STRUCTURAL DESIGN OF CONCRETE BLOCK PAVEMENT STRUCTURES FOR POLISH CONDITIONS

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This paper presents structural design of typical concrete block pavement structures for roads and streets, for Polish conditions. The design was based on mechanistic principles. The deformation (rutting) of the pavement was considered as the principal mode of concrete block pavement distress. For pavements with granular unbound bases the subgrade strain criterion was applied. For pavements with cement bound bases two criteria were applied: the fatigue cracking criterion for the cement bound base, and the subgrade strain criterion for the analysis of pavement deformation. Sensitivity of pavement behaviour to variations of effective modulus of elasticity of the concrete block layer was studied. The following types of base courses were included in the design: natural aggregate, crushed aggregate, cement stabilized aggregate, and lean concrete. Classifications of subgrades, traffic categories and frost resistance criteria were adopted from the existing Polish catalogue of flexible pavements.

1. INTRODUCTION

There is a need for typical Concrete Block Pavements structures (abbreviated in this paper as CBP) in Poland. It is due to rapidly increasing use of such pavements and lack of a method of their design. The catalogue of typical bituminous pavements for roads has been used in Poland since 1977 [1]. The proposal of a catalogue of typical CBP for roads and streets was worked out by the authors of this paper in 1994. The catalogue has not undergone an official acceptance procedure by the road administration, but is used locally, especially in Gdansk region. The proposed structure of this catalogue follows the system which had been applied in the existing catalogue of road bituminous pavements. It includes subgrade classification, traffic classification, strengthening of weaker subgrades, and prevention of damages caused by frost.

There is no method available for design CBPs in Poland. Mechanistic methods of pavement analysis were selected to design CBPs due to more general nature as compared with empirical methods, and possibility of adaptation to local conditions.

Two modes of failure were considered: cracking of cement bound bases and rutting of the pavement. Important issues in the mechanistic design of CPB pavements are the assumption of moduli of elasticity of pavement layers and appropriate fatigue criteria. Sensitivity analysis was performed to study the influence of variation of the modulus of concrete block layer on pavement behaviour. Comparison of fatigue criteria was carried out to select suitable criteria for Polish condition.

2. PRINCIPLES OF DESIGN

2.1. Pavement model

The pavement was modelled as a multi - layer structure, as presented in Fig. 1. It was assumed that each layer, including concrete blocks, is homogeneous, elastic and isotropic and is characterized by E - modulus of elasticity and ν - Poisson's ratio.

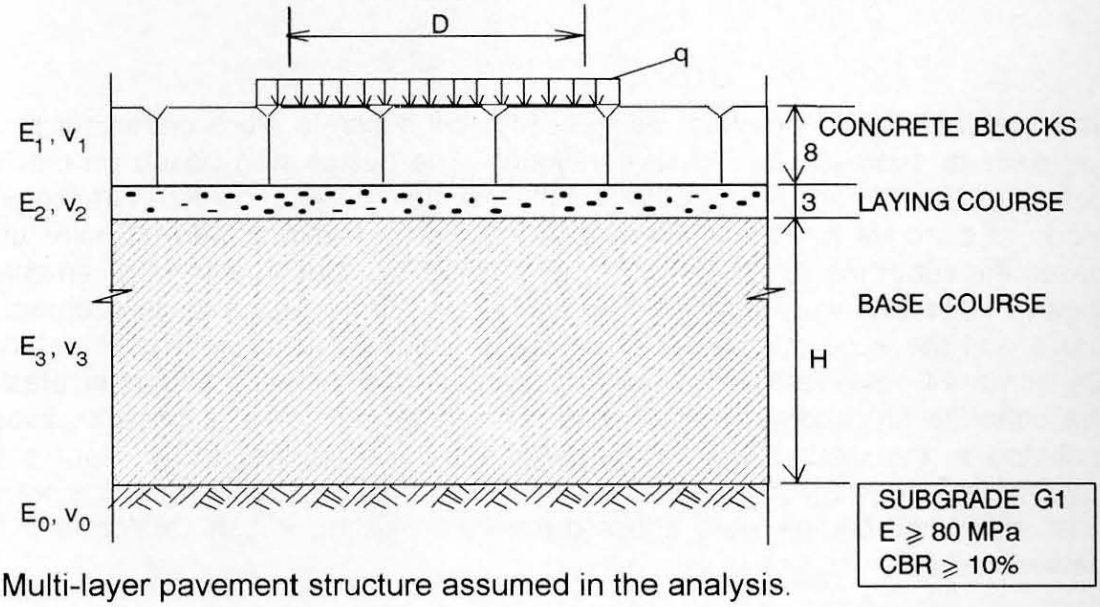


Fig. 1 Multi-layer pavement structure assumed in the analysis.

Typical CBP structures were designed assuming that they are placed on a good quality subgrade, characterized by CBR not less than 10%, and E - modulus not less than 80 MPa. If subgrade is weaker additional subbase layers are designed (see chapter 5).

Under such assumption the model of the CBP structures consists of four layers, including concrete blocks 80 mm thick, sand-cement laying course 30 mm thick, base course and subgrade. In contrast to some other design methods, the sand/cement laying course was treated as a separate layer of low E - modulus, equal to 200 MPa. It was believed that this assumption leads to more realistic computation of stress and strain distribution in the pavement structure, especially at the top of base course.

2.2. Traffic

The traffic load was classified, in the same way as in the Polish catalogue of typical bituminous pavements for roads [1], as shown in Table 1. The CBPs were designed only for three lower categories of traffic, designated as R2, R3 and R4. The design

of CBPs for heavy and very heavy traffic was left open, as till now there is no experience in their construction in Poland. In addition, a heavy duty CBP for bus stops on urban streets was designed to meet urgent current needs.

Table 1. Traffic classification

Traffic designation	Category	Number of 100 kN axle load applications per day per traffic lane	Number of 100 kN axle load applications during 20-year design life
R2	Light	< 12	< 88 000
R3	Light - medium	13 - 24	88 000 - 175 000
R4	Medium	25 - 70	175 000 - 510 000
R5	Heavy	71 - 335	510 000 - 2 450 000
R6	Very heavy	> 335	> 2 450 000

The design axle load was equal to 100 kN. The wheel load was applied to the pavement structure on a single circular contact area, 32.5 cm in diameter, with unit pressure 650 kPa. The design life of the pavement was assumed to be 20 years.

2.3. Subgrade

Subgrade soil was classified into four groups of bearing capacity, in the same way as in the Polish catalogue of typical bituminous pavements for roads [1], as shown in Table 2. If the CBR value is not available, the subgrade can be classified according to the Polish standard soil classification system and water conditions [1]. Typical structures were designed for subgrade G1. For weaker subgrades, G2, G3 and G4, additional subbase courses made of soil stabilized with hydraulic binders were designed, as described in chapter 5.

Table 2. Subgrade soil classification

Group of bearing capacity	CBR [%]
G1	≥ 10
G2	5 - 10
G3	3 - 5
G4	< 3

2.4. Bases

The following bases were included: natural aggregate, crushed aggregate, cement stablilized aggregate, lean concrete and a high quality cement concrete base for heavily loaded bus stops only.

2.5. Fatigue criteria

Permanent deformations, especially rutting of CBP was considered as the principal mode of their distress. To control the rutting the subgrade strain criterion was applied. For pavements with cement bound bases two criteria were applied: the subgrade strain criterion, and additinally the fatigue cracking criterion for cement bound bases.

A comparative study was carried out to select appropriate fatigue criteria (JUDYCKI [2]). The study resulted in selection of The Asphalt Institute subgrade strain criterion [3] and the University of Illinois fatigue criterion for cracking of cement bound bases (DEMPSEY [4]).

The Asphalt Institute subgrade strain criterion is:

$$\varepsilon_s = 0.0105 \, (1 / N_f)^{0.223} \qquad (1)$$

where: ε_s - subgrade strain,
N - number of load applications until occurrence of ruts of critical depth.

The critical rut depth in The Asphalt Institute method for asphalt pavements was assumed to be 12.5 mm. There is no evidence that this assumption is true for CBPs. Therefore, although equation (1) was used by the authors the critical value of rut depth of CBPs was not defined.

The University of Illinois criterion for cracking of cement bound bases is:

$$\log N_f = 11.784 - 12.121 \, (\sigma / \sigma_{crit})$$

where: σ - maximum tensile stress induced in cement bound base by standard axle load.
σ_{crit} - flexural strength at static single loading of base material specimens.

2.6. Design

Pavements with granular bases were designed to prevent occurrence of critical deformations (ruttings) during assumed design life.

Pavements with cement bound bases were analysed in two stages. The first stage lasts from the road opening to occurrence of fatigue cracking of cement bound base. The second stage lasts from occurrence of cracking of the base to occurrence of critical rutting on the pavement surface. Moduli of elasticity of cement bound base course in the pre-cracked and post-cracked states differ significantly. After cracking cement bound base course works in blocks and its modulus significantly decreases. The Miner hypothesis of accumulated damage was used to calculate the total fatigue life of the pavement.

As thicknesses of concrete blocks (80 mm) and laying course (30 mm) were predetermined, the aim of the design was to establish appropriate thickness of the base course in relation to traffic load, base material used and its specified properties.

3. MATERIAL ELASTIC PROPERTIES FOR DESIGN

3.1. Concrete block layer

It was assumed that CBP for roads and streets will be constructed with use of 80 mm concrete blocks. It is rather common practice in Poland. Thinner concrete blocks (60 mm) are used only for sidewalks and bicycle lanes. Thicker blocks (100 mm) are used in small quantities in some regions of Poland.

Modelling of the wearing course made of concrete blocks as a homogeneous, isotropic and elastic layer is a distinct simplification. However, for the time being it has to be accepted due to lack of more exact engineering solutions. The values of effective modulus of elasticity E_1 of this layer suggested in several references [5,6,7,8] are within the range of 300 - 5 000 MPa, but some results of testing are as high as 12 500 MPa (ROLLINGS et al [8]). It was proven that after construction the E_1 - modulus is relatively low but increases under initial traffic and thermal action due to interlocking of blocks (SHACKEL [8]).

The effect of variation of E_1 - modulus of concrete block layer on CBPs behaviour was studied. The E_1 - modulus was assumed to be in the range from 300 to 10 000 MPa. The subgrade soil modulus was assumed at two levels 60 and 100 MPa. Firstly, thicknesses of granular (crushed stone) and cement stabilized base courses were calculated for medium traffic (see Table 1) for varying input data. Secondly, it was assumed that the thickness of the base course is equal to 35 cm and stresses and strains within the pavements, under 50 kN wheel load acting on 32.5 cm circular area, were calculated. Some results are presented in Fig. 2. The results of sensitivity analysis of CBPs on variation of E_1- modulus are presented in Table 3.

Table 3. Results of sensitivity analysis of concrete block pavements to variation in modulus of the concrete block layer

Analyzed value	Effect of increase of modulus of CB layer from 300 to 3 000 MPa		Effect of increase of modulus of CB layer from 1 000 to 3 000 MPa		Effect of increase of subgrade modulus from 60 to 100 MPa	
	GB	CSB	GB	CSB	GB	CSB
Decrease of thickness of base required for medium traffic, %	**14**	**11**	**8**	**7**	**16**	**12**
Decrease of vertical strain on the top of subgrade, %	**20**	**10**	**11**	**7**	**22**	**16**
Decrease of vertical stress on the top of subgrade, %	**22**	**11**	**12**	**7**	**-30 increase**	**-40 increase**
Decrease of vertical stress on the top of base, %	**33**	**20**	**23**	**16**	**±0**	**±0**
Decrease of tensile stress in cement stabilized base, %	-	**8**	-	**6**	-	**10**

Note: GB - Granular base (crushed stone); CSB - Cement Stabilized Base

The results of the analysis indicated that the CBP with cement stabilized base is less sensitive to changes of the modulus of concrete block layer and to changes of the modulus of subgrade than the CBP with granular base. It should be noted that the variations in E_1 - modulus of concrete block layer from 1 000 to 3 000 MPa have less effects on both types of pavements than the change of subgrade modulus from 60 to 100 MPa. The effect of variations in E_1 from 300 MPa to 3 000 MPa is more significant, especially in case of granular bases. It was found that vertical stresses acting on the base course are rather high, up to 580 kPa. It could cause rutting in the lower quality granular base. Vertical stresses and strains acting on subgrade soil are high in case of granular bases and may cause rutting in the subgrade. They are from 2.5 to 3.5 times lower in case of cement stabilized bases. Therefore, the conclusion

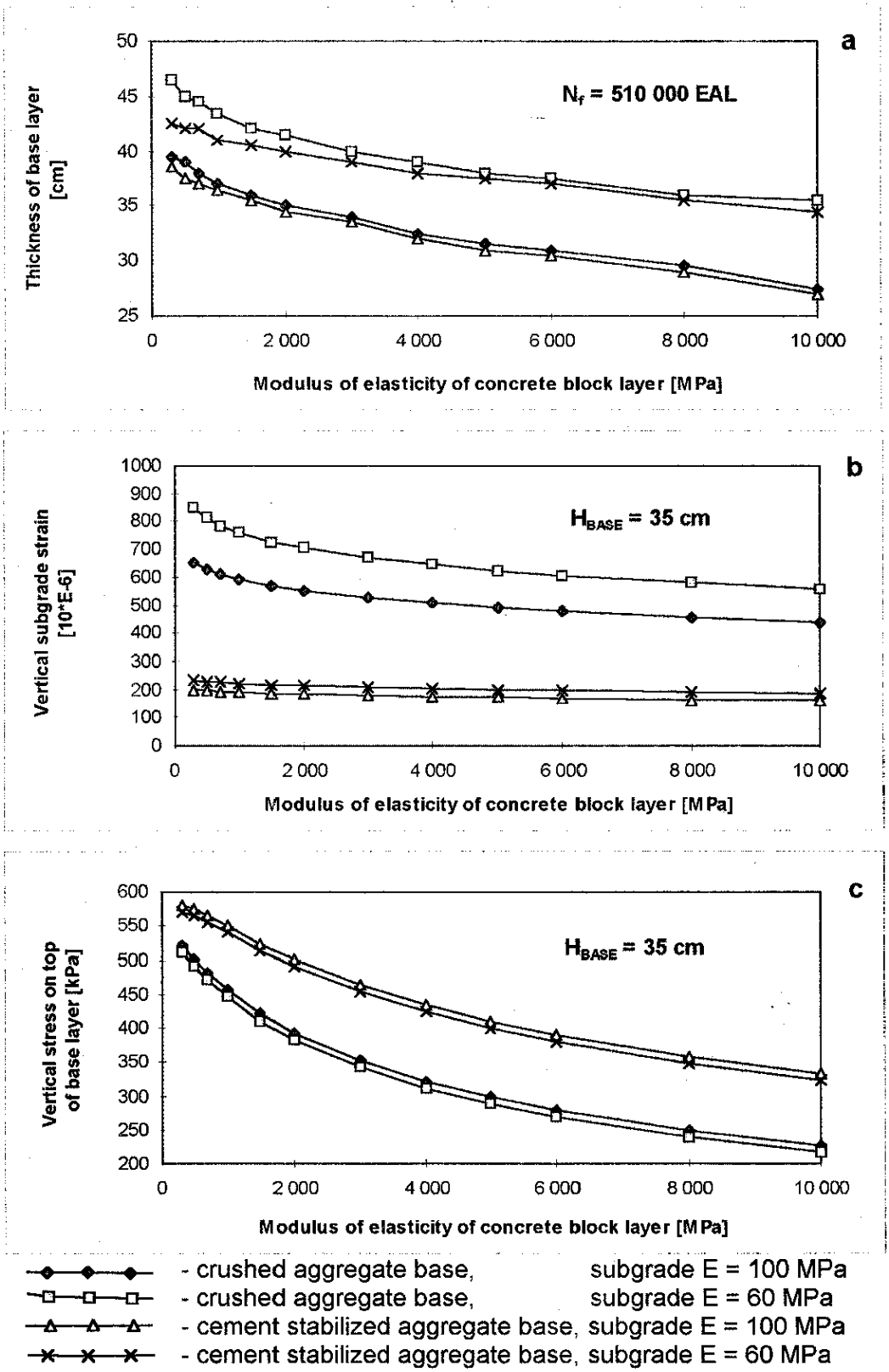


Fig 2. Influence of modulus of elasticity of concrete block layer on: (a) thickness of base layer for medium traffic R3, (b) vertical subgrade strain, (c) vertical stress on top of base layer, for different subgrade conditions.

can be drawn that granular unbound bases, especially made of natural aggregate, shall be limited to roads and streets carrying low traffic. Cement bound bases provide greater resistance to rutting and can be economically attractive, as lower quality aggregate can be effectively improved with cement.

As a result of both, literature study and sensitivity analysis of pavements, the following elastic properties were assumed by the authors for the concrete block layer: E_1 = 3 000 MPa and ν = 0.3.

More general finding from the analysis is related to vertical stress distribution in the pavement. It was found that the greater vertical stresses are imposed by wheel load on stronger layers and vice versa, all other factors being constant. If modulus of subgrade decreases from 100 to 60 MPa vertical stresses decrease by 30-40%. Vertical stresses imposed on the granular base are from 10 to 30% lower than on the cement stabilized base.

3.2. Laying course

For the laying course, made of cement-sand mixture, the value of the modulus of elasticity E = 200 MPa and the Poisson's ratio ν = 0,2 were assumed. In the mechanistic analyses the layer was not combined with the concrete block layer, but assumed as a seperate one.

3.3. Granular base course

Grading of granular bases - both natural and crushed - is designed according to specified grading requirements. For the granular base courses the following values of the modulus of elasticity were assumed:

- natural aggregate E = 200 MPa,
- crushed aggregate E = 300 MPa.

The Poisson's ratio ν = 0,3 was assumed for both natural and crushed aggregate base layers.

3.4. Cement bound base

The material properties assumed for the cement bound base are given in Table 4. Cement concrete B25 was assumed as the base for a heavy duty pavement for bus stops on urban streets.

Table 4. Mechanical properties of cement bound base layers

Base material	Compressive strength after 28 days -R_c [MPa]	Before cracking of the base layer		After cracking of the base layer	
		E [MPa]	ν	E [MPa]	ν
Cement-stabilized aggregate	2,5 - 5,0	4 500	0,2	300	0,3
Lean concrete	6,0 - 9,0	13 000	0,2	400	0,3
Cement concrete B25	25,0	30 000	0,16	Assumed that cracking will not occur	

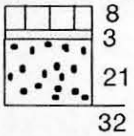
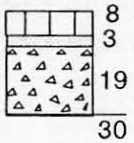
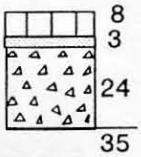
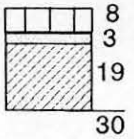
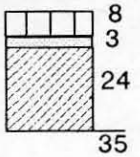
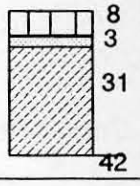
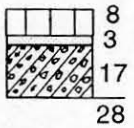
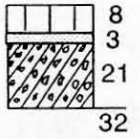
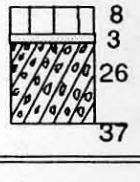
3.5. Subgrade

For the G1 subgrade the value of the modulus of elasticity E = 80 MPa and the Poisson's ratio ν = 0,3 were assumed.

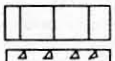
4. DESIGNED PAVEMENT STRUCTURES

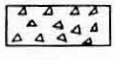
The pavement structures designed as a result of mechanistic analysis for three traffic categories - R2, R3 and R4 are given in Table 5. It was decided that use of unbound aggregate base layers should be limited to traffic category R2 (natural aggregate) and categoriies R2 and R3 (crushed aggregate) only, in order to prevent rutting of CBP.

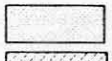
Table 5 Pavement structures for G1 subgrade

Traffic designation	**Light R2**	**Light - medium R3**	**Medium R4**
Number of 100 kN EAL applications per day per traffic lane	< 12	13 - 24	25 - 70
Natural aggregate base			
Crushed aggregate base			
Cement stabilized base R_c = 2.5 ÷ 5 MPa			
Lean concrete base R_c = 6 ÷ 9 MPa			

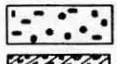
Note: Thicknesses given in cm.

 concrete blocks

 crushed aggregate base

 laying course

 cement stabilized base

 natural aggregate base

 lean concrete base

The pavement designed for bus stops on urban streets has the following structure:

- concrete block layer 8 cm,
- laying course (sand-cement) 3 cm,
- base of B25 cement concrete 25 cm,
- cement stabilized aggregate R_c = 5 MPa 15 cm.

5. DESIGN FOR WEAKER SUBGRADES AND FROST EFFECTS

The pavement structures given in Table 5 were designed with an assumption that the subgrade conditions are good, with modulus of elasticity at least 80 MPa. In case of weaker subgrades - G2, G3 and G4 (see Table 2), typical strenghtening procedures, as specified in the Polish catalogue for bituminous pavements [1] were adopted. The following additional subbase courses were added for subgrades of lower bearing capacity:

- Subgrade G2 - 10 cm soil stabilization with a hydraulic binder, compressive strength after 28 days 0,5 - 1,5 MPa,
- Subgrade G3 - 15 cm soil stabilization with a hydraulic binder, compressive strength after 28 days 1,5 - 2,5 MPa,
- Subgrade G4 - 25 cm soil stabilization with a hydraulic binder, compressive strength after 28 days 1,5 - 2,5 MPa, or alternatively two 15 cm layers - the upper with compressive strength after 28 days 1,5 - 2,5 MPa, the lower 0,5 - 1,5 MPa.

Regardless the designing of the pavement for the required bearing capacity the pavement structures in Polish conditions have to be designed to be frost resistant. The authors assumed that the frost resistance of the CBP pavements will be checked according to the standard Polish procedure [1]. The total thickness of the pavement H must be not less than the required minimum value H_{req}, which is given as a percent of the depth of frost penetration for the area. H_{req} can be from 40% to 80 % of the depth of frost penetration depending on subgrade conditions and traffic category.

6. SPECIFICATIONS FOR MATERIALS

Assumed durability of the pavement structures will be achieved only when the assumptions and requirements concerning material properties and the quality of works are achieved. The basic requirements, which were formulated include (where applicable): grading of the aggregate, abrasion, compressive strength, soaking, frost resistance, compaction requirements and several other engineering properties.

These requirements are given in detail in [9] and usually follow General Specifications for Highway Works and Polish Standards.

7. FINAL REMARKS

Pavement structures proposed by the authors have been constructed in Gdansk region since 1994. Out of several possible CBPs given in Table 5 the most popular are structures with cement bound bases i.e. cement stabilized aggregate or lean concrete. In general, such bases are economically atractive due to lack of rock deposits and crushed aggregate in northern Poland and they are most often used for

asphalt pavements in this part of the country. The main disadvantage of cement bound bases in case of asphalt pavements - reflective crackings, is not important in case of concrete block pavements. Taking into account better resistance of CBPs on cement bond bases to rutting and their economical advantages the authors are inclined to the opinion that the natural aggregate base for light traffic, as given in Table 5, could be much improved by stabilization with small addition of cement (2 - 3% by weight).

REFERENCES

1. Instytut Badawczy Dróg i Mostów "Katalog typowych konstrukcji jezdni podatnych", ("Catalogue of Typical Structures of Flexible Pavements"), 2nd edn, Warsaw, 1983.
2. Judycki, J. "Comparison of fatigue criteria for flexible and semi-rigid pavements", Annual Meeting of European Flexible Pavement Study Group, Gdansk, Poland, September, 1995.
3. The Asphalt Institute, "Research and Development of The Asphalt Institute Thickness Design Manual (MS-1)", 9th edn, Maryland, USA, 1982.
4. Dempsey, B.J. et al. "Development of a Preliminary ALRS Stabilized Material Pavement (SPAS)", Department of Civil Engineering, University of Illinois, Urbana, Report ESL-TR-83-34, Engineering and Service Laboratory, Air Force Engineering and Service Center, Tyndall Air Force Base, Florida, 1984.
5. Kuipers, G. "The Effect of Concrete Block Lock-up on Pavement Performance", Proceedings of the Fourth International Conference on Concrete Block Paving, Pave New Zealand '92, University of Auckland, New Zealand, February 1992, pp. 51 - 60.
6. Rada, G.R., Smith, D.R., Miller, J.S., Witczak, M.W., Structural Design of Interlocking Concrete Pavements in America, Proceedings of the Fourth International Conference on Concrete Block Paving, Pave New Zealand '92, University of Auckland, New Zealand, February 1992, pp. 99 - 116.
7. Rollings, R.S., Rollings, M.P., Sharp K.G. "Evaluation of Thickness Design Concepts for Block Pavements", Proceedings of the Fourth International Conference on Concrete Block Paving, Pave New Zealand '92; University of Auckland, New Zealand, February 1992, pp. 61 - 70.
8. Shackel, B. "Computer Based Procedures for the Design and Specifications of Concrete Block Pavements", Proceedings of the Fourth International Conference on Concrete Block Paving, Pave New Zealand '92, University of Auckland, New Zealand, February 1992, pp. 79 - 87.
9. Judycki J., Alenowicz J., Cyske W., "Katalog typowych konstrukcji nawierzchni z warstwą ścieralną z kostki betonowej." ("Catalogue of typical pavement structures with wearing course made of concrete blocks."), Gdańsk 1994, unpublished (in Polish).