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EFFECT OF COMPONENTS CONTENT ON PROPERTIES OF HOT MIX ASPHALT MIXTURE AND CONCRETE

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Abstract. The article contains general characteristics of Lithuanian motor roads and possibilities of their development. 63.72% of Lithuanian motor roads of national importance (according to their length) have asphalt pavement. It is shown that modernization of national motor roads mainly includes paving of gravel roads. It is pointed out that the main indices characterizing the condition and service life of asphalt pavement and its construction are: hot mix asphalt (HMA) concrete resistance to binding tension, tensile elasticity modulus and fatigue resistance. The values of these indices highly depend on the componential composition and structure of HMA concrete as well as on the degree of its compaction. The suitability of HMA concrete for road pavement construction is well characterized by its physical mechanical indices according to Marshall: stability S, flow F, volume of air voids V_a etc. These indices also are highly dependent on the composition and structure of HMA concrete. Investigations carried out in the Lithuanian motor roads and in laboratory helped to determine asphalt concrete dependencies between the componential composition of HMA concrete and values of its physical and mechanical properties according to Marshall. Conclusions and recommendations are included.

Keywords: pavement, hot mix asphalt (HMA), mixture mix, components content, quality indices.

1. Introduction

According to *Lithuanian Road Administration under the Ministry of Transport and Communications*, the construction, reconstruction, repairs and management of roads are well budgeted: in 1998 – 575 mln. Lt, in 2003 – 693 mln. Lt and in 2007 – 1154 mln. Lt. The budget is really very large and it is important that the fund is used rationally.

Its large part was invested in production of HMA. In the last decade, HMA production has increased in Lithuania from 760 thou t to 1730 thou t (Sivilevičius, Šukevičius 2009).

When drafting the guidelines for motor road development in 2006–2015, the necessity of development and possibilities of implementation were evaluated. After 2004, the traffic volume (especially the traffic volume of heavy vehicles) has dramatically increased. About 40% of country's main roads require reconstruction. The priorities and measures of road network development have been established taking into consideration the international commitments and public benefit. A special attention is paid to preservation and development of the existing motor roads. The Gravel Road Paving Programme is further implemented: in 2002–2008, from 107 to 360 km of gavel roads were paved every year (210 km on the average every year).

The given data convince that modernization of the Lithuanian gravel roads of national importance is mainly related with construction of HMA pavement. Sparing the allocations, it is necessary to guarantee the reliability and durability of the new HMA pavement. When the pavement is strong (strength coefficient $K_{st} > 1.0$) the short service life of pavement is predetermined by an inadequate quality of HMA mixture and its insufficient compaction in the pavement (Sivilevičius, Petkevičius 2002). Investigations of Ceylan *et al.* (2009a; 2009b), Pell (1971), Petkevičius and Podagėlis (2000) have proved that the main indices characterizing the condition and durability of HMA pavement construction are: HMA concrete resistance to binding tension $R_b^{(a)}$, tensile resilient modulus $E^{(a)}$, dynamic modulus E^* and fatigue resistance $N^{(a)}$. Selection of relevant quality mineral agregates and bitumen may help to obtain the adequate values of $R_b^{(a)}$, $E^{(a)}$ and $N^{(a)}$ and to predict the condition of HMA pavement in 1, 2, …, n years (Petkevičius, Sivilevičius 2000). Nevertheless, it is not easy to determine the values of $R_b^{(a)}$, $E^{(a)}$ and $N^{(a)}$ because this task requires sophisticated and expensive instruments. For this reason, in many West European and other developed countries, the properties of HMA concrete in the road pavement are modelled based on the following indices: stability S, flow

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F, and volume of air voids V_a according to Marshall. So far, the dependence between the physical and mechanical properties of HMA concrete according Marshall and service life of HMA pavement has not been determined for certain. The requirements for physical and mechanical properties of HMA contained in the normative documentation often are insufficiently grounded. They should be revised taking into account asphalt concrete behaviour conditions of HMA concrete and HMA pavement.

Pell (1971); Petkevičius, Podagėlis (2000) and other investigations (Петкявичюс *и др*. 2007) show that the greatest durability is characteristic of the HMA pavement where the composition of HMA mixture is close to its optimal composition, i.e. it is rational and guarantees the best physical and mechanical HMA properties according to Marshall and other best quality indices. In Lithuania, HMA mixture is the main material used for HMA concrete or any other asphalt pavement. The HMA mixtures often are heterogeneous due to varying amounts of components. The method of stochastic modelling of HMA mineral composition (Sivilevičius, Vislavičius 2008) allowed determining the homogeneity of materials used for its production. Homogeneity of the bituminous surfacing of HMA concrete increases the variation of the content of reclaimed asphalt pavement (RAP) components (Mučinis *et al.* 2009).

The aim of the present investigation is to determine the influence of content (mass %) of HMA mixture components on the physical and mechanical properties of HMA concrete according to Marshall.

The object of investigation: compositions of HMA mixture and HMA concrete in pavements; physical and mechanical properties of HMA mixture and HMA concrete; compaction coefficient of the wearing layer of HMA pavement.

The applied research methods: mathematical statistics; experimental laboratory; experimental *in situ* (on the motor roads).

2. The condition of asphalt concrete pavement of motor roads and its construction and possibilities of their improvement

Recently, the rates of degradation of asphalt pavement and RPC in the Lithuanian main, national and regional roads (used by heavy vehicles) has intensified producing many asphalt pavement and RPC defects. The cracks and their network, waves, ruts, shear deformations, eroded surfaces and pits show intensive corrosion of not only the pavement but also of the road base layers. The defects in the road pavement deteriorate travelling conditions: unevenness of road pavement reduces comfort of ride, average speed of ride and traffic safety.

In order to elongate the service life of asphalt concrete pavements, different measures. The main solution of this problem in developed countries is the following: the RPC is strengthened not only by thin asphalt pavement layers but also by adequately thick upper layers of asphalt pavement. This method of pavement and RPC strengthening makes it possible to maintain their performance for long yet it is very expensive. There must be no delay in strengthening the road pavement. This should be done until the defects are not marked (distress level $D \le 8\%$ (Petkevičius, Sivilevičius 2000)), because, as it has been reported by different authors from many countries, the budget required for improving the condition of roads from bad to good is twice as large as the budget of improving the condition of roads from fair to good (Кейрос 1995).

The smoothness of road pavement is most often described by the International Roughness Index (IRI) (Sayers *et al.* 1986). The IRI is derived based on mathematical processing of roughness measuring data. The measuring data are represented by irregularities of the pavement, i.e. the deviations of the pavement surface from the test bars put on the pavement. Other alternative testers can be used with an established correlation link between the readings and roughness values.

Roughness is the main characteristics of durability of HMA pavement. It depends on the strength of pavement as well as on the composition and structure of HMA concrete, i.e. on its physical, mechanical, deformation and other indices.

Operation of wearing course HMA pavement leads to their various defects and irregularities in the pavement surface. The pavement defects may be classified into the following main groups: surface disintegration, residual shear deformations, climate cracks, fatigue cracks and network of cracks, shear cracks (occurring as a result of insufficient strength of pavement), pits and potholes (Sivilevičius, Petkevičius 2002).

The surface course disintegration (chippings and potholes) occurs as a result of poor quality of HMA mixture, poor cohesion of bitumen with mineral materials, poor cohesion of pavement layers and poor drainage from the pavement surface. These defects usually occur in localities where in cold season weather conditions frequently change (more than 60 times/season) from negative to positive and vice versa. The water contained in the voids of HMA concrete expands when freezing and erodes the wet porous upper layers of HMA pavement (wearing course in particular).

The residual shear deformations in the HMA pavement occur when HMA concrete of the pavement is insufficiently shear resistant, i.e. when its rheological properties do not meet the rheological requirements for HMA concrete during usage. The shear defects sometimes occur due to insufficient bond of the upper and lower layers of HMA pavement. When the bond between the layers is poor, cracks occur in place of other shear defects (waves and shear displacements).

Thermal cracks occur when the real values of rheological indices of HMA concrete and the thickness of pavement layers are at variance with the mandatory values for certain climate conditions. The cracks usually occur at the weather cooling rate $v \ge 6$ °C/h. The occurrence of thermal cracks also is affected by the type of the base. When the base is rigid, thermal cracks occur more frequently than when the base is flexible: this is predetermined by different coefficients of thermal expansion of the two types of base.

The fatigue and shear cracks and flaws mainly form when the HMA pavement strength is insufficient for resisting the traffic loads during a design time span. The cracks resembling the alligator skin develop due to insufficient road bed and base strength.

The adequate strength and design service life of asphalt pavement are ensured by the following properties of asphalt concrete in pavement:

– durability: ability to resist the recurrent loads of vehicle axes and resulting stretching tension and stretching deformations;
– shear resistance: ability to resist repeated horizontal loads entailed by vehicles;
– resistance to temperature cracks: long-lasting ability to resist temperature tensions;
– ability of bitumen to cohere with the grains of mineral material;
– age resistance: long-lasting ability of binder to preserve its initial properties;
– resistance to erosion: ability to preserve homogeneity (remain monolithic) for a long time under the conditions of recurring water and cold effects.

When the mentioned properties are not ensured, the pavement disintegrates rapidly and looses its initial strength and roughness.

The HMA pavement of Lithuanian motor roads mainly deteriorates due to cracks and erosion (Petkevičius, Podagėlis 2000). The plastic defects in the HMA pavement occur in the first 3–5 years under the conditions of positive ambient temperature. Wheel tracks occurring in each lane are especially widespread. Waves and displacements bear local character. They mainly occur in crossings, bus-stops, standing-posts, and acceleration and deceleration lanes.

Standard LST 1518:1998 "Roads. Quality Management and Quality Assurance. Application of Statistical Methods. Vocabulary" points out that quality is an entirety of object properties allowing meeting the designed requirements. HMA concrete is designed for construction of road pavement therefore its quality must be evaluated according to the properties modelling its condition during pavement usage. These properties can be defined by physical and mechanical indices according to Marshall. It has been reported (Petkevičius, Sivilevičius 2008) that in more than 65% of cases the poor quality of HMA concrete is the main cause of early fatigue of HMA pavement of Lithuanian roads (and roads of other countries with similar climate conditions).

For evaluation of compatibility of quality indices K with the standard described in normative documentation and with other requirements, the following inequalities with single-sided or double-sided limits (the smallest $T_{\min}$) and/or largest values $T_{\max}$) can be used:

$$K \le T_{\max} \text{ for indices } K_n, \frac{P_1}{P_2}, \text{ when } t = +50\ °\text{C}, \quad (1)$$

$$K \ge T_{\min} \text{ for indices } \frac{P_1}{P_2},$$

$$\text{when } t = -10\ °\text{C}, S, \frac{S}{F}, R_b^{(a)}, E^{(a)}, N^{(a)}, K_d, \quad (2)$$

$$T_{\min} \le K \le T_{\max}$$

$$\text{for indices } V_a, P^{(a)}, F, CA, FM, MF, B, \frac{B}{MF}, \quad (3)$$

where K_n, $\frac{P_1}{P_2}$ – HMA concrete energy loss coefficient at +10 °C and its kinetic characteristics (at +50 °C and −10 °C) whose recommended permissible values are given in (Petkevičius, Sivilevičius 2000); K_d – HMA concrete density coefficient; CA, FA, MF, B – the content of coarce aggregate more than 2 mm, 0.063 (0.09) – 2 mm fine aggregate, less than 0.063 (0.09) mm mineral filler and bitumen in HMA concrete respectively (mass %).

Specifying the permissible values of physical and mechanical properties of HMA concrete, it is necessary to determine how each of them models the its performance in pavement. When two or more indices model the same property of HMA concrete performance in pavement it is recommended to discard the indices weakly correlated with the HMA pavement condition or operation properties and use only the indices best describing the condition and performance of pavement. The composition and structure of HMA concrete and the materials used for its production not only predetermine its physical and mechanical indices but also the condition of HMA pavement. Homogeneity of composition and structure is a very important quality index of HMA concrete. It is shown (Petkevičius, Sivilevičius 2000; Sivilevičius, Vislavičius 2008) that ensuring proper homogeneity of HMA mixture composition it is possible to ensure the required homogeneity of physical and mechanical indices. Moreover, ensuring the proper values of HMA concrete density coefficient K_d, flexible pavement strength, expressed by strength coefficient K_{st}, and initial roughness of pavement Y_{in} would help to ensure the necessary roughness of HMA pavement and its condition not exceeding the permissible distress level D (when $D \le D_p$) during the whole project time span between repairs.

3. Analysis of the influence components content in hot-mix asphalt on its physical, and mechanical properties

The suitability of HMA for motor road pavement is characterized by its physical and mechanical indices according to Marshall and its compaction level described by K_d. As the rational composition of HMA concrete used for road in Lithuania and ensuring sufficient durability of $T \ge 8.5$ already has been established (Petkevičius, Podagėlis 2000) it is to the purpose to determine rational values for physical and mechanical indices according to Marshall and K_d which would ensure sufficient durability of motor road HMA pavement. For this purpose, the relationship between the content of HMA components (mass %) and physical-mechanical indices according to Marshall and K_d was analysed. Samples of HMA concrete were taken from the Lithuanian motor road pavement service for a sufficiently long time span ($T \ge 8$ years). The samples were taken from the pavements in 10 place on motor roads and 5 samples from each place of very good D = 1–3%, good D = 3–5%, fair D = 5–8%, satisfactory D = 8–12% and critical D = 12–16% quality. During laboratory investigations, the componential composition and the values of physical-mechanical indices and coefficient K_d were determined. Based on the data obtained, the relationships between the indices of componential composition of asphalt concrete, V_a and K_d were determined (Figs 1 and 2).

The double correlation regression relationships also were determined between the indices of componential composition of HMA concrete and other physical and mechanical indices:

– Marshall stability

$$S = 7.32e^{-\frac{(CA-81.35)^2}{2(41.73)^2}}, \quad R^2 = 0.736, \tag{4}$$

$$S = 4.06 + 0.887MF - 0.071MF^2, \quad R^2 = 0.922, \tag{5}$$

$$S = e^{-12.35 + \frac{32.8}{B} + 4.85\ln B}, \quad R^2 = 0.949, \tag{6}$$

$$S = 1.51 + 9.96\frac{B}{MF} - 4.49\left(\frac{B}{MF}\right)^2, \quad R^2 = 0.874; \tag{7}$$

– Marshall flow

$$F = \frac{3.36}{1-8597e^{-0.21CA}}, \; R^2 = 0.637, \tag{8}$$

a) $V_a = \frac{5.08}{1-11656e^{-0.185CA}}$, $R^2 = 0.935$

b) $V_a = 6.67 - 0.121MF - 0.017MF^2$, $R^2 = 0.990$

c) $V_a = \frac{3.72}{1-109786e^{-2.02B}}$, $R^2 = 0.976$

d) $V_a = 10.30 - 3.87\frac{B}{MF} - 1.428\left(\frac{B}{MF}\right)^2$, $R^2 = 0.856$

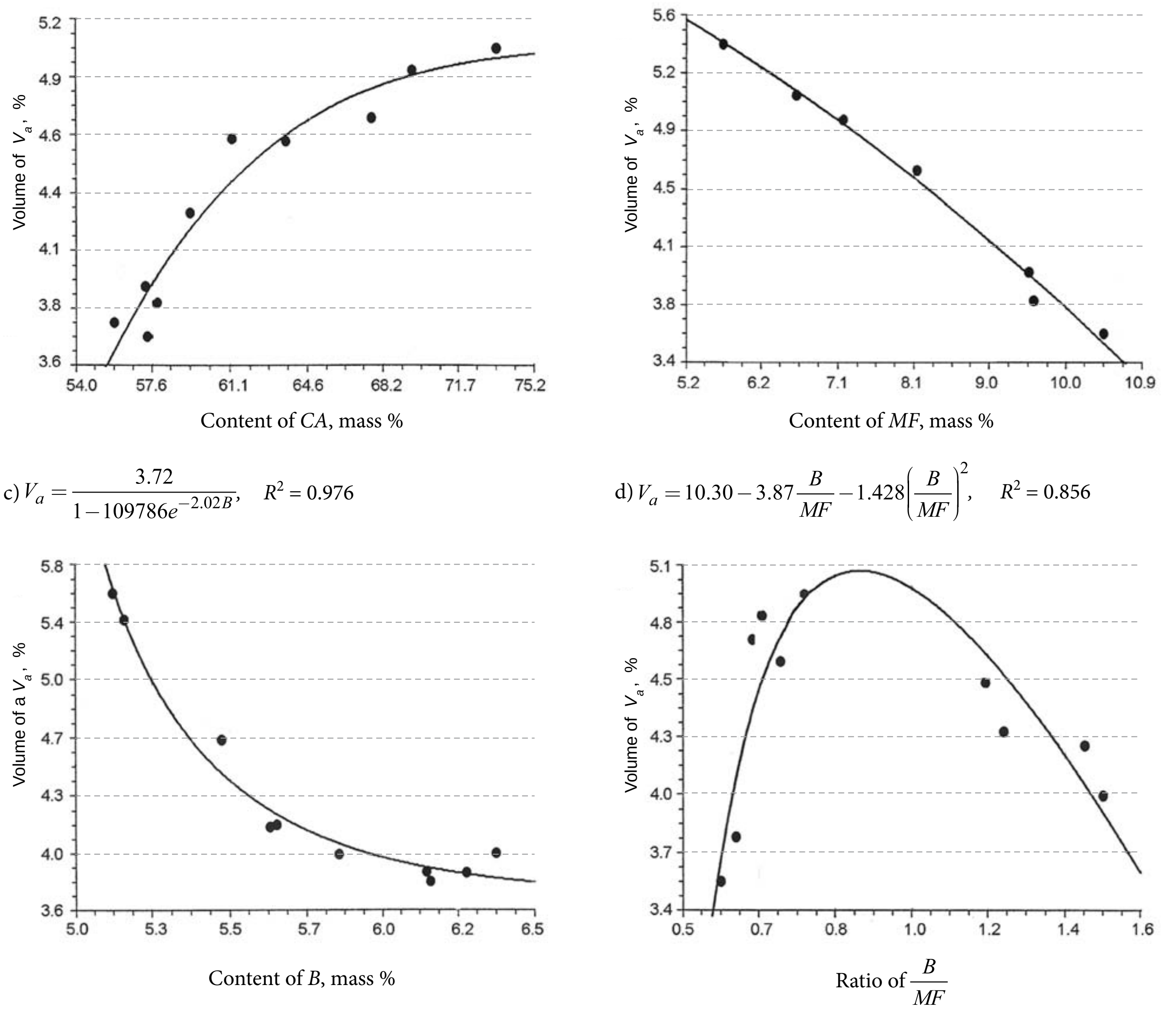

Fig. 1. Relationship between V_a in motor road pavement and content of its components: a – CA; b – MF; c – B, mass %; d – $\frac{B}{MF}$

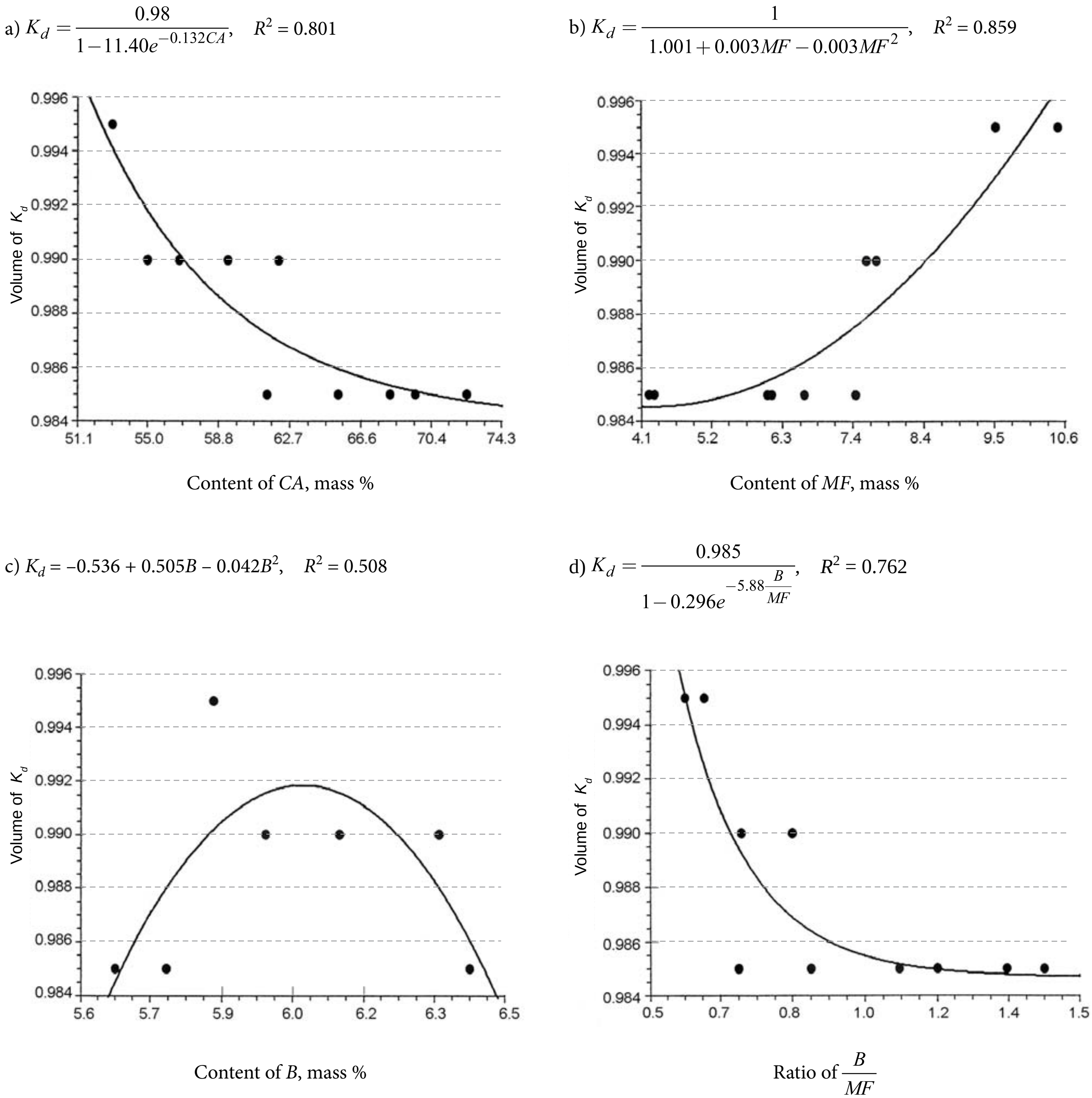

Fig. 2. Relationship between K_d in motor road pavement and contents of its components: a – CA; b – MF; c – B; d – $\frac{B}{MF}$

$$PL = \frac{1}{0.16 + 0.026F - 0.001F^{-0.001}}, \; R^2 = 0.637, \quad (9)$$

$$F = 3.16B^{0.007B}, \quad R^2 = 0.736, \quad (10)$$

$$PL = \frac{1}{0.30 - 0.001F\left(\frac{B}{MF}\right)^{3.79}}, \; R^2 = 0.398. \quad (11)$$

The investigation results served as a basis for determining multiple correlation regression relationships with standardized regression coefficients between the indices of componential composition of HMA concrete and its physical-mechanical indices according to Marshall and density coefficient K_d:

– percent air voids content

$$V_a = 1.826B + 2.37\frac{B}{MF} - 186.58\frac{B}{CA} - 18.84\frac{B}{FA} + 0.334MF + 14.83\frac{MF}{CA} + 0.098CA + 5.58\frac{FA}{CA}, \; R^2 = 0.398; \quad (12)$$

– density coefficient of HMA concrete in wearing course

$$K_d = 0.163B + 0.041\frac{B}{MF} - 11.002\frac{B}{CA} -$$
$$0.365\frac{B}{FA} + 0.064MF - 3.31\frac{MF}{CA} +$$
$$0.013CA + 0.067\frac{FA}{CA}, \quad R^2 = 0.998; \quad (13)$$

– Marshall stability

$$S = 0.283CA + 0.0206MF - 5.14B + 0.71\frac{B}{MF} +$$
$$300.57\frac{B}{CA} - 9.27\frac{MF}{CA} - 12.49\frac{FA}{CA} -$$
$$15.66\frac{B}{FA}, \quad R^2 = 0.994; \quad (14)$$

– Marshall flow

$$P = 0.0257CA + 0.931MF + 1.569B +$$
$$2.096\frac{B}{MF} - 127.78\frac{B}{CA} - 25.59\frac{MF}{CA} +$$
$$6.84\frac{FA}{CA} - 5.19\frac{B}{FA}, \quad R^2 = 0.998. \quad (15)$$

The values of components in the samples taken from motor road pavement ranged within the following limits: CA = 51.5–76.3; FA = 15.0–37.9; MF = 4.2–10.5; B = 3.3–6.6. The values of components CA and FA varied within wider limits than the recommended permissible (Petkevičius, Sivilevičius 2000; Petkevičius, Podagėlis 2000), MF (in 83.7% of cases) varied beyond the recommended permissible limits and B (in 68.6% of cases) also varied beyond the permissible limits without reaching the highest permissible value and considerably exceeding the smallest permissible value (2.25 mass %). In (Petkevičius, Sivilevičius 2000) it is shown that the greatest durability under cyclic loads until disintegration is characteristic of HMA concrete of the following composition: CA = 64.3 mass, %; FA = 23.8 mass %; MF = 11.9 mass %; B = 6.8 mass %; in (Подагель 1987) it is shown that the highest values of resistance to binding tension $R_b^{(a)}$ and the highest fatigue resistance are ensured by HMA concrete of the following componential composition: CA = 56.5–71.5 mass %; FA = 16.0–34.0 mass %; MF = 9.5–13.5 mass %; B = 6.0–7.0 mass %. In (Petkevičius, Sivilevičius 2000) – MF = 9.5–13.5 mass %; B = 6.5–8.5 mass % – the rational values of physical and mechanical indices are given which ensure the highest fatigue resistance of HMA concrete of best componential composition. HMA concrete of this composition ensured high quality of HMA concrete pavement after not less than 8 years ($T \geq 8$ years). Its distress level was D = 1–3%). The rational values of the physical and mechanical indices of HMA concrete in the Lithuanian motor road pavement (top layer) and K_d are given in Table 1.

Table 1. Rational values of the quality indices of the top layer of motor road HMA pavement

Asphalt concrete quality indices and measuring unit	Rational values of quality indices
Stability S, kN	≥ 7.0
Flow F, mm	2.5–4.0
Air voids content V_a, volume %	1.5–3.5
Density coefficient K_d	≥ 0.99

The given rational values were determined after analysis of relationships given in Figs 1 and 2 and Eqs (4)–(15). The rational values of HMA concrete indices during HMA mixture production and pavement construction given in Table 1 would ensure the highest fatigue resistance of HMA concrete and its fairly long durability till the repair T: $T \geq 8$ years.

4. Conclusions

Results reported by different authors and the data obtained during our investigations show that the longest durability under the conditions of increasing flows of heavy vehicles was characteristic of HMA concrete with componential composition very close to the composition of fatigue resistant HMA concrete. This composition of HMA concrete is ration for Lithuanian main roads.

HMA mixtures is commonly used for construction of asphalt pavement in Lithuania. The resistance of HMA pavements constructed of HMA concrete to various kinds of defects (cracks, chippings, potholes, plastic residual deformations etc.) is well modelled by physical and mechanical indices of HMA mixtures and HMA concrete in pavements according to Marshall and K_d.

Analysis of the quality of HMA concrete pavement which servise for a sufficiently long time span ($T \geq 8$ years), its physical mechanical properties and K_d served as a basis for establishing the rational values of quality indices according to Marshall and K_d ensuring a very good quality and durability of HMA pavement with distress level D ≤ 3%.

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