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DESIGN SOLUTIONS FOR PAVEMENTS STRUCTURE AFFECTED BY STATIC AND IMPACT LOAD

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Abstract. Pavements of aprons, container and logistic terminals, areas of storage, parking lots, areas of waste utilization are affected by high pressure static and impact loads. These loads strongly influence pavement performance by causing permanent deformations and distresses in the surface and even sometimes pavement failure in the beginning of pavement service. The types of structure, materials and layer thicknesses are the main factors relative to pavement performance. In order to correctly understand the particularity of static and impact loading, distresses of pavement structures affected by such load are emphasized, the load specification and climatic conditions influencing pavement performance are characterized. After analysis of the best practise, the flow chart of pavement structure design model was introduced. The paper gives reasonable pavement type and thickness determination dependent on object of application pavement structure.

Keywords: static loading, impact loading, pavement distress, pavement structure, design model.

1. Introduction

There are many methods, procedures and guides for pavement structure design of roads or streets where usually a moving heavy vehicle traffic load is considered. Asphalt Institute, Lithuanian Road Administration under the Ministry of Transport and Communications, Directorate General Transport of European Commission and other institutes responsible for road sections have an attitude that designed pavement is the one in which there is no structural deterioration over the time of design. Mostly pavements are designed for 20 years according to equivalent single axle load which is accepted as 8 t, 10 t, 11.5 t or other depending on dominating traffic loads. However, pavement design procedures for roads cannot be applied for others special objects such as parking aprons of aircrafts, ports and container terminals, logistics terminals, industrial areas, parking lots, waste recycling areas and etc., where different types of loading – static and impact loads – affect pavements.

Researchers describe wheel load as static, quasi-static or dynamic. A static load represents a constant load, which is defined by geometry of contact and mass of the load. A quasi-static load – a moving constant load, which is defined by stiffness and mass of the load without damping force in the equation of equilibrium. And a dynamic load – a changeable moving load, which involves inertia, damping, stiffness and mass terms in the equation of motion (Woodrooffe, LeBlanc 1988; Yoo, Al-Qadi 2007). From experience it is observed that falling object or special machinery induce impact loads. Impact load represents a force of potential energy, which is defined by multiplying object weight, drop height and acceleration of gravity. These kinds of loading produce many distresses in pavements of special objects.

Consequently, it is very important to design a stable pavement, i.e. pavement structure resistant to static and impact load. In other countries this kind of pavements are designed by using special design charts, guides, manuals and computer programs. However, Lithuania has no solution for the design of such pavements (only design of road (street) pavements is regulated). Contribution to this is a lack of information about influence of different loading type on pavement structure and its performance. The aim of this article is to study types of pavement distresses, to analyze load specification and influence of climatic conditions on pavement performance, to suggest a design model for pavements affected by static and impact load and to review design solutions of foreign countries using this kind of pavements.

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2. Distresses of pavement structures affected by static and impact load

In general, pavement degradation is a function of pavement roughness, which is a sum of all types of distresses and increases with pavement age (Fwa *et al.* 2012; Mogawer *et al.* 2011; Žiliūtė *et al.* 2008). The type of pavement distress depends on the pavement structure and materials properties.

Due to easy construction and rehabilitation flexible pavements are the most common type of pavement structure used in Lithuania and in other countries. However, flexible pavement design life is shorter than of rigid pavements and usually after 20 year of service needs full rehabilitation. Pavement distresses are classified as: surface defects (raveling, bleeding and polishing), surface deformations (rutting, shoving, corrugation, bumps, heaves, settlements and blow ups (curling)), cracks (fatigue, thermal, longitudinal and slippage) and potholes. Though, in the asphalt pavements the most common distresses are fatigue cracking, rutting (permanent deformations) and thermal cracking, meanwhile in pavements affected by static and impact load – permanent deformations and thermal cracking.

Permanent deformations are associated with viscous-elastic-plastic properties of asphalt and variance of ambient temperature (Ferne 2006; Kim *et al.* 1993; Wasage *et al.* 2010). According to Highway Development and Management (HDM–4) volume 6: *Modelling Road Deterioration and Works Effects* and National Cooperative Highway Research Program Report No. 1–37A: *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures* four types of permanent deformation occurs in asphalt pavement: surface rutting, initial densification, structural deformations and plastic (flow) deformations (rutting). The last type of permanent deformation develops due to decrement of bitumen binder properties at high temperatures (to +60 °C and more) resulting in relaxation of asphalt mixture strength (Vaitkus, Paliukaitė 2013). Examples of permanent deformation observed in pavements of special objects are shown in Fig. 1. In most cases (as the bearing capacity of whole pavement structure is sufficient) this kind of deformation develops in surface (wearing) layer of asphalt pavement and is directly dependent on the properties of it (Žiliūtė, Laurinavičius 2013).

Thermal cracking is divided into low-temperature cracking and thermal fatigue cracking. Low temperature cracking is primarily associated with fast temperature decrement (below –16 °C to –35 °C) at the surface of asphalt layer. Due to low temperature the binder film gets thinner around aggregates. When the temperature drops below the point where asphalt binder becomes brittle, low-temperature crack is initiated in the surface of asphalt pavement and immediately grows. Meanwhile, thermal fatigue cracking occurs due to accumulation of thermal stress induced by daily temperature cycling (Boutin, Lupien 2000; Doré, Zubeck 2009; Isacsson, Zeng 1998).

3. Load specification and climatic conditions

The static and impact load is usually induced by aircrafts, containers, handling equipment (rubber tire gantry cranes (RTGs), straddle carriers, reach stackers, front lift trucks, side loader lift trucks and etc.), storage goods, trucks, cars

Fig. 1. Examples of permanent deformation observe in pavements of special objects

and/or falling stuff. In areas where is considerable expectation of this kind of loading, the magnitude of loads and loading time is higher comparing with traffic loads. Moreover, loads are concentrated and affect pavement within small contact area. Consequently, it causes high pressure in the pavement. If the source of load is stackable, contact pressure strongly depends on the height of stacking. Table 1 gives contact pressure considering characteristics of the load source. It is emphasized that contact pressure to pavements affected by static and impact load is significantly higher comparing with contact pressure induced in roads pavements.

On purpose to simplify calculations a tire-pavement contact area is assumed as a circle area equals to ellipse's (rectangle) area. The research on *Effects of Wide Single Tyres and Dual Tyres* (2001) implemented by European Cooperation in the Field of Scientific and Technical Research showed that contact area changes by increasing/decreasing magnitude of load and/or by changing inflation pressure. However, common the tire-pavement contact pressure is assumed equal to inflation pressure.

Impact load is characterized by drop height and/or weight of falling object. As these characteristics increase, the negative effect of this kind of load on pavement performance increases, too.

In design process of special objects attention is paid to different loading, i.e. static (containers, standing equipment, storage goods and etc.) and slow dynamic loading (handling equipment's movements, cornering, accelerating and braking). Mostly, slow dynamic loading is assessed by applying a load multiplication factor.

Climatic conditions such as temperature, moisture, frost and number of freeze-thaw cycles strongly influence pavement performance and its service. Climatic conditions in Lithuania are similar to other countries of the cold regions. The surface temperature of asphalt pavement varies from –22 °C to +53 °C (Vaitkus *et al.* 2012). Moreover, the number of freezing/thawing cycles of pavement surface exceeds 80 times and more during a year (Laurinavičius, Juknevičiūtė-Žilinskienė 2011). Consequently, pavement structure is designed evaluating resistance to frost heave.

It is well known, that moisture influences the behavior of unbound layers, while temperature – the stiffness (elastic modulus) of bituminous layers and thermal stresses in cement layers. Pavement failures (distresses) related to high moisture content in unbound layers is common phenomenon in cold region pavements (Motiejūnas *et al.* 2010; Saevarsdottir, Erlingsson 2013; Simonsen, Isacsson 1999). Increasing water content causes more permanent deformations in unbound layers (Simonsen, Isacsson 1999). Moisture content and pavement stiffness depend on season, because pore water crystallizes into ice lenses during cold season conditioning increase of stiffness of unbound layers (Motiejūnas *et al.* 2010; Simonsen, Isacsson 1999). The negative influence of moisture and frost on pavement structure performance is solved by ensuring sufficient drainage and thickness of the whole pavement structure, respectively.

Variations of temperature affect the viscous-elastic-plastic properties of asphalt pavement. The elastic modulus decreases as the temperature increases and increases as the temperature decreases (Motiejūnas *et al.* 2010). In

Table 1. Contact pressure considering characteristics of load source[a)]

Object (load source)	Contact area, mm^2	Maximum high of stacking	Contact pressure, MPa
Aircraft	[b)]	–	0.3–1.7[c)]
Reach stacker, stacker	[b)]	–	0.7–1.7
Ship–to Shore	[b)]	–	1.9–5.2
Mobile Harbor Crane	[b)]	–	0.1–0.3
	4400 000–9900 000[d)]	–	0.01–0.02
Rubber Tired Gantry	[b)]	–	0.7–2.3
Container	22 000[e)]	6–8 (12)[f)]	2.6–12.5[g)]
Heavy vehicle	[b)]	–	0.6–1.0
Trailer dolly (wheel)	8800	–	35–40
Trailer pivot plate	33 750	–	2.0
Handling equipment of industrial areas	[b)]	–	0.5–1.0
EuroPallet	120 000[h)]	2–4[i)]	0.01–0.03[j)]
Car	[b)]	–	0.20–0.25

Notes: [a)] – sources of impact load are not included into the table due to their large variety; [b)] – the leg of load source is wheel. Contact area of tire-pavement depends on characteristics of tire; [c)] – contact pressure depends on type of aircraft; [d)] – the legs of Mobile Harbor Crane are wheels and pads. Contact area of pad depends on total weight of crane; [e)] – it is useful area of container casting (taking into the central hollow). In design process the contact area is assumed as 28 836 mm^2; [f)] – fully loaded containers are usually stacked up to 6 high and empty containers – 8 high. In some cases containers are stacked up to 12 high; [g)] – when only 1 container is on the pavement the contact pressure is 2.59 MPa, when containers are stacked up to 8 high – 12.5 MPa; [h)] – contact area of EuroPallet consists of three rectangles: the outside rectangles are at 100×1200 mm, the central rectangle is 145×1200 mm; [i)] – EuroPallets are usually stacked up to 2 high for transportation and up to 4 high for storage; [j)] – when only 1 EuroPallet with goods is on the pavement the contact pressure (contact area is 120 000 mm^2) is from 0.01 MPa depending on the weight of goods, when EuroPallets with goods are stacked up to 4 high – by 0.03 MPa depending on the weight of goods.

design process, it is assessed by including the non-linear asphalt behavior.

In rigid pavements, daily temperature variations cause curling of the slab: the slab blows up (expansion of the pavement surface) when the top of the slab is warmer than the bottom of the slab (daytime) and the slab blows down (contraction of the pavement surface) when the top of the slab is cooler than the bottom of the slab (nighttime). Furthermore, the temperature variations initiate thermal stresses in the slab, which must be estimated in the process of pavement design (Westergaard 1926).

4. Pavement structure design model

All types of pavement structure are used for areas affected by static and impact load. According to the layers of pavement structure and mechanical performance of materials the pavement structures are:

- flexible – asphalt layer(s) or stone/concrete blocks on unbound granular base or asphalt base layer;
- rigid – concrete layer(s) or stone/concrete blocks on bound granular base or asphalt base layer or concrete layer;
- composite – semi-rigid/semi-flexible – ultra-thin concrete layer or concrete paving flags on flexible pavement structure, asphalt layer(s) on concrete pavement, porous asphalt with cement grout on flexible pavement structure.

The practice of foreign countries has shown that traditionally pavements of special objects have been design using design charts. According to them the whole thickness of pavement structure and/or each thickness of pavement layer are selected. However, this design method has low accuracy. Consequently, it is necessary to apply other design model instead of design charts. Design charts are useful only for selection of whole thickness of pavement structure. Hence, the upper part of the pavement (generally, a wearing layer) needs to be analyzed separately according to development of permanent deformations and thermal cracks.

Considering the foreign countries practice and normative requirements or guides of pavement design for special objects, a design model is suggested for pavements affected by static and impact load (Table 2). A design model consists of three main parts: field of application, input

Table 2. Flow chart of pavement structure design model

FIELD OF APPLICATION					
Parking aprons of aircraft	Ports and containers terminals	Logistics terminals	Industrial areas	Parking lots	Areas affected by impact load
INPUT DATA					
	Characteristic			For new construction	For rehabilitation
Environmental/ Climate conditions	– Environmental temperature			+	+
	– Pavement temperature				+
	– Moisture			+	+
	– Hidrothermal conditions of pavement structure				+
	– Frost heave				+
	– Depth of freeze			+	+
	– Ground water level			+	+
Structural conditions	– Pavement structure composition, condition and materials				+
	– Bearing capacity of pavement structure and separate layers				+
	– Subgrade conditions, materials (soils) and bearing capacity			+	+
	– Embankment conditions and materials (soils)			+	+
	– Distress types and levels				+
Design materials	– Asphalt mixture			+	+
	– Asphalt with cement group			+	+
	– Portland cement concrete (PCC)			+	+
	– Concrete paving blocks, flags			+	+
	– Layer bonding materials			+	+
	– Bonded granular layer materials			+	+
	– Unbounded granular layer materials			+	+
	– Soils (subgrade/embankement)			+	+
	– Special materials			+	+
	– Special rehabilitation materials				+

Continued Table 2

Loading conditions	– Type of loading		+	+
	– Gross weight		+	+
	– Contact load		+	+
	– Load interval frequency		+	+
	– Load-pavement contact area		+	+
	– Contact pressure		+	+
	– Maximum drop weight (impact loading)		+	+
	– Maximum drop height (impact loading)		+	+
	– Forecasting (history)		+	+
ANALYSIS PROCEDURE				
	Model	Criteria	For flexible/ composite pavement	For rigid pavement
Pavement response to load	– Multi-layer linear elastic model	Calculate stresses, strains, deflection	+	+
	– Multi-layer viscoelastic model		+	
	– Finite difference method		+	
	– Boundary element method		+	
	– Finite element model		+	+
Pavement response to frost heave	Empirical (from experience)	– Max freeze depth	+	+
		– Min pavement structure thickness	+	+
		– Allowable moisture content in structure (during thaw season)	+	+
Performance (design) criteria	– Alligator cracking (bottom-up)	– 10–35% lane area	+	
	– Fatigue cracking (bottom-up)	– 10–35% lane area	+	+
	– Permanent deformation	– 10–17 mm rut depth	+	
	– Thermal cracking	– 95–133 m/km	+	+
	– Flow deformation	– 10–17 mm rut depth	+	
	– Mean joint faulting	– 4–6 mm		+
	– Slab cracking (frost heave)	– 10–20%		+
	– Ponchouts			+

data and analysis procedure. Following the design process step-by-step, the designer selects the best solution for new or rehabilitated pavement structure depending on environmental/climate conditions, structural conditions, design materials and loading conditions.

5. Design solutions for pavements structure affected by static and impact load

Analysis of practice of foreign countries in using pavement structures resistant to static and impact load has shown that pavement performance directly relies on type of surface course (asphalt, concrete paving blocks, concrete, porous asphalt with cement grout). Table 3 gives recommendable and alternative solutions of course layer of pavement structure affected by static and impact load considering susceptibility to the development of permanent deformations.

According to the normative requirements of Germany *Richtlinien für die Anlage und den Bau von Straßen für militärische Schwerstfahrzeuge* the thickness of all asphalt layers is needed to be more than 14 cm for heavy loading as there is unbound base layer. The thickness of asphalt binder course usually varies from 4 cm to 8 cm depending on load. Asphalt Institute recommends that the thickness of all asphalt layers has to be more than 18 cm.

The bearing capacity and performance of concrete pavement is determined by optimal thickness of concrete slab. According to *Advisory Circular No. 150/5320–6E Airport Pavement Design and Evaluation* the slab thickness varies from 8 cm to 60 cm depending on load magnitude in the areas affected by static load. Furthermore, on these pavements sometimes it is serviceable to construct a supplementary layer of porous asphalt with cement grout. The thickness of such layer varies from 3 cm to 7 cm. Also, this kind of solution is applied on asphalt base course of 5–18 cm thickness as described in *Merkblatt für die Herstellung von Halbstarren Deckschichten*.

Table 3. Recommendable and alternative solutions of course layer of pavement structure affected by static and impact load

Object of application	Type of course layer			
	Asphalt	Porous asphalt with cement grout	Concrete paving blocks	Concrete
Parking aprons of aircraft	±		+	+
Ports and container terminals	±[b)]		+	+[a)]
Logistics terminals	±	+	+	+
Industrial areas	±[b)]	+	+	+[a)]
Parking lots	+			

Notes: [a)] – concrete pavements are strongly recommended for containers or goods stacking areas; [b)] – asphalt pavements are used only as alternative choice for areas affected by moving handling equipment.

According to the practice of construction of concrete paving blocks, it is recommended to use the concrete paving blocks having a minimum thickness of 80 mm and to place in 25–40 mm thick layer of bedding sand (Knapton 1996, 2006; Knapton, Smith 1997; McQueen *et al.* 2010). Due to loading and inappropriate aggregate selection for base and bedding course the migration of bedding sand into base can happen. Consequently, the usage of geotextile on top of the aggregate base is desirable.

The analysis of pavement structures showed that unbound granular course(s) consists of unbound granular base and subbase course or only of unbound granular base course. The subbase thickness depends on subgrade strength (California Bearing Ratio (CBR)) and varies from 15 cm to 30 cm, while the base thickness – from 10 cm to 30 cm.

The investigation pointed out that the base course is often treated with asphalt or cement. Asphalt-treated base course is typical for pavement structures supporting loads in logistics terminals, industrial areas and parking lots. In such way, the thickness of asphalt-treated base course is ≥8 cm. Cement-treated base course is typical applied in rigid pavements independent on the field of application and in composite pavements of parking aprons of aircraft, ports and container terminals. This kind of base course is required when the wheel load exceeds 11.4 t (Knapton, Smith 1997) or gross load of aircraft is more than 45 t (McQueen *et al.* 2010). Otherwise, the base course is constructed from unbound granular aggregates.

In order to ensure the sufficient strength of existing subgrade as CBR is less than 5% a capping layer is constructed. The thickness of this kind layer varies from 25 cm to 90 cm according to CBR of existing subgrade (Knapton, Bullen 1996).

Conclusions

1. In Lithuania pavement structures for special purposes are designed according to the experience and standardized pavement structure catalogue for roads. There is lack of procedures, requirements, guides and/or manuals for it.

2. The long-term static or short-term impact loading on special-purpose pavement structures is assumed as the most common negative factor for pavement distress. Moreover, due to the brittleness of bitumen at low temperature thermal cracking is assumed as a very significant distress, too.

3. Considering specification of static and impact loading, especially a wide range of contact pressure (from 0.01 MPa up to 40 MPa), design procedures applied for pavement structures of roads and streets cannot be applied for pavements of special objects – terminals, aprons, parking and storage lots.

4. The negative influence of moisture and frost on pavement structure performance is solved by insuring sufficient drainage and thickness of whole pavement structure, respectively. While influence of temperature is assessed by different stiffness modulus of bituminous layers and thermal stresses in cement layers.

5. Research represents the pavement structure design model with three main objectives: field of application, input data (environmental/climate conditions, structural conditions, design materials and loading conditions) and analysis procedure (pavement response to load, pavement response to frost heave and performance (design) criteria).

6. In order to reduce the susceptibility to permanent deformations of surface course, there were constructed: 2.5–10 cm thick asphalt surface course, ≥8 cm thick course of concrete paving blocks, 10–60 cm thick concrete course or 3–7 cm thick course of porous asphalt with cement grout. The type and thickness of course depends on the field of application and contact pressure, respectively.

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