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FUNCTIONAL CONDITIONS AND STATE OF HOT MIX ASPHALT PAVEMENT AND ITS STRUCTURE OF LITHUANIAN MOTOR ROADS

Kazys Petkevičius[1], Daiva Žilionienė[2], Viktoras Vorobjovas[3]

Dept of Roads, Vilnius Gediminas Technical University, Saulėtekio al. 11, LT 10223 Vilnius, Lithuania
E-mails: [1]kk@vgtu.lt; [2]daizil@vgtu.lt; [3]viktoras.vorobjovas@vgtu.lt

Abstract. The state of hot mix asphalt pavement and its structure, predetermined by the distress level, largely depends on the functional conditions. The factors predetermining the functional conditions and service life of hot mix asphalt pavement and its structure are discussed in the present article: traffic loads, local climate and weather conditions, local soils (their properties), and other local factors (soil water level and moisturizing conditions, etc.). It is shown that the state of the road pavement and its structure expressed in the distress level, the roughness of hot mix asphalt pavement strength, expressed by strength coefficient K_{st}, largely depends on the componential composition of the upper layer of hot mix asphalt pavement and its physical and mechanical properties. The article contains recommendations for maintaining the required state of hot mix asphalt pavement and its structure (when $D \le 8\%$) and for renewal of the service life of the pavement and its structure.

Keywords: motor road, hot mix asphalt pavement (HMA), road pavement construction (RPC), functional conditions, pavement state, distress level (*D*), service life (SL).

1. Introduction

The project of management and development of Lithuanian national roads for 2002–2015 schedules fundamental improvement of motor road infrastructure. In order to achieve this purpose, it is necessary to ensure sufficiently good properties of hot mix asphalt pavement (HMA) pavement and its structure: relevant roughness of HMA, low degree of HMA and its structure disintegration, and relevant strength of pavement structure and cohesion between the wheels of vehicles and pavement. It is necessary to determine the permissible quality, maintenance and strength indices for HMA pavement and its structure and ensure the service life (SL) of HMA pavement and its structure provided for in the project.

Lithuania is yet far behind many developed countries in the density and technical level of the network of motor roads. At the beginning of 2009, the length of national roads was 21 320 km. Only 13 586 km (63.7%) of them had asphalt pavement. The length of the roads of category E (European Corridors) was 1510 km and the length of the roads of category I and higher categories was 564 km including 309 km of main roads.

Under the conditions of increasing number of vehicles (1.29 mln in 2000 and over 2.12 mln in 2008) and the portion of heavy-weight multi-axial cargo vehicles, it is very important to evaluate the HMA pavement and its structure functional conditions and to correctly forecast the future state of HMA pavement and its structure and real SL taking into account the real quality of HMA pavement and strength of its structure. These data are necessary for scheduling the timely HMA pavement and its structure repairs in order to ensure safe, convenient and fast transportation of passengers and cargo, i.e. to ensure the required pavement evenness.

The aim of the present paper is to discuss the functional conditions and acceptable state of HMA pavement and its structure of Lithuanian motor roads.

2. Substantiation of the analysed problem

The Ministry of Transportation Ontario (MTO) and the University of Waterloo examined the feasibility of using automated pavement distress collection techniques in addition to data collected through manual surveys. Base on these studies results Tighe *et al.* (2008) state that these surveys should be supplemented with manual surveys, especially for design purposes, because some of the pavement distresses were difficult to identify with the automated methods.

The roughness of HMA pavement and strength of its structure are closely related with the state of pavement which, using the formula is described by the distress level *D*, expressed in % (Petkevičius 2000):

$$D = \frac{\left(S_e + S_{cr} + S_{sh} + S_{sd} + S_{od} + \sum_{i=1}^{n} l_i b_i\right) \times 100}{S}, \quad (1)$$

where S – width of HMA pavement in the investigated road section, m^2; S_e – area of pavement destructed by erosion, m^2; S_{cr} – area of pavement damaged by crack net, m^2; S_{sh} – area of pavement damaged by plastic (shear) defects, m^2; S_{sd} – area of pavement damaged by surface defects, m^2; S_{od} – area of pavement damaged by other defects, m^2; l_i – length of solitary crack, m; b_i – width of road stretch which has lost strength (on both sides of crack i and depending on the crack width), m.

The main results of the study Dahstedt (2003) have show that a subjective roughness seems to be a linear function of roughness according to International Roughness Index (IRI) within the studied roughness range. For some road sections with a nontypical spectral composition of the road roughness, it was found that the correlation between IRI and subjective roughness decreased considerably, and the simulations of random errors added to the IRI values showed that within the studied range and with the fairly large number of observations (45), random measurement errors up to at least +/–0.2 IRI (mm/m) can be considered insignificant.

Investigations by Sivilevičius and Petkevičius (2002) have shown that the values of roughness (Y) of HMA pavement and D depend on the strength coefficient K_{st} of HMA pavement structure and on the SL (T) of the HMA pavement and its structure. The higher are the values of the defects of pavement the smaller are the values K_{st} and reability of HMA pavement (P_{HMA}) and the lower is the reliability of its HMA pavement structure (P_P): defects in the roads of satisfactory or fairly good condition account for 0–10% of the pavement area ($K_{st} \geq 1.0$ and P_{HMA} = 88–100%) and in the bad roads for 20–30% and more ($K_{st} \leq$ 0.8 and $P_P \leq$ 70–80%) (Table 1).

Table 1. Condition of HMA pavement according to D

Condition	Level	D, %
Perfect	10	< 1
Very good	9	1–3
Good	8	3–5
Sufficient	7	5–8
Satisfactory	6	8–12
Critical	5	12–16
Unsatisfactory	4	16–20
Bad	3	20–25
Very bad	2	25–30
Extremely bad	1	> 30

When the K_{st} is low, in short time pavement defects appear which reduce the P_P. When a section of HMA pavement structure has an almost equal strength value, i.e deviations of parameter K_{st} from the average value are insignificant, the probability of defects reduces and the P_P increases. The evenness of HMA pavement structure can be evaluated by the standard deviation σ_E of its resilient module E or variation coefficient v_E.

The defects of HMA pavement structure usually are classified according to their visible features (form, size, etc.) (Petkevičius 2000; Sivilevičius, Petkevičius 2002). Applying formula (1) it is possible to more precisely and objectively determine the HMA pavement D and using the classification given in Table 1 to evaluate its condition according to D.

At a critical condition, the pavement should be repaired as soon as possible. For safe and comfortable driving the HMA pavement should be repaired when the $D \geq 8\%$ (Petkevičius 2002) (Table 1) (when reability $P_{HMA} \leq 92\%$).

In order to precisely evaluate the condition of pavement according to D values measuring is necessary whereas an approx evaluation (levels) only requires visual observation and examination of reference photographs.

In recent years, the rutting and the number of distress cracks in the HMA pavement of Lithuanian roads has been considerably increasing due to the growing number of heavy vehicles and insufficient strength of HMA pavement structure unsuited to new loads. The reduced volume of annual repairs enhanced the D and weakening of the HMA pavement structure. The data of the Transport and Road Research Institute shows that the strength index *SNC* every year has been reducing by 2% on the average (Sivilevičius, Petkevičius 2002). The *SNC* index in the main roads and national roads has been increasing only since 2003 as a result of the measures taken for HMA pavement structure strengthening.

Investigations (Petkevičius, Petkevičienė 2005) have shown that with the improving quality of repairs the IRI of HMA pavement Y_{IRI} (m/km) has been every year increasing since 1992: 0.041 m/km in main roads, 0.054 m/km in national roads and 0.054 m/km in regional roads on the average.

Full-scale accelerated pavement testing (APT) leads to significant advances in practice and economic savings for the evaluation of new pavement configurations, stress level related factors, new materials, and design improvements (Guo, Prozzi 2009). Park *et al.* (2008) test results show that the predicted pavement fatigue lift based on horizontal strains at the bottom of asphalt layer is different by tire types and analysis methods while the predicted rutting life based on vertical strains at the top of subgrade layer shows no significant difference.

Recently, the SL of pavement has been reducing: according to the Lithuanian standards of 1987, the designed SL for the roads of categories I was T_s = 14 years. The time span between pavement repairs (Petkevičius 2000) and the real interim time span for Lithuanian pavement established in 2002 was only T_s = 9 years (Table 2).

Investigations (Petkevičius, Podagėlis 2000; Sivilevičius, Petkevičius 2002) have revealed that the D of HMA pavement in the Lithuanian roads ranges from 0 to 61.27% and its reliability value P_{HMA} ranges from 38.63% to 100%. In most cases (75.7%), the greatest part of D (40.0–56.5%) can be accounted for by fatigue of HMA. The increasing number of heavy vehicles is expected to increase the fatigue portion in the value of D even more (Butkevičius *et al.* 2007).

Table 2. Statistical characteristics of the interim time spans T_s between HMA pavement structure repairs

Road No.	Statistical characteristics of time spans T_s			Number of examined sectors, n
	Arithmetic mean $\bar{X}_T$, years	Standard deviation σ_T, years	Variation coefficient V, %	
Vilnius–Kaunas–Klaipėda (A1)	9.09	2.83	31.2	47
Vilnius–Panevėžys (A2)	8.77	3.42	39.1	26
A1 and A2	8.97	3.04	33.8	73

The correlation link (with standardized regression coefficients) between the Y index and factors T, D_n, D_t, and D_e has been determined (Буткявичюс, Петкявичюс 2006):

$$Y = 0.0508T + 0.0457D_n + 0.030D_t + 0.00674D_e, \quad (2)$$
(determ. coef. $R^2 = 0.656$),

where Y – roughness index, mm, measured with a 4 m long bar, T – behaviour duration of the pavement, years, D_n, D_t, and D_e – distress level D, %, predetermined by HMA pavement fatigue, cracks (produced by temperature variations) and erosion (cracking and crumbling entailed by freezes and thaws), respectively.

The correlation link (2) shows that the roughness of pavement mainly depends on the D due to HMA pavement fatigue D_n.

The D is related to the strength of HMA pavement structure expressed in K_{st} and K_{st} in its turn is related with the HMA pavement Y, cm/km (Petkevičius 2000):

$$K_{st} = 2.41D^{-0.321} \ (R^2 = 0.884), \quad (3)$$

$$Y = 174K_{st}^2 - 526K_{st} + 794 \ (R^2 = 0.980). \quad (4)$$

It has been determined (Sivilevičius, Petkevičius 2002) that there exist functional links between the velocity of traffic flow v and pavement roughness Y and also between the transport costs I_t and pavement roughness Y. The indexes of pavement roughness Y, strength HMA pavement structure, D and interim time spans between repairs T_p and T_s (minor and major) should be standardized.

The research results described in the present section should prove the importance and relevance of investigation of functional conditions, properties and state of HMA pavement and its structure of Lithuanian roads.

3. Functional conditions of HMA pavement structure and its structure

HMA pavement and its structure function under objective local conditions which depend on many factors: properties of components of HMA pavement and its structure layers and soil properties of subgrade, thickness and compression of these layers, climate factors (annual number of clear and rainy days, time spans with snow cover, time spans with positive or negative temperature, depth of frozen ground, and passages from positive to negative temperatures and vice versa), traffic loads, local conditions (groundwater horizon and irrigation conditions), and properties of HMA pavement and its structure (roughness, D, etc.) (Fig. 1) (Petkevičius 2008).

The values of all indices shown in Fig. 1 (E_1–E_5, h_1–h_5 and E_{sub}) except index h_{sub} can be taken from normative documentation according to HMA pavement structure materials and knowing the type of soil in a locality. The index E_D can be derived from the known dependencies (index $E_D \geq K_{st}E_r$, where E_r is the required resilient module of HMA pavement structure determined by evaluation of future (after 10–20 years) traffic volume N_D). The index h_{sub} can be derived from the following interdependence:

$$h_{sub} = h\frac{(E - E_D)}{(E_D - E_{sub})}, \quad (5)$$

where h is capacity of HMA pavement structure layers (in this case $h = h_1 + h_2 + ... + h_5$); E – average weighted resilient module of HMA pavement structure layers (in this case:

$$E = \frac{E_1h_1 + E_2h_2 + ... + E_5h_5}{h_1 + h_2 + ...h_5}.$$

Index h_{sub} shows the equivalent thickness of subgrade soil when at soil resilient module E_{sub} HMA pavement structure designed resilient module will be E_D (Fig. 1) (in this case:

$$E_D = \frac{E_1h_1 + E_2h_2 + ... + E_5h_5 + E_{sub}h_{sub}}{h_1 + h_2 + ...h_5 + h_{sub}}.$$

The SL of HMA pavement before the repair usually is shorter than that of the whole HMA pavement structure. Investigations (Petkevičius, Petkevičienė 2005) have revealed that rutting of HMA pavement has been significantly increasing. This is a serious problem of HMA quality showing that shear stress-resistant HMA must be used in the roads with heavy traffic.

HMA in the pavement disintegrates under the impact of the following factors (Petkevičius 2008) (Fig. 1).

– *Destructive impact of heavy-weight cargo vehicles* causing fatigue cracks in HMA pavement;
– *Meteorological conditions:*
  a) *Sudden weather cooling in winter*. When cooling velocity reaches the value v_t = 6–10 °C/h, there appear transverse cracks in the pavement;
  b) *Frequent changes of meteorological conditions, i.e. temperature passages from positive to negative or vice versa.* In Lithuania, these temperature pas-

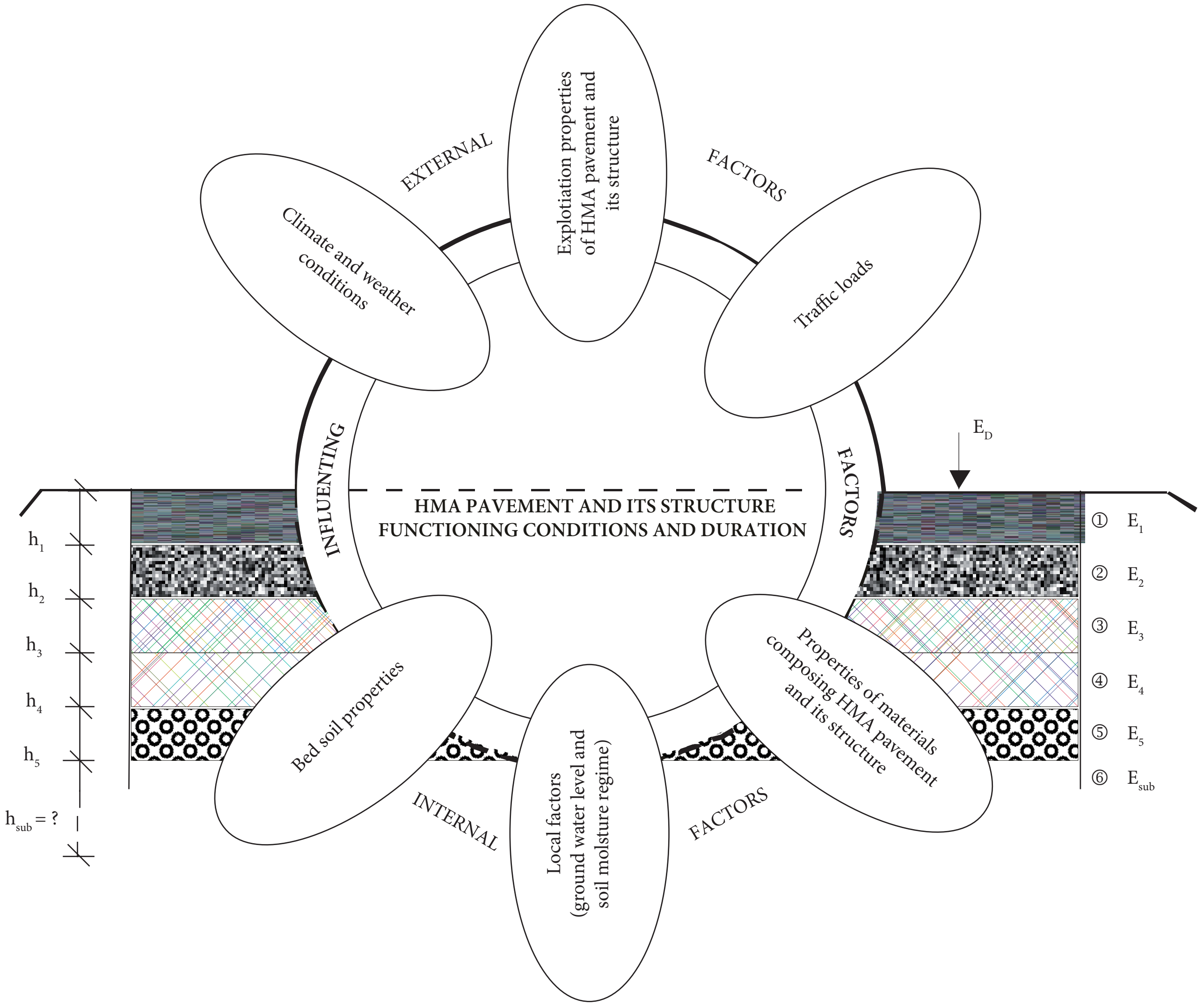

Fig. 1. Model of interdependence between the factors predetermining HMA pavement and its structure functional conditions and duration: ①–⑤ – HMA pavement structure layers (① and ② – upper and lower layers of HMA pavement; ③ and ④ coarse aggregate (CA) or gravel road bed layers; ⑤ – frost blanked course from sand (S) or other material; ⑥ – subgrade; $E_1 – E_5$ and $h_1 – h_5$ – respectively, resilient modules of the indicated HMA pavement structure layers and thickness of these layers; E_{sub} and h_{sub} – respectively, resilient module of subgrade and equivalent thickness of active zone

sages occur 60–80 times per year and more (one autumn–winter–spring season) (Petkevichyus 2008; Petkevičius, Sivilevičius 2000). Under these conditions, the pavement begins to crack and later crumbles away;

c) *Solar radiation*. Solar radiation heats the HMA pavement (on a clear day when air temperature reaches $t \geq 30$ °C, the HMA pavement heats up to 50–60 °C) causing the following consequences:

– reduction of resilient module of HMA pavement and reduction of the strength of its structure;
– rapid ageing of the pavement. In 3 or 5 years cracks may appear what considerably reduce the resilient module and HMA pavement structure strength;
– reduction of HMA resistance to shear stress produced by heavy-weight vehicles resulting in the appearance of ruts, waves, displacements and potholes;
– The *insufficient strength of HMA structure* causes transverse cracks and breaks in the HMA pavement;
– Due to insufficient strength, the whole HMA structure or its part under the HMA pavement becomes very sensitive to:
  a) *destructive impact of vehicles* (heavy-weighed ones in particular),
  b) *climate factors*:
– *negative impact of temperature* when in the poorly cohered layers composed of low filtration capacity materials (when filtration coefficient is lower than 3 m/day) HMA pavement someplace bulges out and then cracks;

– *negative impact of atmospheric water*: rainfalls wet out the road bed. The excessive water reduces the resilient module of the soil (especially clay) under the road bed.

c) *groundwater impact.* Shallow groundwater reduces resilient module of subgrade soil.

4. The condition of HMA pavement and its structure, rational service life and other important indices

Investigation results (Petkevičius 2000; Petkevičius, Podagėlis 2000; Petkevičius, Sivilevičius 2000) have revealed that the condition of HMA pavement and the condition and SL of HMA pavement structure is best modelled by HMA resistance to tension by bending R_b, resilient modules of pavement and other structure layers (HMA pavement – E_{HMA}, subgrade layers: coarse aggregate E_{CA}, sand – E_S, etc.), HMA pavement structure strength coefficient K_{st}, and fatigue resistance of HMA N_{AC}. The values of indices R_b, E_{AC} and N_{AC} can be derived using the common formulae with respect to the chosen type and sort (composition and structure) of HMA. By modelling HMA composition (composed of chosen required materials and bitumen), it is possible to derive the values of indices R_b, E_{AC}, N_{AC} and E_{CA} and forecast the future quality of HMA pavement and its structure (after 1, 2 and *n* years) (Petkevičius, Sivilevičius 2000).

For modelling the quality of HMA pavement it is relevant to determine the physical and mechanical properties of HMA. In many developed West European countries, it has been reported that HMA functional in the pavement is modelled by the following indices: stability *S*, flow *F*, volume of air voids V_a according to Marshal, E_{AC}, N_{AC}, etc. According to Petkevičius and Sivilevičius (2000) investigations the HMA composition is a decisive factor for pavement roughness *Y*, pavement quality (*D*), HMA pavement structure strength (strength coefficient K_{st}), and absorptive power *W*. *D* is highly dependent on *W* (the properties of HMA modelled by *W* and V_a are comparable):

$$D = 27.5 + 12.27W^2 + 30.1W \ (R^2 = 0.884), \tag{6}$$

$$D = 539 + 13.48B^2 - 170.4B \ (R^2 = 0.980), \tag{7}$$

$$Y = 1218 + 19.83B^2 - 246B \ (R^2 = 0.672), \tag{8}$$

$$K_{st} = -34.93 - 97.47\left(\frac{B}{F}\right)^2 + 119.56\left(\frac{B}{F}\right) \quad (R^2 = 0.792), \tag{9}$$

$$W = 26.7 + 48.2\left(\frac{F}{CA}\right) - 0.064F^2 - 114.3\left(\frac{B}{CA}\right) + 8.36\left(\frac{B}{F}\right) - 9.6B - 1.12B^2 \ (R^2 = 0.810), \tag{10}$$

where *B*, *F* and *CA* in 6–10 are relative portions (mass %) of bitumen, grains finer than 0.071 mm and grains coarser than 5 mm in HMA pavement respectively.

The expected SL T_s of HMA pavement structure is ensured when $E_f \geq E_D$, and $E_D \geq E_r$ $\left(K_{st} = \frac{E_D}{E_r} \geq 1.0\right)$. The E_f of HMA pavement structure reduces in the course of time: at first at a slower rate which is gradually increasing. Sivilevičius and Petkevičius (2002) investigations have shown that the reduced average HMA pavement structure E_f entails a higher value of its standard deviation σ_E. The increasing traffic volume *N* requires higher E_f of HMA pavement structure. When in the course of time the reducing min HMA pavement structure $E_f \left(E_f^{(\min)}\right)$, usually ensured with probability *P* = 90–99%, equals the required increasing E_r (provision $E_f^{(\min)} = E_r$) and continues to reduce further ($E_f^{(\min)} \leq E_r$), the rational SL T_s of HMA pavement structure comes to an end and the HMA pavement structure requires a prompt major repair.

The real SL of HMA pavement will equal the expected one when at the end of the time span its roughness index is not lower than the permissible one (when the index of real roughness Y_f is not higher than the permissible index Y_p, i.e. $Y_f \leq Y_p$). The roughness of the HMA pavement functional for *T* years is consistently deteriorating (the roughness index Y_f is increasing). The increasing *N* requires higher quality of roughness (roughness index Y_p should be lower). In length of time, the real roughness index I_f increases from the starting $Y_f = Y_0$ to permissible $Y_f = Y_p$ and continues to increase to $Y_f > Y_p$ when the rational SL of HMA pavement $T_{HMA}{}^{(r)}$ comes to an end and the pavement needs an immediate repair improving its roughness (the smoothening effect ΔY). After repaired roughness, i.e. implementation of the condition $Y_f < Y_p$, the pavement can be again used until $Y_f = Y_p$, i.e. until the following repair $T_{HMA}{}^{(i)}$. The pavement SL until the first repair $T_{HMA}{}^{(1)}$ depends on its starting roughness Y_0 and on the time span for the pavement to deteriorate, i.e. on the *N*, on the properties of the materials of the pavement and HMA pavement structure layers, and on the thickness of HMA pavement structure layers and degree of their compression (K_{st}). Deterioration of pavement roughness *Y* depends on the increasing value of *D* influenced by the described factors. The pavement SL until the second repair $T_{HMA}{}^{(2)}$ and the subsequent repairs depends on the smoothening effect ΔY and on the character of repairs (method of smoothening, used materials, technologies, etc.) (Petkevičius, Sivilevičius 2000).

The better is the roughness index Y_{IRI} (the higher is ΔY), the longer is the time span of pavement SL $T_{AC.}$

Investigation results (Petkevičius 2000; Sivilevičius, Petkevičius 2002) have shown that the *D* is an important index of the state of HMA pavement and its structure. Using formulae (2) and (3), the limit permissible values of *D* have been determined $D_1^{(p)}$ = 8% and $D_2^{(p)}$ = 16% which are taken as criteria for calculating the time span after which repairs of the HMA pavement (T_{HMA}) and its structure (T_s) are necessary. The following formulae are suggested for determining the values of indices T_{HMA} and T_s (Petkevičius 2002):

$$T_{HMA} = \frac{D_1^{(p)}}{\Delta D_1^{(p)}}, \quad T_s = \frac{D_2^{(p)}}{\Delta D^{(p)}}, \qquad (11)$$

where $\Delta D_1^{(p)}$, $\Delta D_2^{(p)}$ are the absolute average increments of index D per year at respective time spans from 0 to $D_1^{(p)}$ and from 0 to $D_2^{(p)}$. The time spans and values of $\Delta D_1^{(p)}$ and $\Delta D_2^{(p)}$ can be determined using a graph of interdependence between the D and SL T_f (Fig. 2).

Fig. 2. Interdependence of SL T of HMA pavement and its D

Taking into account the average annual values $\Delta D_1^{(p)}$ and $\Delta D_2^{(p)}$ of HMA pavement D and value ΔY_{IRI} = 0.09 m/km of annual deterioration of pavement roughness index Y ΔY_{IRI} = 0.09 m/km we determined the permissible values of the quality indices of HMA pavement and its structure (Petkevičius 2000; Petkevičius, Sivilevičius 2000; Sivilevičius, Petkevičius 2002) (Table 3). Also their HMA pavement and its structure rational reliability values were determined – respectively $P_{HMA} \geq 92\%$ and $P_p \geq 84\%$.

Table 3. The values of HMA pavement and its structure condition of the Lithuanian roads and the recommended values of quality indices

Quality index and measuring unit	Temporary value
Pavement roughness Y_{IRI}, m/km:	
Before the pavement repair	≤ 2.50
Before the HMA pavement structure repair	≤ 2.75
Quality indices of the upper pavement layer:	
Thickness h_v, mm	≥ 40
Compression index (coefficient) K_c	≥ 1.00
Service life T, years:	
Before the pavement repair T_{HMA}	≥ 5.5
Before the HMA pavement structure repair T_s	≥ 8.0

Also the rational starting HMA pavement structure strength coefficient K_{st} was determined for national roads of different categories with HMA pavement: K_{st} = 1.5–1.6 for highways; K_{st} = 1.4–1.5 for roads of category I; K_{st} = 1.3–1.4 for roads of category II; K_{st} = 1.2–1.3 for roads of category III; K_{st} = 1.1–1.2 for roads of category IV; K_{st} = 0.5–1.1 for roads of category V (Butkevičius *et al.* 2007). It is recommended to repair the HMA pavement and its structure when the values are: K_{st} = 0.95–1.00 for highways and roads of category I; K_{st} = 0.90–0.95 for roads of categories II and III; K_{st} = 0.85–0.90 for roads of category IV and K_{st} = 0.80–0.85 for roads of category V.

5. Conclusions

A decisive influence on the functional conditions and SL of HMA pavement of motor roads and its structure is produced by the following factors: traffic loads (heavy-weight vehicles in particular), local climate and weather conditions, local soils (their properties) and other local conditions (shallow groundwater horizon, soil moisture regime and pavement construction conditions – whether the road is built on an embankment or in an excavation, etc.).

The functional conditions and SL of HMA pavement and its structure also depend on the factors related with qualification and experience of road constructors and technologists: chosen materials for building HMA pavement structure (the following indices of chosen materials are of major importance: values of resilient modules and thickening coefficients, filtration coefficient of sand, etc.), capacities (designed and real) of layers, roughness of HMA pavement (mostly dependent on the technologist), etc.

Investigations revealed that the state and SL of HMA pavement and its structure is best reflected by the pavement D and the state of HMA pavement structure is also well reflected by its strength expressed in the K_{st}. The article contains recommendations on the critical values of pavement D indicating the necessity for operative and preventive repairs of HMA pavement and major repair of HMA pavement structure. Critical values of K_{st} indicating the necessity of immediate major repairs of HMA pavement structure (by building a new HMA pavement) are recommended for roads of different categories.

Implementation of given recommendations on the regularity of repairs of HMA pavement and its structure of Lithuanian national roads would ensure the required conditions for safe, comfortable and fast transportation of passengers and cargo and would contribute to saving funds allocated to HMA pavement structure repairs.

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