RESPONSE ANALYSIS BASED ON TWO-YEAR MONITORING ON LIGHT-WEIGHT STRUCTURES WITH EPS GEOFOAM

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ABSTRACT: In the scope of reconstruction and widening of the A15motorway (Rotterdam-Germany) and associated slip roads and overpasses a total quantity of nearly 100,000 m^3 EPS has been built-in. The motorway is located in an area where the subsoil consists of very compressible peat and organic clay layers with average thickness of 10 meters. The existing embankments and abutments are only partly reused. Where possible high sand pre-consolidation embankments have been placed to minimise EPS quantity for cost-saving reasons. In order to investigate occurring settlements and general pavement behaviour critical cross-sections of the A15 project have been monitored. The considered road structures have a sub-base that consists of more then 3.5 m thick EPS layer. Settlement hoses, telescopic rods and profile measurements, registered the time settlements, the creep behaviour and compression of EPS-blocks. Furthermore, pressure gauges measured occurring stress values in unbound roadbase. Finally, asphalt strain measurements and surface deflection measurements have been carried out by means of the Falling Weight Deflectometer and strain transducers (at the bottom of the asphalt layer). The back-calculated E-values in the pavement structure layers are used to translate the measured asphalt strain values to a reference temperature and to present the trend of the translated strain values as a function of the pavement structure age. The conclusions and recommendations address shape changes of light-weight embankment during consolidation and structural behaviour of the pavement layers under traffic loading.

1 INTRODUCTION

Through a substantial reduction of the total road structure weight, EPS (Expanded Polystyrene, also called geofoam) blocks as a sub-base material provides a major cause-directed solution for reduction of the settlements of new road structures and road-widening in areas with soils of poor load-bearing capacity. Such areas are present around Rotterdam where large scale reconstruction of the A15 motorway and its slip roads and overpasses is taking place.

The scale on which the EPS is used as well as in areas of high intensity traffic reflects increased confidence in this approach of using light-weight EPS-blocks. It is based on positive experience over last two decades and improvements in the Dutch design manual for this type of road structures (Duškov & Houben, 2000). However, the application of EPS-blocks (with much lower elasticity modulus than sand) affects the performance of the overlaying structures. Furthermore, success of implementation of preload combined with reduction of the EPS-thickness is dependent on how accurate the consolidation process can be predicted over time. The load bearing capacity of the subsoil is often overestimated. One possible consequence is additional settlements despite the use of light-weight materials due to insufficient thickness of the EPS-layer. There is always an inclination to minimize the quantity of EPS for cost-saving reasons. The light-weight embankments are almost exclusively planned for the most critical locations of A15 project. A total quantity of nearly 100,000 m^3 of EPS has been built-in.

Investigations of the extent to which structural behaviour and real settlements fit with design assumptions on site measurements over a two-year period have been carried out on slip roads at the Sliedrecht-East junction. This paper deals with the outcomes, findings, conclusions and recommendations based on that monitoring.

2 RECONSTRUCTION OF THE A15 MOTORWAY

Confronted with the fact that regular maintenance measures do not provide adequate improvement of traffic conditions on the A15 motorway near Sliedrecht, the Dutch authorities decided on a total reconstruction. High traffic intensity of approximately 90,000 vehicles including 8000 heavy trucks per day makes it clear why frequent maintenance is an undesirable option. In particular settlement problems and the need for extra traffic capacity strongly influenced the decision process.

During reconstruction four existing junctions around Sliedrecht were radically rearranged. The total motorway length to be reconstructed amounts to about 8 km. Project realisation started in 1998 and the completion of most of the activities is planned for 2004. The long list of reconstruction activities includes not only new approach roads and widening of existing roadways but also dismantling of all existing fly-overs and building of new ones as well as crossovers. Continuously growing traffic on this important road connection should not be restricted by either insufficient head-room or road capacity in the future.

2.1 *Location of monitored light-weight embankments*

The outlook of the Sliedrecht-East junction including the location of two monitored cross sections is illustrated in Figure 1. In the scope of reconstruction the entire junction has been redesigned. All approach roads on both sides of the motorway are repositioned. The new fly-over is located 15 m south of the old one. This explains the necessity for radical positional changes. New abutments had to overcome a difference in height of about 5 m between the upper counter line of the new fly-over and the local ground level. Such demands in combination with established extreme compressibility of the subsoil and relatively limited time available explain why the light-weight approach with EPS was chosen.

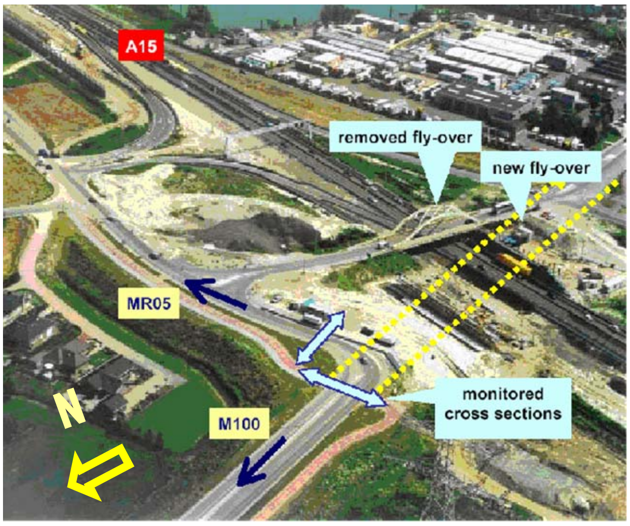


Figure 1 Sliedrecht-East junction including the new fly-over over the A15 motorway and the monitored approach roads with light-weight embankments of EPS geofoam

2.2 *Details of design with EPS geofoam*

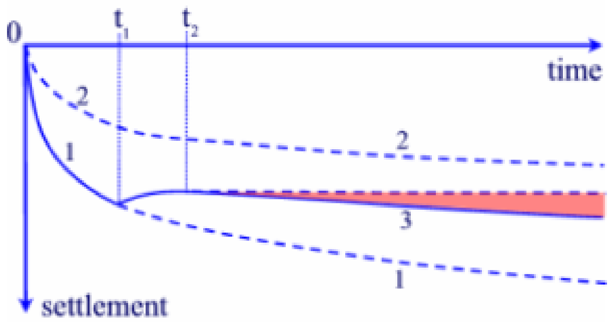
In Figure 3 uncovered EPS-blocks are shown during construction of one of two monitored light-weight embankments situated on the northern side of Sliedrecht-East junction. The EPS package is up to 4.5 m high and consists of 1.0 m thick blocks. The light-weight part of the approach road along axis M100 reaches 175 m from the new fly-over. The light-weight section along axis MR05 is about 100 m long. The upper pavement layers, identical for all approach roads, consist of 1 to 1.3 m sand sub-base, 0.25 m thick roadbase of unbound material and 0.25 m thick asphalt package. No concrete capping is applied; the sub-base lies directly on the EPS-blocks. Besides price, the advantage from the Dutch contractors' viewpoint seems to be the possibility of building road furniture directly into sand, in the way they are used to. However, such a thick sand layer does not contribute to a higher bearing capacity and longer lifetime of the pavement structure.

Figure 2 Partly covered EPS-blocks of the monitored approach road on the north side of the Sliedrecht-East junction

Most blocks used have dimensions 6.0×1.2×1.0m. EPS with a density of 20 kg/m3 has been applied with a modulus of elasticity between 8 and 9 MPa. Such huge EPS blocks are not easy to move and require mechanical handling. However, stacking up is very efficient plus the EPS package consists of only few layers. As illustrated in Figure 2 EPS-blocks are covered by an (oil resistant) impermeable membrane for protection against oil spills. These characteristics are more or less valid for the remaining locations with EPS on the southern side of the Sliedrecht-East junction.

Regarding the total deadweight, implementation of the sand sub-base does not mean any extra weight. Excavating and removing an equal thickness of sand belonging to the preload, compensates for that weight.

On all locations along the A15 motorway where light-weight solutions are applied a preload was placed before construction. Actually, preloading and creation of balance through partial replacement of sand by EPS may be considered as the standard procedure for the entire project. Stimulation of the consolidation process leads to a gradual increase of the bearing capacity of the subsoil and consequent reduction of the settlements occurring under deadweight as illustrated in Figure 3. As already mentioned, the major motivation for preloading was to use less EPS-blocks. Sand costs significantly less and for contractors transport of the sand yields a higher profit than using the blocks.



$t=0$: putting on initial preload (surcharge)
$t=t_1$: partial removing of preload
t_1-t_2: construction time including stacking up EPS-blocks
$t=t_2$: road opening for traffic
1: settlements due to initial preload
2: settlements due to remaining preload
3: settlements due to deadweight of light-weight road structure
... settlements since the road is service

Figure 3 Principal scheme of settlement progress in the case with preliminary use of preload before construction of a light-weight road embankment

Consolidation is time consuming, a few years is not unusual. In the case of the road structures under consideration the available time was shorter, about 6 months. Original deadlines in the time planning were extended, however, creating extra time for the consolidation process. In fact, the preload stayed about one year in the locations. During that period there is about 40% or 3 m of preload consolidation as a consequence of the settlement process.

The impact of extra preloading time and the deadweight of more than a 5 m high temporary embankment even resulted in design revisions. Based on additional soil mechanical analyses it was decided to reduce the EPS thickness for 1.5 m. In practice 1.5 m less sand is removed before stacking of the blocks. As an additional bonus, the higher sand level made it possible to lay geofoam blocks in dry without extra measures in spite of high groundwater level.

3 MONITORING PROGRAMME

3.1 *Reasons for monitoring*

The monitoring program is being carried out in order to get a better insight into structural behaviour in practice and to control whether the predictions are realised. Whether or not the light-weight approach after partial consolidation of the subsoil from preloading will lead to sufficient reduction of the settlements is basically a matter of timing. The consolidation process should have progressed enough so that the subsoil could bear the total load equal to remaining preload (total preload minus removed part before building-in of EPS-blocks starts) and deadweight of the light-weight road structure. Such an approach is not without risk. Already a slightly incorrect interpretation of the consolidation process (illustrated in Figure 3) could result in unacceptable settlements. Keeping in mind that fly-overs founded on piles are settlement free it is obvious that the margin is narrow, in particular for the abutments.

3.2 *Monitoring strategy end measuring equipment*

Resulting settlements and general pavement behaviour in critical cross-sections of the north side of the Sliedrecht-East junction were being monitored for two years until July 2003. The road structures being considered have a sub-base that consists of more then 3.5 m thick EPS layer. Hydrostatic profile gauges (in both longitudinal and lateral directions as illustrated in Figure 4), piezometers, pressure cells and telescopic rod with plate magnets register the time settlements, porewater pressure and the creep behaviour of EPS.

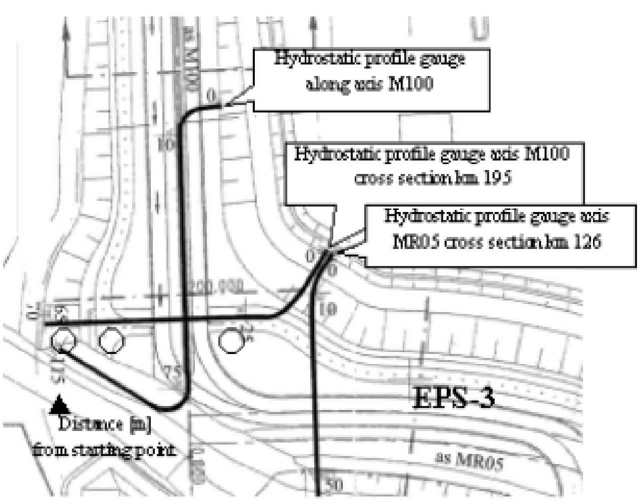


Figure 4 Situation drawn with hydrostatic profile gauges for registration of settlements of light-weight road structures on locations EPS-2 and EPS-3 belonging to the northern quadrant of the Sliedrecht-East junction

Horizontal deformations were observed by built-in inclinometers and periodical profile measurements. Furthermore, pressure gauges measured stress values in unbound roadbase. Finally, asphalt strain measurements and surface deflection measurements were carried out periodically by means of the Falling Weight Deflectometer (FWD) and four strain transducers (at the bottom of the asphalt layer).

4 MONITORING RESULTS

The measurements started in September 2001 and were carried out until July 2003. In following paragraphs observed settlements, creep within the EPS layer, vertical stress values above and below EPS and strain values at the bottom of the asphalt layer are presented.

4.1 *Settlements*

As mentioned above the initial design made use of a combination of a surcharge and light-weight EPS geofoam to reduce consolidation settlements in service. Figure 5 shows the height, duration and resulting settlements of preloading on location close to the monitored cross section of axis M100 - km 195 (see Figure 1).

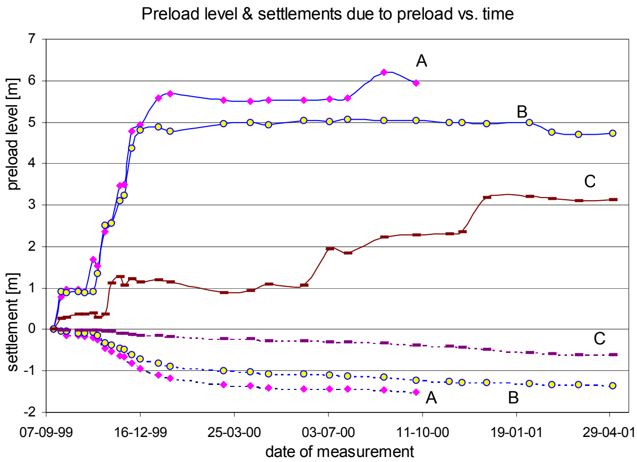


Figure 5 The height and duration of preload and resulting settlements registered on A, B and C (Fig. 4) near to the cross section on axis M100 – km 195

The prediction for the performance of the light-weight road embankments were such that settlements in service are indeed minimized. The measurements of settlements during 2-year period after replacing of preload by EPS geofoam and pavement layers show that the rate of settlement reduces and the total amount of settlement is about 0,15 m. If we exclude construction time the settlements amounts to approximately 0,08 m since the road has been in service as illustrated in Figure 6.

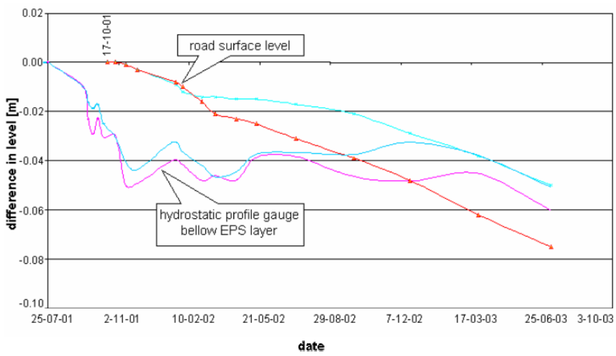


Figure 6 Settlements registered by the hydrostatic profile gauge below a 3.5 m thick EPS layer as well as measured road surface levels in the middle of cross section - km 195 of axis M100 between July 2001 and July 2003

4.2 *Creep*

The deadweight of the pavement layers above the EPS sub-base provides a constant load on the EPS. Due to creep the corresponding negative strain in the material increases in time at constant stress. A practical consequence of this phenomenon for EPS in a road structure is the increase of the vertical permanent deformation of this layer in a certain period of time after completion of the light-weight embankments. The settlement measured exclusively within a 3.5 m thick EPS layer (cross section on km 126 – axis MR05) between July 2001 and July 2003 is illustrated in Figure 7.

At the beginning the lack of parallelism between the surfaces of EPS-blocks affected the results. Empty spaces between imperfectly flat EPS-blocks disappear under the deadweight of pavement layers. Therefore the major part occurred during construction before asphalt layer was laid. Despite of limited vertical deformation due to creep such an additional 'settlement' means in practice an extra few centimetres thick sand layer.

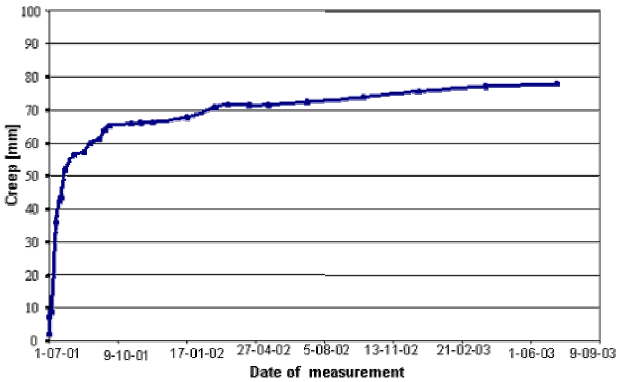


Figure 7 The increase of the vertical deformation during 2-year periode in a 3.5 m thick EPS layer in cross section - km 126 on axis MR05

4.3 *Vertical stress values*

The sub-base loading conditions are characterized by both the deadweight of the overlaying layers and the dynamic loads due to the traffic passing above. In the case of the pavement structures being considered with an extremely thick (1 to 1.3 m) sand layer the occurrence of static stress had been expected to be much higher than the dynamic component. The values measured by pressure cells placed above and below the EPS layer, are shown in Figure 8.

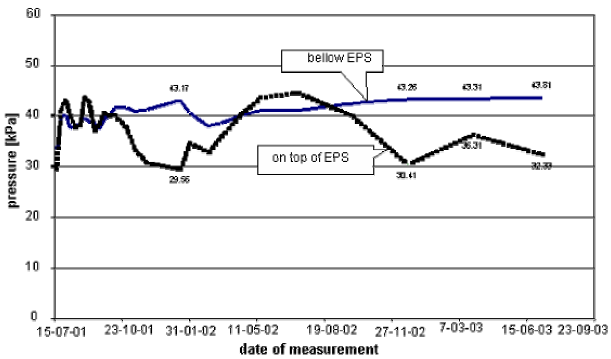


Figure 8 Measured vertical stress values above and below 3.5 m thick EPS layer in cross section - km 126 on axis MR05

A stress of 43 kPa in EPS means relatively high static loading. Generally speaking, sufficiently thick pavement layers cause up to 20 kPa. However, according test results (Duškov 1997) no permanent deformations of practical importance will occur. Regarding dynamic loads the effects on the considered EPS sub-base are very limited. The pavement layers with a total thickness of 1.5 m contribute to very good load spreading above EPS.

4.4 *FWD measurements results*

The structural condition of pavements is followed by means of four transducers built-in at the bottom of the asphalt layer and the Falling Weight Deflectometer (FWD). In this way the asphalt strains (under FWD loading) and the surface vertical displacements (deflections) due to a dynamic loading have been measured. The deflections and strains were due to both a 50 kN (corresponding to a 100 kN standard axle load) and 67 kN force.

The temperature dependent behaviour of the asphalt layers has a big influence on the behaviour of the whole pavement structure. With respect to the FWD measurements the influence of temperature on pavement behaviour was expressed in higher measured deflections at higher temperatures. A clear correlation between the measured deflection and temperature values can be seen in Figure 9 which shows the measured deflections as a function of temperature for the measuring point 4. This figure shows that the maximum deflection (in the load centre) as measured using 50 kN FWD load was linearly dependent on the temperature.

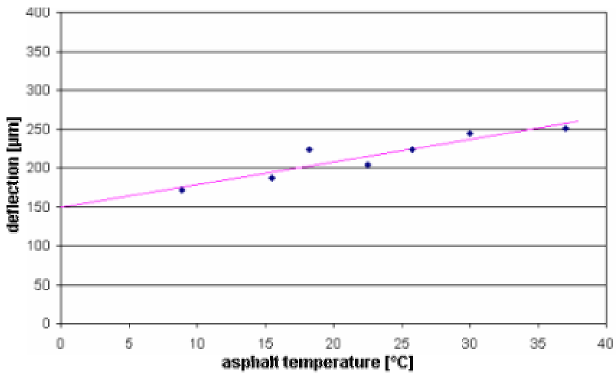


Figure 9 The measured maximum deflections (in the load centre) as a function of temperature for the measuring point 4 on the lightweight road structure belonging to the northern quadrant of junction Sliedrecht-East

4.5 *Asphalt strain values*

The temperature dependent behaviour of the asphalt layer prevents a direct comparison between the measured strain values. It implies that those values have to be translated to a reference temperature before comparison. The back-calculated E-values in the pavement structure layers were used to translate the measured asphalt strain values to a reference temperature of 20°C and to present the trend of the translated strain values as a function of the pavement structure age. In Figure 10 both the measured strains with belonging temperatures and the calculated asphalt strain for the asphalt temperature of 20°C are shown as a function of time.

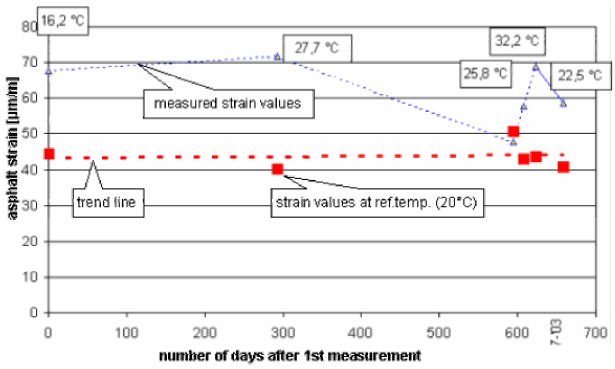


Figure 10 The measured strains with associated temperatures and the calculated asphalt strain for the asphalt temperature of 20°C as a function of time for the measuring point 4 on the light-weight road structure belonging to the northern quadrant of the Sliedrecht-East junction

From Figure 10 it can be observed that the asphalt strain at the reference temperature (20°C) remains more or less constant two years after pavement completion. The constant value of the strain is a sign of a good condition of the pavement structure. Furthermore, both measured small asphalt strain values and low deflections suggest sufficient bearing capacity of the pavement structure with a 0,25 m thick asphalt layer.

5 PROBLEMATICAL CONSTRUCTION ASPECTS

During the reconstruction activities in the northern quadrant of the Sliedrecht-East junction, the project schedule was repeatedly adjusted for extensions of the deadlines. From one reason or another, the construction of monitored light-weight road structures started much later than originally planned and were accomplished for not less than fourth mounts. In the meantime also the design of the structures was repeatedly adjusted for presumed increasing bearing capacity of the subsoil. So EPS layer thickness was minimized because of cost-saving reason. Constantly changing design assumptions and boundary conditions made it extremely difficult to deal properly with the complex estimation of consolidation process stage and balance related calculations. As an additional problem, contractors involved had a legitimate excuse to improvise with less than accurate work performance as final result. In the next alinea, the observed consequences of such an approach are described.

The quality of delivered work became obvious in the middle of 2002. At that stage construction activities started again as a part of finishing of approach road including the abutment and realisation of the new fly-over along axis M100 (see Figure 1). After excavation on the front side it turned out that lower laid EPS-blocks were overloaded by up to 5 m thick sand package. Accordingly, permanent deformation of approximately 17% occurred and instead of the original thickness of 1.0 m the blocks were reduced to 0.83 m. The EPS-blocks in the second layer were compressed to 0.95 m. It was absolutely unacceptable and all those blocks had to be removed and replaced by new ones. Extensive material research (Duškov, 1997) pointed out that after the cell structure is damaged due to overloading effective stiffness of the material decreases. Water also penetrates faster into EPS deformed beyond the failure limit of its cell structure.

Additional shortcomings observed after excavation were wide open joints between the blocks which proved inaccurate stacking due to lack of attention during construction. It is also contrary to the Dutch design guidelines (Duškov and Houben, 2001) where it clearly states that all joints should be closed and load transfer across the joints should be promoted. Finally, as shown in Figure 11, even a 'hanging' corner was discovered with no support at all on the underside.

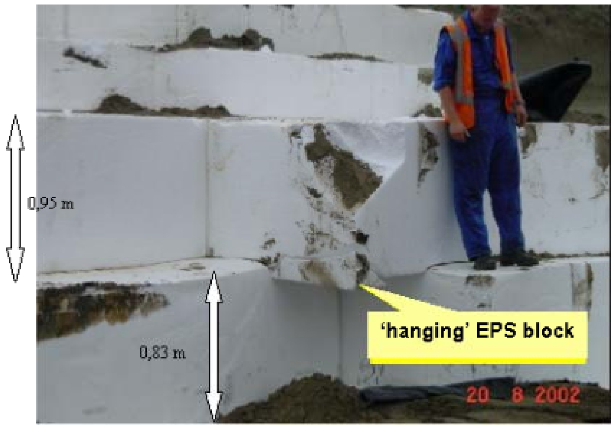


Figure 11 After excavation visible overloaded and permanently deformed (compressed) EPS-blocks on the front (southern) side of light-weight aproach road structure along axis M100

The biggest problem due to this inadequate preloading was significant asymmetrical deformation of the whole south-eastern part of the light-weight embankment of EPS-blocks as illustrated in Figure 12. In the scope preloading geotechnicians did not take into account local differences regarding consolidation history. The location marked by an arrow in Figure 12 with extra settlements was not loaded in the past because of protection by a covering concrete structure founded on piles. Therefore, despite identical sand and EPS thickness in the road cross section the subsoil did not settle uniformly everywhere.

Figure 12 Asymmetrical deformation in the cross section of light-weight road embankment due to not taking into account preload history (1999-2001) in the northern quadrant of the Sliedrecht-East junction

In spite of the demonstrated serious shortcomings of delivered work, the contractor continued the activities without paying extra attention on critical aspects specific for the use of EPS-blocks. Significant asymmetrical deformation in the road cross section was levelled by using very thin geofoam 'boards'. Official Dutch standard (CROW, 2000) prescribes a minimum thickness of an EPS-block of 0,25 m. Figure 13 shows how the contractor simply ignored the prescriptions.

Figure 12 Improvised levelling of asymmetrical deformation in the cross section on axis M100 by means of too thin EPS-blocks which as such might not be used at all according Dutch standard

The settlements on their own are not the real problem from a functional viewpoint but the settlement differences are especially over short distances. Design and/or construction shortcomings are most visible on the locations between light-weight embankments and road parts founded on piles (therefore settlement-free). Figure 13 shows such a short settlement-free road section along axis M100. The attached road parts on both sides are constructed with EPS-blocks but they obviously settled further and a visible 'threshold' still grows. It was necessary to use a thicker EPS-layer on both sides.

Figure 13 'Threshold' arised between on road founded on piles and light-weight road parts along axis MR100 due to settlement differences

6 RECOMMENDATIONS AND CONCLUSIONS

Limited settlements of approximately 0.15 meter within two-year period characterise consolidation of the monitored cross sections of light-weight embankments. The consolidation process is still continuing. In spite of the use of both preload and EPS-blocks the road structures are not settlement-free but, however, monitored settlements are much lower than common values in the area in the case of traditional approach with a sand sub-base. Another positive aspect is that a significant part of the settling took part during the construction period. After completion of the asphalt layer of the road parts under consideration, only about 0.08 m of further settlement occurred. Nevertheless, the final result is not optimal one and both design and construction accuracy should be improved. The progress of consolidation process in not adequately estimated.

The road parts attached to sections founded on piles are critical locations. In the case of the northern quadrant of the Sliedrecht-East junction visible thresholds have arisen on those transitional parts as a result of growing settlement differences. To improve the design thicker EPS-layers are necessary with gradually decreasing thickness at both sides of the settlement-free road section. It is also difficult to reach proper and uniform compaction of unbound roadbase materials applied directly above EPS-blocks on this section.

On top and bellow the EPS-blocks relatively high vertical pressures due to the dead weight are measured. Up to now no relevant deformations are observed as a consequence of those pressures but the creep process is still going on after more than two years. The sand layer is so thick that its own weight causes almost critical pressures. The use of a thinner sand layer in the future is strongly recommended.

By use of piezometers measured horizontal deformations amounted to 0.08 m. These values as well as practically no increase during the last period, point to the achievement of horizontal stabilisation in the light-weight embankments.

Observed water pore pressure values indicate the consolidation process on site is still ongoing. The settlements have not yet reached the final stage.

More than ¾ of total creep of about 0.07 m in EPS-blocks occurs during the construction phase. One of the reasons is that at the beginning empty spaces between imperfectly flat EPS-blocks disappear under the dead-weight of above laid layers. However, measured additional 'settlements' due to creep mean in practice few centimetres extra thick sand layer related to the design thickness.

The asphalt strain remained more or less constant in the two-year period after the completion of light-weight road structure. The constant value of the strain is a sign of a good condition of the pavement structure. The maximum horizontal tensile asphalt strain amounts about 45 μm/m at the reference asphalt temperature of 20°C. The FWD measurement results (maximum deflections of approx. 200 at 20°C) and back-calculated layer moduli confirm sufficient support of the roadbase to the asphalt layer with as the final result above mentioned, limited asphalt strains.

7 REFERENCE

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