Perpetual pavement design and construction using anti-fatigue base layer on expressway S8 in Poland

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ABSTRACT

Within the frame of realisation of express way S8 close to Warsaw in formula "Design & Build" the Contractor decided to design alternative pavement structure based on principle of perpetual pavement using anti-fatigue base layer. The construction started in 2014. The authors present the design assumptions and methodology based on French design method, short analysis of different conceptions for asphalt mixtures for anti-fatigue base course and high-modulus base and binder course together with test results. The pavement was designed for 50 years traffic load with assumption that no serious structural heavy maintenance will be required, except regular renewal of wearing course. The results of life cycle cost showing the benefits for public Investor comparing to traditional pavement structure is also presented.

Keywords: Asphalt, Design of pavement, Fatigue Cracking, Social and economic cost-benefit analysis

1. INTRODUCTION

Idea of perpetual asphalt pavement structures with anti-fatigue course at the bottom of asphalt layers is known from literature (e.g. Newcomb and all, 2000), however its application in construction practice is still random. Figure 1 shows the principle of such pavement structures. Perpetual pavement means that pavement will be designed to withstand at least 50 years trafficking and no heavy (structural) maintenance will be required. Only renewing of the wearing course will regularly take a place. At the bottom of asphalt layers, at the place of tensile strain occurrence, so called anti-fatigue course with high fatigue resistance, has to be designed. This minimize the risk of fatigue cracking at the bottom of the pavement, which is one of the main structure failures. Underneath the pavement surface, in the zone of high compression and shear stresses, the course with high resistance to deformation and resistance to low temperature cracking (depending on the climate) has to be designed. This will minimize the permanent deformation occurrence, such as rutting and risk of low temperature cracking.

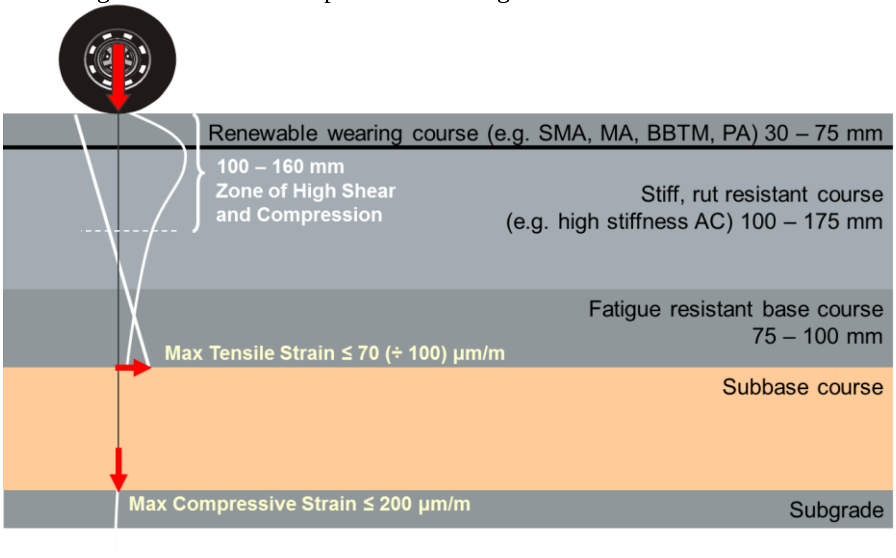

Figure 1: Idea of perpetual asphalt pavement structure

The first perpetual asphalt pavement in Poland, based on a/m idea, located on S8 expressway between Opacz and Paszków, in total length of 12,4 km, was designed by TPA and constructed by STRABAG in years 2014-2015 under employment of GDDKiA and supervision of ECM Group.

2. A BRIEF HISTORY OF FIRST PERPETUAL PAVEMENT IN POLAND

2.1 Testing using Heavy Vehicle Simulator

In 2008 at Pruszków in the vicinity of Warsaw within the frame of SPENS (Sustainable Pavements for European New Member States) a research program, testing different types of pavement structures, was conducted by Polish research institute IBDiM. Four different pavements were constructed by STRABAG and tested in accelerate way using HVS (Heavy Vehicle Simulator) ex VTI from Sweden (see Figure 2). Test pavement structures were instrumented with strain and stress gauges. Main purpose of this program was to validate the benefits of application of asphalt concrete with high stiffness modulus (further AC WMS - Polish abbreviation). This asphalt mixture type, ACWMS, was locally, experimentally used on Polish network since 2004, first as the base course and later on as the binder course as well. High stiffness modulus (required more than 14.000 $MN.mm^{-2}$ at 4PB-PR at 10 ºC and 10 Hz) had to be achieved mainly using harder as conventionally used penetration grade bitumen: 20/30. Relatively high fatigue resistance of this mixture (required ε_6 more than 130µm/m at 4PB-PR at 10 ºC and 10 Hz) had to be achieved by low air voids content – about 4 % and relatively high binder content - about 5 %. There were many doubts at that time concerning a risk of low temperature cracking in Polish climate conditions, applying such a stiff bitumen (20/30). Maximum grading size of AC WMS aggregate mix was 16 mm. Mixture design was based on French experiences with so called high modulus courses EME (in French: enrobé à module élevé), however fitted into Polish national application standards and conditions. Stiffness and fatigue tests were carried out using four point bending tests on prismatic specimens, 4PB-PR, at the temperature of 10 ºC and frequency of 10 Hz. One of four tested pavements of above mentioned research program, namely section D, was inspired by the idea of perpetual asphalt pavement with high fatigue resistant asphalt course at the bottom of the asphalt layers. However the biggest engineering questions during designing of perpetual pavement was what is the best material (which asphalt mix type, gradation, air void, binder type, etc.) and what is the optimal thickness of so called anti-fatigue (AF) base course. For AF course on this project the asphalt mixture with fine aggregate grading and with relatively high content of highly polymer modified binder PMB Orbiton DE 80 C with addition of viscosity lowering additive Sasobit was designed and applied in order to obtain high fatigue resistance.

Figure 2: Heavy Vehicle Simulator HVS during testing of four types of asphalt pavements in 2008

The results of the accelerating testing by HVS (figure 3) showed that the pavement with high modulus asphalt base course AC WMS (section A) gives significantly better fatigue life in comparison to pavement with traditional asphalt concrete base courses (section B). However, the best fatigue behavior showed pavement with anti-fatigue (AF) course with high content of highly modified binder at the bottom of the asphalt pavement. The perpetual pavement type on section D showed higher deflection on pavement surface as well as strain at the bottom of asphalt layer in comparison to the pavement on section A. However the fatigue damage of the perpetual pavement, given as the strain increase in time (under load), increased very slowly and remained practically without changes. Thus the material at the bottom of asphalt layers significantly improved the pavement fatigue life.

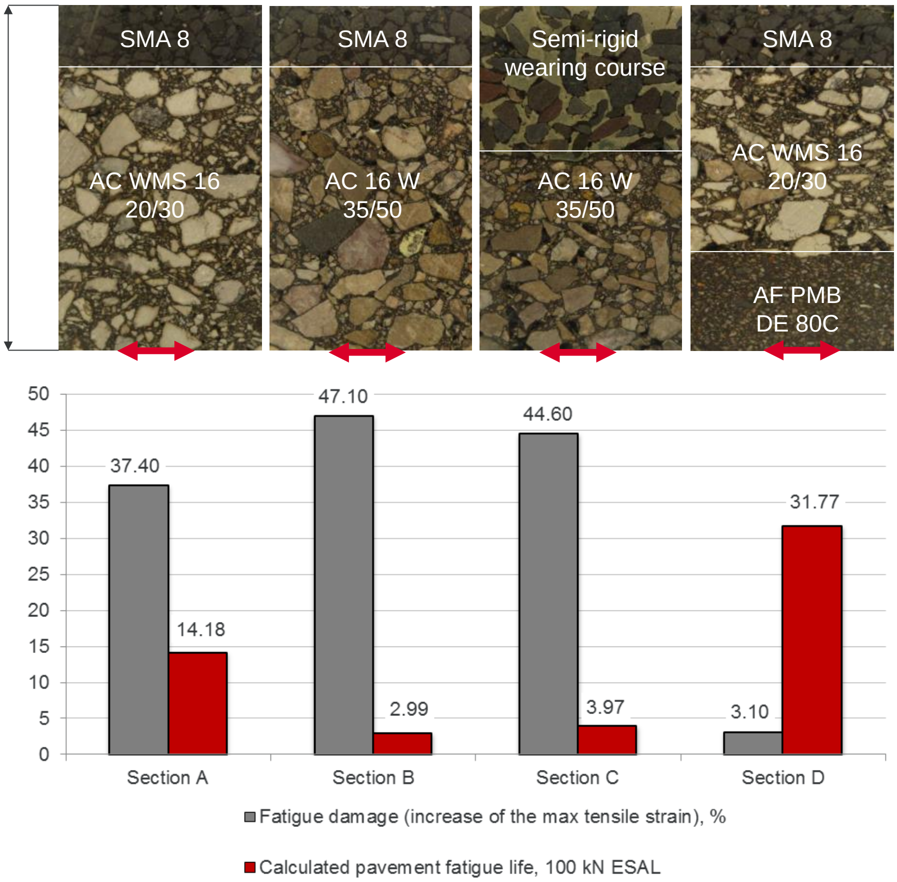

Figure 3: Results of fatigue behaviour of four pavement types after HVS tests

2.2 Experiences with asphalt concrete with high stiffness modulus

A lot of innovative technologies could be implemented and applied during last 15 years into the road construction practice in Poland. One of those technologies was application of high modulus courses (EME), based on French experiences and its adoption to Polish conditions, so called asphalt concrete with high stiffness modulus AC WMS. In 2004 first motorway section with base course of AC WMS with bitumen 20/30 was constructed. Since 2008 till 2011 plenty of newly constructed sections of expressways and motorways were designed and constructed with base as well as binder course using ACWMS either with bitumen 20/30 or PMB 25/55-60. However during cold winter 2012, low temperature cracking (figure 4) occurred at large scale in the form of transversal cracks, mainly at the area of working joints, but also in-between. A lot of section was under construction, without surface course. The majority of cracked pavement were designed and constructed using bitumen 20/30. So the whole implementation process was revised and currently use of PMBs only is permitted. In some “warmer” parts of Poland 20/30 is still allowed however with increased requirements as before. Quality of binder plays thus most important role in order to assure durability of pavements with high stiffness modulus courses.

Figure 4: Low temperature cracking on unfinished pavement surface with high stiffness modulus courses with bitumen 20/30 during winter 2012

2.3 Laboratory testing

TPA research laboratory in Pruszków carried out in 2012 and 2013 an extensive testing program focused on evaluation of functional properties of asphalt mixtures for base and binder courses using different available binders in order to find optimal and most durable solution for design of pavement structures with high stiffness modulus asphalt mixes for climatic conditions in Poland. Among others it was confirmed that using of 20/30 normally available on Polish market is extremely risky and PMBs only can provide sufficient resistance to low cracking. Furthermore, by analyzing different combination of materials and thicknesses of pavement layers, containing once stiffer binder (such as 20/30) and once more flexible binder (such as PMB), that application of stiffer material at upper part of asphalt layer (bellow wearing course) and flexible material at bottom of asphalt layers provides the highest calculation fatigue life of the pavement. The main conclusion of carried out tests and analysis was that in order to achieve ultimate prolongation of pavement structure life, asphalt mixes at the bottom of the pavement have to be more flexible and more fatigue resistant as traditional asphalt concrete base courses. This actually confirmed also the idea of perpetual asphalt pavement with anti-fatigue course at the bottom. Replacing bottom part of asphalt base course with high stiffness modulus by mixture with higher fatigue resistance, not necessarily stiff, is resulting in improvement of fatigue life of pavement.

3. PAVEMENT DESIGN FOR S8 EXPRESSWAY

One of the most trafficked road sections in Poland is the road at the south border of Warsaw joining direction to two big cities to Krakow and to Wroclaw with about 100.000 vehicles per day. This road had to be reconstructed and partly build as new express road S8 section Opacz-Paszków in total length of 12,4 km. The chance given to Contractor by main public investor GDDKiA in Poland, tendering this expressway projects in the newly applied formula of realizing “Design and Build”, as well as the possibility to apply the “Value Engineering”, both helped to design alternatively and realize the first construction project with perpetual asphalt pavement with anti-fatigue course in Poland. Design process started 2013. Approval process of pavement design change took more than one year. Total construction took two years.

3.1 Design assumptions and material choice for particular courses

Original assumption of Employer for pavement design on the Project S8 Opacz-Paszkow was a traditional asphalt pavement structure with total thickness of asphalt layers of 31 cm, with SMA wearing course at the top and sub-base of unbound aggregate mixture of 20 cm at the bottom. This structure was designed for at least 20 years traffic: 31,7 million of 100 kN standard axle loads. Alternative proposal based on idea of perpetual asphalt pavement was designed for 50 years traffic load: 95,0 millions of standard axle loads.
The most popular wearing course in Poland and probably in whole Europe is stone mastic asphalt SMA, due to its durability. Mastic asphalt MA is even more durable, however not that popular due to higher costs. Therefore for wearing

course SMA 8 PMB with 45/80-55 in thickness of 3 cm was chosen. For the cost analysis it was assumed that first maintenance action – necessity of renewal of wearing course will not occur earlier than after 10 years of exploitation, what can be proved by Polish experiences.

As the binder (or middle) course for perpetual asphalt pavement has to be stiff and resistant to deformation, the asphalt concrete with high stiffness modulus AC WMS 16 with PMB 25/55-60 was chosen due to its good resistance to rutting as well as good fatigue resistance. Stiffness and fatigue requirements were described above. Specifications for AC WMS require a maximum proportional rut depth of 7,5 % at 60 ºC using large device. Additionally minimizing the risk of occurrence of low temperature cracking the resistance of the binder course mix was increased using polymer modified bitumen PMB 25/55-60 based on previous application experiences in Poland. Results of TSRST (Thermal Stress Restrained Specimen Test) of this PMB showed sufficient resistance to low temperature cracking (less than -25 ºC) considering local climatic conditions. Thickness of this course was designed to 15 cm, optimized during calculations in order to achieve desired fatigue life.

To choose the material for the lower flexible course with high fatigue resistance, so called anti-fatigue course, was the most crucial decision to make. As written above this is the biggest engineering challenge designing perpetual asphalt pavements.

3.2 Anti-fatigue course and pavement structure design

Mixture for anti-fatigue course of perpetual asphalt pavements has to be durable and has to have a high resistance to fatigue and sufficient stiffness (not necessarily high). Its thickness has to be sufficient in order to ensure structural functionality of this course, e.g. to cover the stresses at the bottom tension zone of the bounded pavement.

Following the principle of endurance limit approach (e.g. Newcomb and all, 2000) it is recommended that maximum tensile strain at the bottom of asphalt layers shall be less than 70 micro-strain, however other sources proves that it can be higher when the used material has better fatigue performance. At previous field applications known from literature a variety of used materials (asphalt mixture types) for bottom layer can be observed. The conclusions can be made that further research has to be done on this subject in order to find best practice. The goal is to find an optimum between material longevity, thickness efficiency and costs. The high quality binders should be used to guarantee longevity of the layer and its improved resistance to fatigue. These binder shall yield high fatigue crack resistance, good water sensitivity and adhesion. For the purpose of our project authors were looking for optimal solution between technological feasibility and economical profitability. Generally optimum between parameters of mix grading (air voids and binder content), course thickness (from mechanistic point of view and technological possibilities) and quality of binder has to be found. Many options were analyzed, such as mastic asphalt, stone mastic asphalt, fine graded asphalt concretes with different maximum nominal aggregate grading size and different course thicknesses. As the result of these analysis for AF course was chosen the AC mixture with maximum nominal aggregate grading of 16 mm using special PMB Polygum 45/55-70 providing highest fatigue resistance of mix. Thickness of the course was designed finally to 8 cm in order to assure that anti-fatigue material will cover the tensile stresses zone.

Figure 5 shows results of fatigue tests on mix type AC 16 for AF course with different tested binders. The extraordinary results showed a specially modified binder (directed modification with pre-selected bitumen blend for modification) PMB Polygum 45/80-70 (market as SM), with penetration about 70, softening point more than 80 ºC and breaking temperature less than -20 ºC. Mixture with this binder showed excellent resistance to fatigue in comparison with other binders, even better than highly modified binders (at figure 5 marked as HM) which show in lab conditions usually highest results.

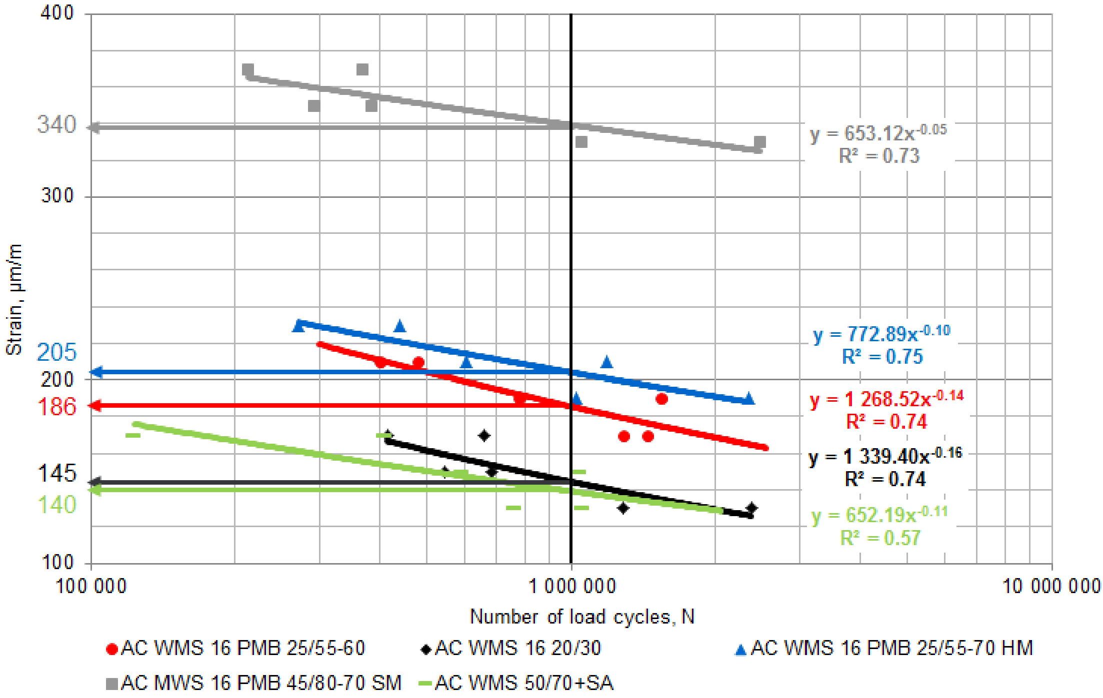

Figure 5: Results of fatigue test on asphalt concrete with different binders (at top excellent behaviour of PMB POLYGUM 45/80-70 SM)

Figure 6 shows comparison of fatigue life of selected three different pavement structures considered for S8 expressway. It demonstrates that by improving the binder and mix quality the thickness of asphalt layers can be reduced, and fatigue life can be still significantly higher. Using binder and base course made of high stiffness modulus asphalt concrete AC WMS 16 using PMB 25/55-60 in upper part (better low temperature cracking resistance) and in lower part (better fatigue resistance), reducing the thickness of 5 cm in comparison with traditional AC mixes in binder and base course with standard bitumen 35/50 or 50/70 significantly higher pavement fatigue life can be achieved. Furthermore, controversially, replacing the lower part of base course with high stiffness modulus asphalt mix by more elastic one (with stiffness modulus of about one half of course above), but higher fatigue resistant (about two times higher as course above) leads to ultimate pavement life improvement and gives perpetual pavement for this particular case.

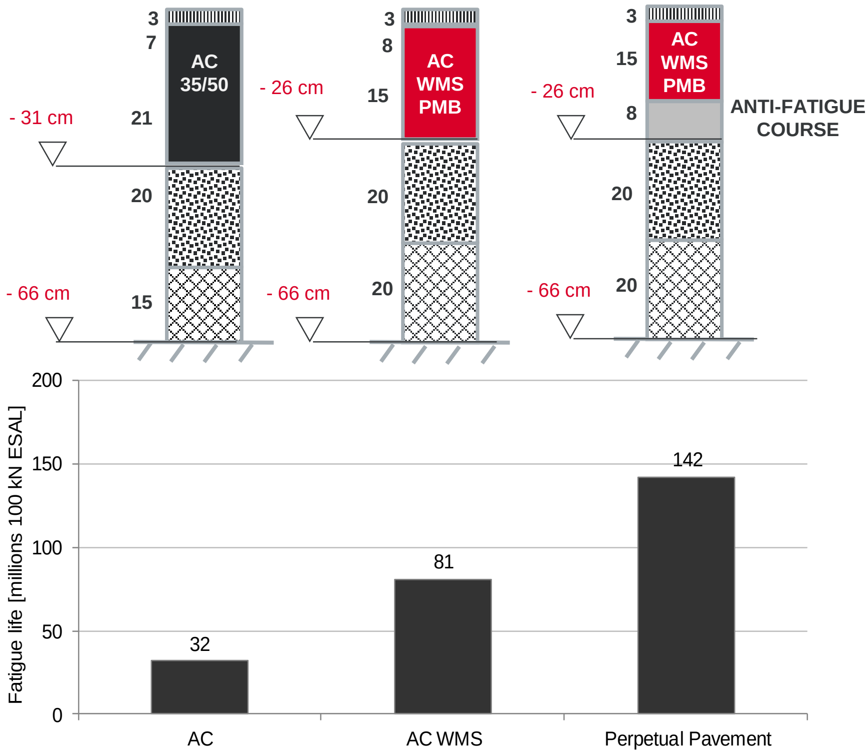

Figure 6: Durability of three different asphalt pavements: traditional pavement, pavement with the use of high stiffness modulus (AC WMS) courses and perpetual pavement with anti-fatigue course

French design method was applied for pavement design on this project as the fatigue criteria reconsider not only stiffness and fatigue resistance at particular strain but also slope of the fatigue curve what is very important considering different laboratory results on different materials. Mix parameters (stiffness and fatigue) used at this design method were tested using two point bending beam tests on trapezoidal specimen (at laboratory conditions specified in France). Parallel for quality assurance purposes for later construction in Poland all mixes were tested on four point bending tests.

Resulting pavement structure of perpetual asphalt pavement with anti-fatigue base course for S8 expressway in Poland in comparison with originally scheduled traditional standard pavement structure with course graded asphalt mixes with standard bitumen in base and binder course is presented on figure 7.

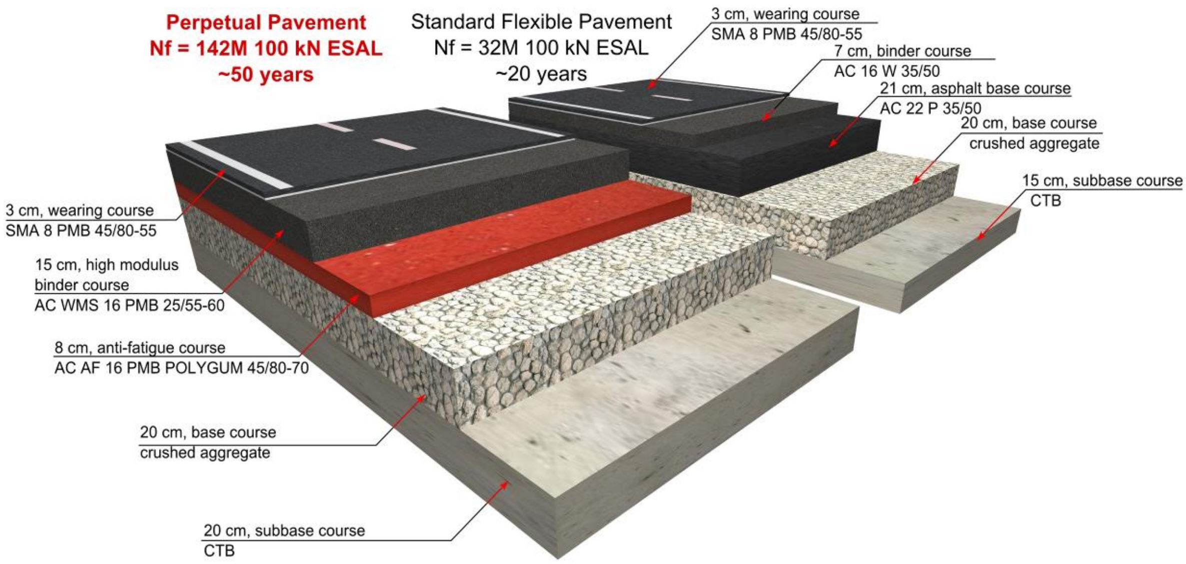

Figure 7: Cross section of perpetual asphalt pavement for S8 expressway in comparison with traditional standard asphalt pavement

The detailed analysis of life cycle costs as well analysis of benefits for public Investor comparing to traditional pavement structure showed clearly profitability of investments in perpetual pavement. Analysis assumed for maintenance that first renewal of wearing course will happen after 10 years and then regularly each 10 years. First deeper maintenance, renewal of first 6 cm of binder course will take a place after 35 years. The cost-benefit analysis was prepared in accordance with Blue Book - Road Infrastructure. The total sum of all project costs and benefits have been quantified and valued in monetary terms. Figure 8 presents the calculated Economic Net Present Value (ENPV) for the perpetual and standard pavement. The difference between ENPV for both structures is the Investor's real profit generated by the change of the structure and is equal 368 million PLN. Total costs of construction due to application of perpetual asphalt pavement increased on S8 about 2 %, however the durability increased more than twice.

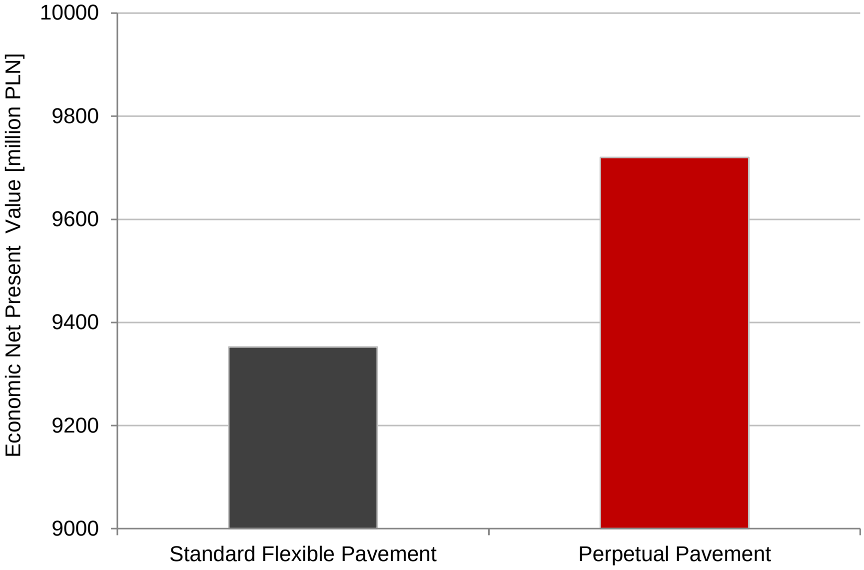

Figure 8: Economic Net Present Value (ENPV) fo the perpetual pavement and traditional asphalt pavement

Figure 9: Construction of trial section of anti-fatigue course using special PMB binder, September 2014?

Figure 10: Expressway S8 between Opacz and Paszków with perpetual pavement opened to traffic in July 2015 – 5 months before schedule

CONCLUSIONS

The perpetual asphalt pavements withstanding 50 years traffic load without significant structural maintenance can be designed by the implementing of the anti-fatigue course at the bottom of asphalt layers in sufficient thickness in order to ensure structural functionality at the critical tensile zone of the pavement. For this course on the S8 project in Poland special PMB binder with extraordinary fatigue properties (ε_6 more than 340 µm/m at 4PB-PR at 10 ºC and 10 Hz) was used. The thickness of this course was designed to 8 cm. AC mixture of maximum aggregate grading of 16 mm was used. Thus an economically effective solution was provided. The middle, stiff and rut resistant course of AC WMS 16 mixture with high stiffness module (14.000 MN.mm^{-2} at 4PB-PR at 10 ºC and 10 Hz) with standard PMB 25/55-60 was designed in thickness of 15 cm. Totally asphalt pavement layers thickness was 26 cm. It is assumed that only wearing course will be renewed regularly. For the cost analysis it was assumed that upper part of binder course could be renewed after 35 years.
It was found that pavement structures using for binder and base course mixtures with high stiffness module only, can be significantly improved using more flexible material at the bottom part instead. However very good fatigue resistance is required.
According to authors opinion it should be an ultimate goal of all road authorities to implement and to develop further the perpetual asphalt pavement structures in order to follow up the necessity of sustainable road construction and maintenance.

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