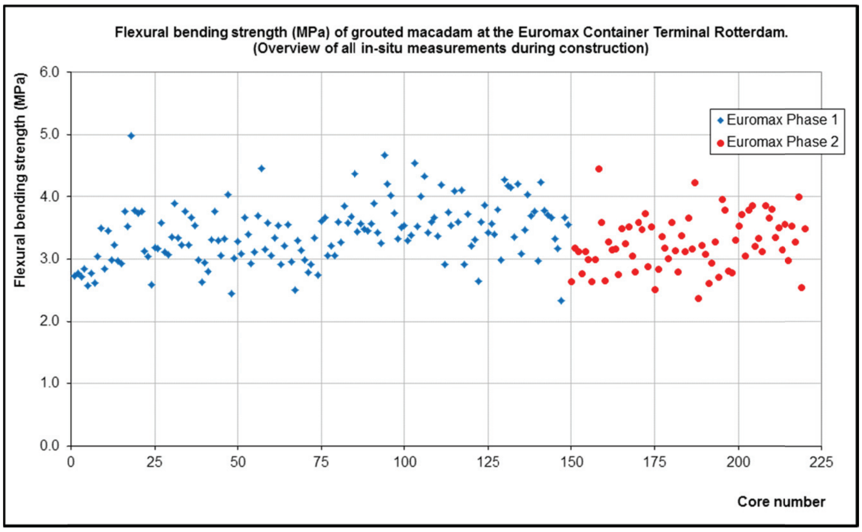

Figure 14: Flexural bending strength of grouted macadam

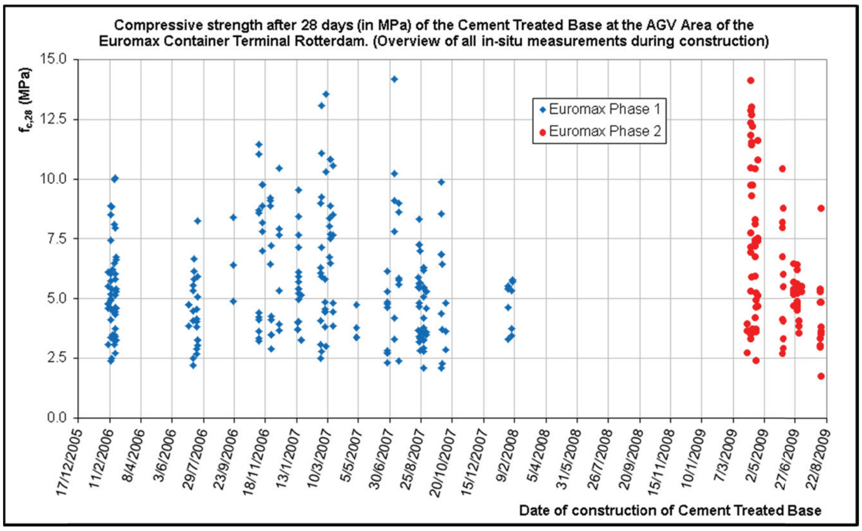

Figure 15: Compressive strength of CTB

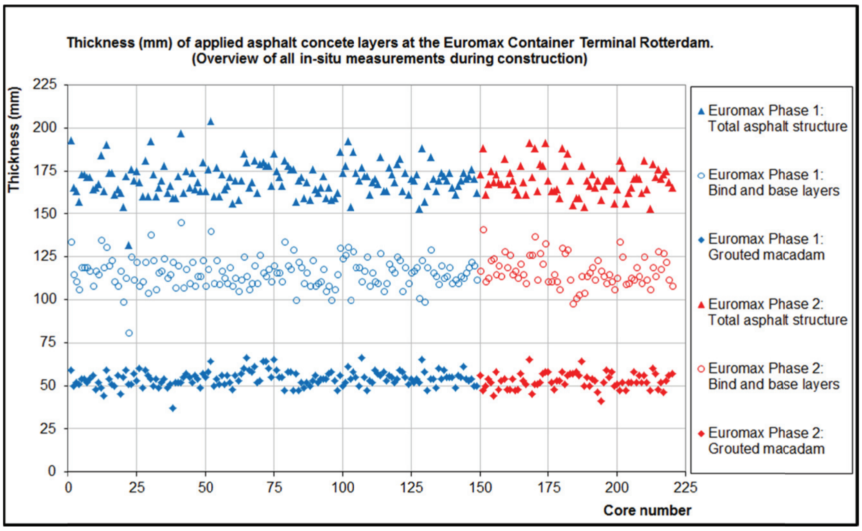

Figure 16: Thickness of asphalt layers

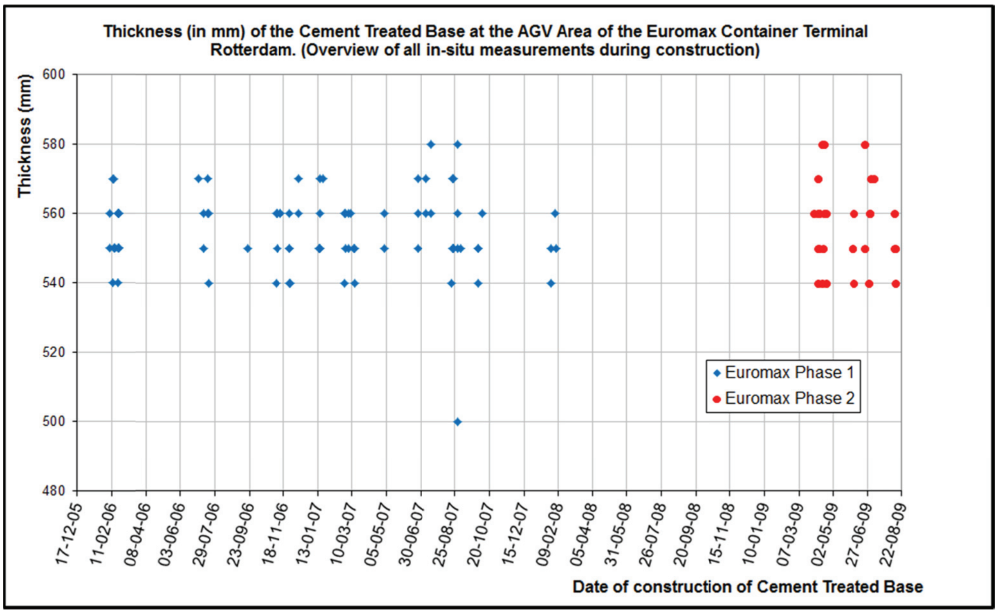

Figure 17: Thickness of CTB

4.1 Heavy weight deflectometer measurements (200 kN)

Heavy weight deflectometer (HWD) measurements (200 kN load) have been performed to verify the bearing capacity of the final pavement structure. A representative example of the results of the HWD-measurements is given in Figure 18.

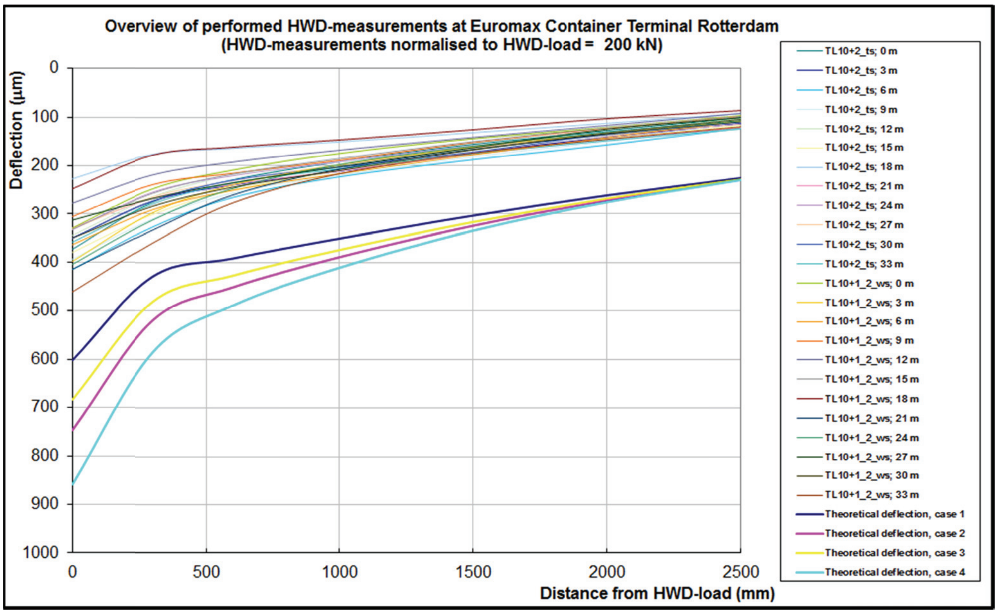

Figure 18: Example of performed HWD-measurement results

The bottom 4 curves of the figure represent the computed deflection of the intended pavement structure (case 1) based on measured field material parameters and three other cases in which some cracking of the CTB has been simulated. The measured deflections do not exceed the computed values at any location. This means that the realized bearing capacity of the total pavement structure is satisfactory.

4.2 Product and process innovations

During the construction phase it became clear that some products and processes needed to be improved to come to a satisfactory completion in terms of cost effectiveness and expected freedom of maintenance at the end of the works. The adaptions were discussed with the Client who was very likely to cooperate as the Client noticed that the adaptions (after their benefit had been proven) would lead to a higher quality of the container terminal in the end. During construction the following products and processes improvements have been made:

- the equipment to apply the notches into the CTB: the length of the blade has been extended from 150 to 200 mm to be sure that the notch should reflect over the full depth of the CTB;
- the moment of applying the notches into the CTB: the best moment appeared to be directly after the bitumen emulsion (the one that should prevent the CTB from drying out) has been applied on top of the CTB. Afterwards a pneumatic roller should take care that the evenness requirements around the notches will be achieved, see also Figure 19 and Figure 20;
- the method of compaction of the natural sand subbase;
- a joint heater should be used during laying the base layers of asphalt concrete;
- using computed tomography (CT) scans for optimizing the porous asphalt concrete mixture;
- the quality of the grouted macadam improved by decreasing the rock aggregate size of the porous asphalt concrete from 11/16 to 8/11 mm;
- performing statistical analysis methods of layer thicknesses and obtained material properties to verify the variability of the bearing capacity;
- judging the bearing capacity of the pavement structure by means of a heavy weight deflectometer (HWD, 200 kN);
- development of high quality quick repair techniques, for instance in case of unexpected uneven settlements.

Figure 19: Notch pattern at the surface of the CTB

Figure 20: Core drilled at a notch in the CTB

5 CONCLUSIONS

This paper describes the design and construction phase of a high-quality asphalt concrete pavement structure for the Automatic Guided Vehicle area of the Euromax Terminal Rotterdam. The final pavement design is both competitive in costs and quality with respect to reinforced concrete and/or concrete bricks. The pavement is operational for 5 years now, without showing any problems.

In case of a D&C(M) contract the Client should have (hired) enough knowledge to judge the (innovative) proposals of the competitor(s) adequately. If the Client is capable to do this (as was the case at the Euromax-project) and also creates room for innovative solutions of the contractor, in the end he/she will obtain more quality for less money.

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