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Section: Roads and Railways

Influence of Static and Impact Load on Pavement Performance

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Abstract

The most researches are done for evaluation of dynamic load of vehicles on pavement response. However, pavements of airports, container terminals, logistic terminals, areas of storage, industrial areas, parking lots, areas operated by falling materials or special machinery and etc. are affected by long term static or impact load. Due to this kind of loading specificity, pavement performance is different comparing to pavement performance operated by repeating dynamic traffic loads. Practice shows, that permanent (plastic) deformations and thermal cracks often appear in such pavements. Consequently, the loading specification of areas affected by static and impact load, development of permanent deformations and thermal cracking and analysis of practice and normative requirements for pavements affected by static and impact load were considered in this research. The research has resulted in serviceable solutions for pavement structures resistant to static and impact loading according to the type of pavement (flexible, rigid, semi-rigid (flexible)) and the scope of application.

Keywords: static load; impact (drop weight) load; pavement failure; pavement structure.

1. Introduction

A pavement is a multi-layer structure, which performance depends on each layer characteristics. As it is well known, stiffness modulus is the basic characteristic for bituminous materials. Meanwhile, resilient modulus and/or California Bearing ratio characterizes unbound granular materials. Whereas flexural and compression strength is the most important characteristic for cement or cement treated materials. The selection of thickness of each layer depends on heavy traffic volume, design period, axle combination, axle load, wheel load, contact area and etc. [1–4]. All of these factors are summed up in pavement design methods.

Approximately 60 % of the European countries use analytical design methods, which are based on linear elastic theory. This concept is used to calculate permissible values of stress or strain at critical locations in the pavement structure [1]. However, it requires lots of computation of time and experiences. So, in most countries there are prepared some catalogues for pavement structure selection according to a number of equivalent single axle load (ESAL) through design period. There are considered into specific climatic conditions (level of groundwater, level of frozen, ambient temperature) of country, too.

The distresses of pavement is accelerated by influence of climatic conditions (temperature, moisture, freeze-thaw cycling) [5–6]. Temperature is emphasized as most critical environmental factor. Temperature variations affect the viscous-elastic-plastic characteristic of asphalt pavement. The change of behavior depends on temperature (low – elastic (stiff) material, medium – viscous-elastic material, high – plastic material) [7–9]. In the rigid pavements, daily temperature variations lead curling of the slab: the slab bend up (expansion of the pavement surface) when the top of the slab is much higher temperature than the bottom of the slab (daytime) and the slab bend down (contraction of the pavement surface) when the temperature at the top of the slab is much lower than the bottom (nighttime). Also, the temperature variations give thermal stresses in the slab [10–12].

Hence, distresses of the pavement are caused due the action of heavy traffic loads and climatic conditions (especially temperature variations). There are noted that asphalt pavements distress are dominated by permanent deformation (rutting in the subgrade, rutting in base layers and/or rutting in bituminous layers), fatigue cracking, thermal cracking, structural cracking, surface cracking, alligator cracking, longitudinal cracking, transverse cracking, reflective cracking, raveling, wear by studded tires, loss of skid resistance [1], [13], [14]. Whereas concrete pavements distress are dominated by curling of slabs, corner breaks, longitudinal cracking, thermal cracking, D-cracking, fatigue cracking, spalling, transverse slab

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cracking, reflective cracking, faulting, blowups [14–17]. Pavements with such kind of distresses don't satisfy the requirements of exploitation and need structural rehabilitation or reconstruction. That is why; the concept of perpetual (long-life) pavements has been developed. It means that a pavement is a maintenance-free – no structural deterioration of the pavement whatever the traffic load. This kind of pavement life is about 50 years and need only periodic surface renewal in response to distresses confined to the top of the pavement [18–20].

Pavement performance and distresses that are discussed above is typical for roads, which are operated by repeating dynamic traffic loads. However, there are some pavements, which are affected by different type of load: static or impact loading. There is known that static load is load, which direction of effect, value and coordinates of added point is constant and source of loading do not take significant acceleration during loading time. Whereas impact load is load (weight), which drops from certain high and suddenly (within 10^{-3} – 10^{-6} s) covers the pavement. At the finish time of impact, the speed of dropping load is zero. This kind of loading is induced by falling materials or special machinery.

Static and/or impact loading emerge at parking aprons of aircraft, ports and containers terminals, logistics terminals, industrial areas, parking lots, waste recycling areas and etc. In these areas the values of loads are several time higher comparing with common traffic loads. Time of loading is longer, too. Moreover, loads of these areas are concentrated and affect pavement within small contact area. Consequently, it leads high pressure into pavement. Hence, these kinds of pavements perform in different way comparing to roads pavements and need to be properly analyzed.

Practice has shown that pavements which are affected by static and impact loading need structural rehabilitation or reconstruction much earlier than projected their design life. The main reason of it is distresses or failures of the upper part of pavement (generally wearing layer). The most significant distresses are permanent (plastic) deformations [21] and thermal cracks (if pavement has been constructed in cold regions) [23], [24]. Often, the form of permanent deformations reflects the shape of contact area of loading source. It obviously appears in flexible or semi-rigid pavements with asphalt layers.

2. Particularity of areas affected by static and impact load

The performance of pavement affecting by static and impact load strongly depends on contact pressure. In calculations it is assumed that the average tire contact pressure is proportional to tire pressure and remains uniform by changing load. Hence, the contact area varies only by changing load. Then the load is increasing (tire pressure is uniform), the contact area is increasing and then the load is decreasing, the contact area is decreasing, too [2].

For current range of load and tire inflation pressures, the real tire-pavement contact area is similar to a rectangle or an ellipse [25]. There is an assumption, that the ellipse's smaller axle or rectangle width is usually considered as 60% of the ellipse's larger axle or rectangle length [26]. In calculations tire-pavement contact area is accepted as a circle, which area is equal to ellipse's (rectangle) area.

In areas affected by static and impact load, the contact pressure closely depends on characteristics of loading source. There dominates such load sources: 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 and/or dropping objects (Fig. 1). Due variety of load sources and their characteristics, contact pressure is given in Table 1.

Table 1. Contact pressure considering to characteristics of load source^{a)} [2], [27–30]

Object (load source)	Contact area, mm ²	Contact pressure, MPa
Aircraft	b)	0.3–1.7 ^{c)}
Handling equipment of ports	b)	0.7–1.7
Container	26 250	2.59–12.5 ^{d)}
Heavy vehicle	b)	0.6–1.0
Trailer dolly (steel wheels)	8800	35–40
Trailer pivot plate	33750	2.0
Handling equipment of industrial areas	b)	0.5–1.0
EuroPallet	116 000	0.03–0.44 ^{e)}
Car	b)	0.20–0.25

^{a)} Sources of impact load haven't been included in to table due to their variety.

^{b)} The leg of load source is wheel. The contact area of tire-pavement depend on characteristics of tire.

^{c)} Contact pressure depends on type of aircraft.

^{d)} Then only one container is on the pavement the contact pressure is 2.59 MPa, then eight containers – 12.5 MPa.

^{e)} Then only one EuroPallet with goods is on the pavement the contact pressure is from 0.03 MPa depending on the weight of goods, then four EuroPallet with goods – by 0.44 MPa depending on the weight of goods.



Fig. 1. Examples of loading sources

The aircraft gear type and geometry needs to be estimated in analysis of pavement performance at parking aprons of aircrafts. Whereas analyzing the pavement performance at ports and container terminals, there should be noticed into different loading, i.e. static loading (containers) and dynamic loading (handling equipment's movements, cornering, accelerating and braking).

According to DIN/ISO standards, fully loaded containers must be stackable at least six high. Practice has shown that fully loaded containers are usually stacked up to six high and empty containers – eight high. However, there can be used modern containers, which can be stacked up to eight or nine high even fully loaded (in some cases containers can be stacked up to twelve high) [28], [30], [31].

EuroPallets are the main type of foundation for goods storing in industrial areas. For storage they can be stacked up to four high and for transportation – up to two high.

There has been assessed that the load on pavement depends on containers and EuroPallets stacking arrangement and wheel configuration. The closer wheels or legs of load are the greater loads on pavement. However, the contact pressure is constant at contact area and varies only by stacking high (if contact area is uniform) [28], [30].

In areas affected by impact load, pavement response to loading depends not only on the load value, contact area, but also on the dropping high. The negative effect of loading increases as the dropping high increases.

3. Distress of pavement structures affected by static and impact load

In pavement structures affected by static and impact load the main distresses are permanent deformations (surface depression in the contact area) (Fig. 2) [32], [33] and thermal cracks (Fig. 3) [34], [41]. As mentioned before, due viscous-elastic-plastic properties of asphalt and ambient temperature variation these distresses commonly appear in asphalt pavements [35], [36]

Permanent deformation of asphalt layer is caused by [4], [34], [37]:

- Densification (volume change);
- Shear flow (no volume change);
- Mechanical deformation (structural failure).

Due loading asphalt layers consolidate. This consolidation results in surface depression in the contact area without an accompanying hump on either side of the depression. This phenomenon is inescapable and can be limited by content of air voids in asphalt mixture. Asphalt pavements are typically constructed at approximately 5–8% in-place air voids. Due loading content of air voids decreases to approximately 4%. Air voids content less than 2–3% leads asphalt's susceptible to shear flow [29], [38]. So, asphalt layers must be not overdensified.

Longitudinal or lateral distortion of asphalt mixture is caused by instability of asphalt layers, i.e. by large shear stresses dominating in the upper part of asphalt layers. This distress can be recognized by humps on either side of the depression. Ratio of this kind of deformation depends on moving speed and temperature. The same load leads higher deformation at lower speed and higher temperature. Permanent deformation caused by shear flow is difficultly predictable phenomenon.

Mechanical deformation is associated with permanent deformation in any of the pavement layers or in the subgrade. It develops due consolidation, densification and/or lateral movement of the unbound materials. The deformations evolving in the lower part of the pavement structure reflects in the upper part of the pavement. If asphalt is too stiff (high elastic modulus), mechanical deformations is usually accompanied by a longitudinal cracking pattern at the pavement's surface.

Development of asphalt's permanent deformation is influenced by characteristics of binder and aggregate, content of air void and binder, ambient temperature, load magnitude, loading time and etc. [37], [38].



Fig. 2. Permanent deformations of pavement effected by static and impact loading



Fig. 3. Thermal cracking of asphalt pavements

During hot summer weather the temperature in the surface course of the asphalt pavement structure can exceed 50 °C. In Lithuania it changes during the year from -21.77 °C to +52.75 °C, the difference is more than 70 °C [39]. The reason of it is that around 55% and 85% of solar radiation is absorbed by the surface of asphalt pavement respectively in winter and summer time [40]. The highest temperature in the surface course is about 12–16 hour in summer time. Researchers has found that majority of surface depression (permanent deformation of asphalt layers) occurs on a few days of the year, when the temperature in the surface course exceeds 45 °C [41]. Due such high temperature the asphalt mixture behaves as plastic material. This problem can be solved by using a stiffer asphalt binder. However, stiffer asphalt binders are more prone to cracking during winter in cold regions [34].

Thermal cracking is primarily associated with cold temperatures (below 10 °C) at the surface of asphalt layer. Due to low temperature the binder film to get thinner around aggregates. When the temperature drops below the point where asphalt binder becomes brittle, thermal cracking is initiated in the surface of asphalt pavement and immediately grows down. This type of distress can be controlled through selection of binder for expected minimum temperature of the pavement [40], [42].

4. Solutions for pavement structure performance

On purpose to establish the best solutions for pavement structure affected by static and impact load, there were researched successful practice in using this kind of pavements and normative requirements for parking aprons of aircraft, ports and containers terminals, logistics terminals, industrial areas, parking lots and etc. The type of pavement (flexible, rigid, semi-rigid (flexible)), layers thickness and characteristics were analyzed by the scope of application. This methodology of the research led to establish the most typical pavement structures resistant to static and impact loading. All analyzed information has been summarized in Appendix A. It represents presumable solutions for pavement structures resistant to static and impact loading.

According to the scope of application, the analysis of foreign countries practice has resulted in such preferable solutions to pavement structures:

- Concrete pavements or pavements with concrete paving blocks are recommended for parking aprons of aircraft. Asphalt pavements are not recommended for these applications. However, it can be used as alternative choice.
- Pavements with paving blocks are recommended for ports and containers terminals. Concrete pavements are strongly recommended for containers stacking areas. While asphalt pavements can be used as alternative choice for areas affected by moving handling equipment.
- Concrete pavements, pavements with concrete paving blocks or porous asphalt with cement grout are recommended for logistics terminals. Asphalt pavements can be used as alternative.
- Concrete pavements and pavements with concrete paving blocks or porous asphalt with cement grout are recommended for industrial areas. Concrete pavements are recommended for goods stacking areas. While asphalt pavements can be used as alternative choice for areas affected by moving handling equipment.
- Asphalt pavements are mostly recommended for parking lots.

5. Conclusions

Due to changes of viscous-elastic-plastic behavior and variations of ambient temperature, asphalt pavements are considered as the most susceptible pavements to static and impact loading.

The use of standardized pavement structures in areas affected by static and impact loads is unreasonable due to significant range of varying contact pressure (contact pressure varies from 0.2 MPa to 12.5 MPa depending on load, axle configuration, gear type and geometry, number of wheel, contact area and etc.).

In the areas affected by static and impact load (such as parking aprons of aircraft, ports and containers terminals, logistics terminals, industrial areas, parking lots, waste recycling areas and etc.) the most significant distresses are permanent deformations and thermal cracking (if pavement has been constructed in cold regions).

The pavement resistance to static and impact loading should be ensured by sufficient bearing capacity of pavement structure and stiffness of payment layers affected by high contact pressure. The solution for this purpose can be achieved by constructing 2.5–10 cm thick stiff asphalt surface course, 8–20 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 thickness of wearing course depends on contact pressure and should be calculated dependent on loading conditions.

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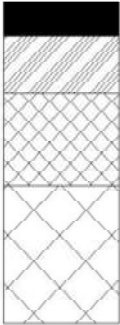
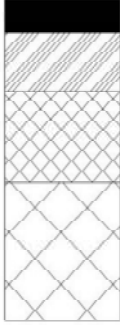
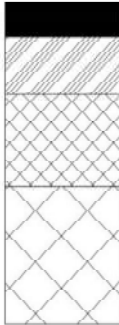
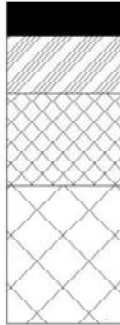
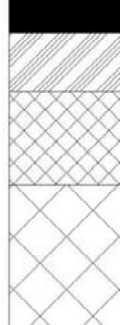





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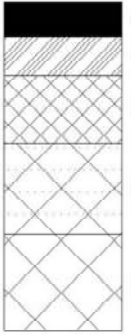

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Appendix A. Pavement structures using for areas affected by static and impact load ^{a)}

Type of pavement	Object of application				
	Parking aprons of aircraft	Ports and containers terminals	Logistics terminals	Industrial areas	Parking lots
Flexible	 <p>5-10 Asphalt surface course 8-9 Asphalt binder course 9-18 Asphalt base course 25-60 Unbound granular subbase course</p>	 <p>5-10 Asphalt surface course 8-9 Asphalt binder course 9-18 Asphalt base course 25-60 Unbound granular subbase course</p>	 <p>3-4 Asphalt surface course 6-8 Asphalt binder course 10-20 Asphalt base course 25-50 Unbound granular subbase course</p>	 <p>3-4 Asphalt surface course 6-8 Asphalt binder course 7-12 Asphalt base course 15-50 Unbound granular subbase course</p>	 <p>2.5-4 Asphalt surface course ^{b)} 4-6 Asphalt binder course 7-10 Asphalt base course 15-30 Unbound granular subbase course</p>
	 <p>≥8 Concrete paving blocks 3-4 Bedding course 12-30 Unbound granular base course 15-30 Unbound granular subbase course</p>	 <p>≥8 Concrete paving blocks 3-4 Bedding course 12-30 Unbound granular base course 15-30 Unbound granular subbase course</p>	 <p>≥8 Concrete paving blocks ^{c)} 3-4 Bedding course 25-50 Unbound granular base course</p>	 <p>≥8 Concrete paving blocks ^{c)} 3-4 Bedding course 25-50 Unbound granular base course</p>	 <p>≥8 Concrete paving blocks ^{c)} 3-4 Bedding course 15-30 Unbound granular base course</p>

Type of pavement	Object of application				
	Parking aprons of aircraft	Ports and containers terminals	Logistics terminals	Industrial areas	Parking lots
Rigid	 <p>15-60 Concrete course d) e) 10-60 Unbound granular base course</p>	 <p>20-60 Concrete course d) e) 10-60 Unbound granular base course</p>	 <p>10-25 Concrete course d) e) 10-30 Unbound granular base course</p>	 <p>10-25 Concrete course d) e) f) 10-30 Unbound granular base course</p>	 <p>8-18 Concrete course d) e) f) 10-30 Unbound granular base course</p>
	 <p>≤10 Asphalt course g) ≥50 Cement-treated base course 20-30 Unbound granular subbase course</p>	 <p>≥8 Concrete paving blocks g) 2.5-4 Bedding course 20-60 Cement-treated base course 15-30 Unbound granular subbase course</p>			

Type of pavement	Object of application				
	Parking aprons of aircraft	Ports and containers terminals	Logistics terminals	Industrial areas	Parking lots
Semi-rigid (flexible)	 <p>5-7 Porous asphalt with cement grout course 8-18 Asphalt base course 15-60 Unbound granular subbase course</p>	 <p>5-6 Porous asphalt with cement grout course 10-18 Asphalt base course 15-60 Unbound granular subbase course</p>	 <p>5-6 Porous asphalt with cement grout course 5-18 Asphalt base course 15-50 Unbound granular subbase course</p>	 <p>5-6 Porous asphalt with cement grout course 5-10 Asphalt base course 15-50 Unbound granular subbase course</p>	
	 <p>4-6 Asphalt surface course ^{g)} 4-8 Asphalt binder course 11-17 Asphalt base course ≥18 Cement-treated base course ≥15 Unbound granular subbase course</p>	 <p>7-9 Asphalt surface course ^{g)} 10-12 Asphalt base course 35-50 Cement-treated base course</p>			

^{a)} it has been found only one solution for areas effected by impact load. It consists of 4-7 cm porous asphalt with cement grout course, 10-14 cm asphalt base course and unbound base granular course.

^{b)} this pavement structure using for parking lots can consist without asphalt binder course.

^{c)} the upper part of the base course (≥8 cm) can consist of asphalt-treated material. Then the thickness of bottom part of the unbound granular base course is 15-30 cm.

^{d)} the porous asphalt with cement grout course (3-7 cm) can be placed on the concrete pavement.

^{e)} the upper part of the base course can consist of cement-treated material.

^{f)} the pavement can consist only of concrete course constructing on subgrade (without base course).

^{g)} the same type of pavement can be used for parking aprons of aircraft, ports and containers terminals.