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MIXTURE STRENGTH CLASS AND SLAB DIMENSIONS' EFFECT ON THE PRECAST CONCRETE PAVEMENT STRUCTURAL PERFORMANCE

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Abstract. Mechanical properties and slab dimensions of concrete are the major parameters based on which the performance of concrete pavement structures is predicted. Precast concrete pavement, as one of the most common modular pavement type, is the advanced next-generation technology characterised as high quality, durable, quickly built and easily maintained. The service conditions of precast concrete pavement (traffic loading and environmental effects) are similar to the conventional cast-in-place jointed plain concrete pavement. Thus, the precast concrete pavement structural design is similar to that of jointed plain concrete pavement. There are several concepts for the design of concrete pavement structure. However, they are based on different distress evaluation

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and critical stresses estimation methods assuming the slab dimensions that for jointed plain concrete pavement are within the wide joint spacing range from 3.5–6.0 m. The objective of this paper is to analytically evaluate the effect of concrete mixture mechanical properties on the thickness and dimensions of precast concrete pavement slab. Also, define the minimal thickness of precast concrete slab dependent on slab dimensions and concrete mixture mechanical properties elastic modulus and tensile splitting strength. The analysis is based on bearing capacity, performance and fatigue boundary conditions as reported by semi-probabilistic pavement design method *Richtlinien für die rechnerische Dimensionierung von Betondecken im Oberbau von Verkehrsflächen RDO Beton 09*. Considering that, concrete mixture has significant effects on pavement performance; the composition of concrete was also discussed in this paper. The optimal slab dimensions, concrete layer thickness, and base layer type is suggested in this paper. The outcomes of this analysis apply to the production of precast concrete pavement slabs.

Keywords: concrete mixture design, concrete slab, modular pavement, pavement design, precast concrete pavement (PCP).

Introduction

Durable, sustainable and easily maintained transport infrastructure is a challenging task for national road administrations and transport agencies. In recent years, the expectations of road users and agencies for the quality of mobility have increased with the development of the research and the innovative engineering solutions. However, many factors lead to inefficient pavement performance, and it is still challenging to meet the expectations. The pavement failure emerges due to underestimated environmental and traffic loading conditions, ineffective pavement design (insufficient layer thickness and inappropriate material selection), delayed maintenance activities. However, the premature defects of pavement surface that significantly decrease pavement service life are mostly related to a poor-quality construction (Chang, Baladi, & Wolff, 2001). Flexible (asphalt) pavements are the most popular in Europe and North America countries, because of lower cost, faster construction and easier repair compared to rigid (concrete) pavement. However, under specific loading conditions and with longer service life, the well-constructed rigid pavement is a competitive alternative (Breyer & Kurzfassung, 2004; Kleizienė, Vaitkus, & Čygas, 2012). The decision-making concept of Life Cycle Cost Analysis (LCCA) is based on the evaluation of long-term economic efficiency between two or more alternative investment options (Walls III & Smith, 1998). One of the promising alternatives of traditional pavements is the modular pavement technology also known as precast concrete pavement

(PCP) (Tayabji & Tyson, 2014; Tayabji, Ye, & Buch, 2014; Vaitkus, Gražulytė, Kleizienė, Vorobjovas, & Šernas, 2019).

Kohler, du Plessis, Smith, Harvey, & Pyle (2007) stated that PCP used for highways, roads, bus lanes, interceptions, parking lots, tunnels, aprons and port pavements as well as repair of traditional concrete pavement. Precast concrete pavement is the advanced next-generation technology characterised as high quality, durable, quickly built and easily maintained. Precast concrete pavement technology has been investigated, produced, constructed and maintained over the past 40 years in different countries and continents. However, the scientific attention and engineering innovations were developed nowadays, when the need for fast, durable pavement construction and repair appeared. The advantages of PCP compared to the cast-in-place jointed plain concrete pavement (JPCP) are as follows (Kohler, du Plessis, Smith, Harvey, & Pyle, 2007; Tayabji & Tyson, 2014):

- an improved and consistent quality of concrete;
- ensured steady conditions of concrete curing;
- minimised influence of weather conditions during production;
- reduced traffic delays after installation;
- reduced risk of joint ravelling.

There are several types of PCP with slab dimensions, reinforcement and jointing (Vaitkus, Gražulytė, Kleizienė, Vorobjovas, & Šernas, 2019): precast pre-stressed concrete pavement, JPCP, incrementally connected PCP. Design of PCP is based on the assumption that the overall service conditions of PCP (traffic loading and environmental effects) will be similar to the cast-in-place JPCP (Smith & Snyder, 2017; Tayabji & Tyson, 2014). Thus, usually, the thickness of PCP is designed in agreement with the traditional concrete pavement design procedures. However, during the production of PCP, the quality is controlled more accurately to assure high reliability compared to the cast-in-place JPCP and therefore, the panel design thickness is reduced. The concrete pavement performance is affected by load weight, driving speed (frequency), stress level (ratio), number of load cycles, concrete pavement slab dimensions and thickness (size effect), load transfer at joint, mechanical properties of concrete and slab.

Concrete pavement joint spacing is determined taking into account the following factors: slab thickness, mechanical and physical properties of concrete (coefficient of thermal expansion, strength and elasticity), foundation bearing capacity, and environmental conditions. Joints have to be designed close enough to prevent curling stress accumulation. Slab curling occurs cyclically: with increasing temperature at daytime, the slab curls downward, and with decreasing temperature, at night it curls upwards. The slab edge-stress due to temperature is a function of concrete thermal expansion, the temperature difference between the top and the bottom of slab, and correction factor determined by the ratio of slab length (L) and radius of relative stiffness (l) (Bradbury, 1938). The is above 4.4 to avoid transverse cracking of slab (American Concrete Institute..., 2002). Even though the stress cycles due to curling are much fewer than to loading joint, the coefficient of thermal expansion of concrete impacts the performance and serviceability of pavement structure (Delatte, 2008).

The concrete pavement of road or runway structures operates under repetitive cyclic loading conditions. However, usual standard concrete tests and design procedures evaluate concrete performance under constant compressive load and resistance to fatigue is determined based on a probabilistic design concept evaluating the reliability. The resistance to fatigue of concrete pavement is mainly subjected to dynamic or static flexural strength of concrete. The fatigue performance of concrete was investigated by many researchers (Disfani, Arulrajah, Haghighi, Mohammadinia, & Horpibulsuk, 2014; Goel, Singh, S. P., & Singh, P. 2012; Graeff, Pilakoutas, Neocleous, & Peres, 2012; Li, Zhang, & Ou, 2007; Mai, Le-Corre, Forêt, & Nedjar, 2012; Zanuy, de la Fuente, & Albajar, 2007) and fatigue is mostly determined using probabilistic methods and S-N curves (providing the number of cycles to failure of a constant amplitude).

The objective of this paper is to define the minimal thickness of precast concrete slab dependent on slab dimensions and concrete mixture mechanical properties, elastic modulus and tensile strength. The tasks of this research involve:

- analysis of concrete pavement design methods;
- analysis of concrete mixture mechanical properties;
- study on the effect of concrete mechanical properties on slab dimensions;
- determine the optimal thickness and slab dimensions for precast cement concrete pavement.

1. Design methods for concrete pavement structure

1.1. The concept of concrete pavement design

Concrete pavement design starts with a definition of parameters, like the level of structural performance, target service life, concrete properties (durability, strength, rigidity, and shrinkage) to achieve optimum performance. Currently, concrete pavement thickness design is a semi-probabilistic analytical method based on mechanical and empirical data (Jung & Zollinger, 2007; Villaret, Kiehne, Riwe, & Villare, 2008; Wojtkiewicz, Khazanovich, Gaurav, & Velasquez, 2010). The principle is mainly based on damage (Minner) hypothesis that pavement response under design conditions has to be less than limit (boundary condition) response under the same traffic load and environmental conditions. The three distress types of JPCP are evaluated in the Mechanistic-Empirical Pavement Design Guide (MEPDG) (American Association of State..., 2008, 2015):

- mean transverse joint faulting – is a result of a combination of repetitive load cycles of moving heavy axles, load transfer at joint, free moisture beneath the slab, permanent deformation of base/subbase, and upward curling of the slab. Khazanovich, Darter, & Yu (2004) proposed a JPCP design algorithm based on transverse joint faulting (Figure 1);
- bottom-up and top-down transverse cracking – is a result of fatigue damage of repeated traffic loading near the longitudinal edge of the slab at the high positive (bottom-up) and high negative (top-down) temperatures;
- smoothness – is a function of the initial profile change over time due to damage (transverse cracking, joint with sapling and joint faulting) percentage accumulation.

The damage under critical locations in the pavement subjected to influence of load and temperature are calculated based on deflections (Khazanovich, Darter, & Yu, 2004), deflection moments (*Richtlinien für die rechnerische Dimensionierung von Betondecken im Oberbau von Verkehrsflächen RDO Beton 09*) or neural network analysis (American Association of State..., 2008, 2015). The critical responses in MEPDG are calculated using neural network analysis based on inputs of slab and base course combined into equivalent stresses of loads and temperature/moisture gradients, and friction between slab and base. The pavement response (stress and strain), traffic load and temperature are calculated under theoretical assumptions such as:

- the shape of concrete plate – rectangular;
- material behaviour – linear elastic;
- Bernoulli hypothesis validation;
- load effect on an unloaded plate – no pre-deformation;
- feasibility of joint edges – none;
- state of tension – uniaxial;
- normal stresses in the plate are not considered.

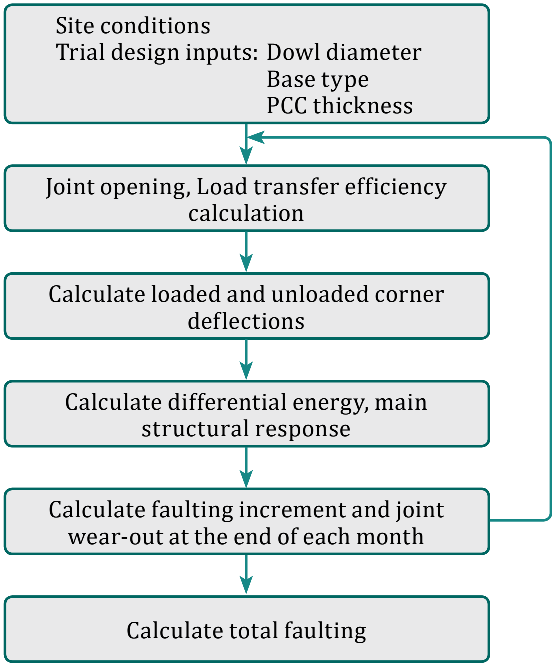


Figure 1. Concrete pavement design based on transverse joint faulting (Khazanovich, Darter, & Yu, 2004)

1.2. Analysis of concrete mixture properties

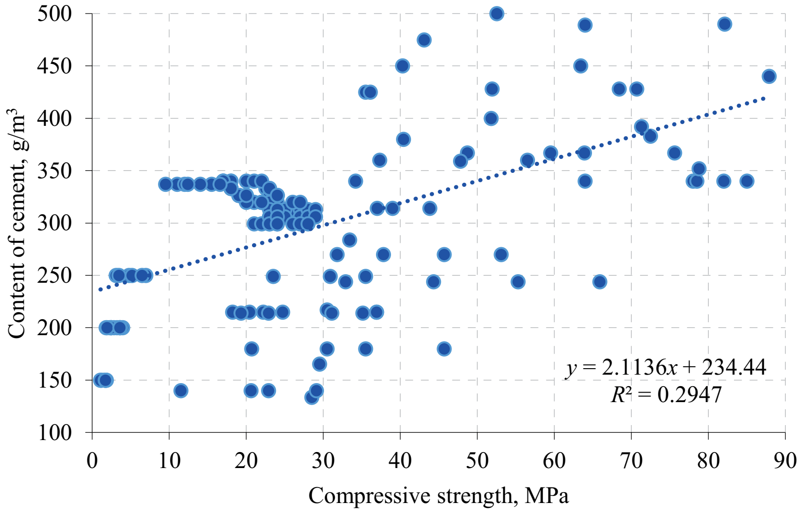
The design of concrete mixture has to be evaluated by analysing economic, technical, mechanical (strength needed for design), workability and durability factors. The proportions of individual constituents of the concrete mixture are determined by prescriptive or performance-based design methods. Concrete mixture design starts with selecting the following parameters (Kosmatka, Kerkhoff, & Panarese, 2002): strength, minimum cement content or maximum water-cement ratio, the nominal maximum size of aggregate, air content, and suitable slump. The required properties of fresh concrete depend on the type of construction, placing and transporting technologies. The required properties of hardened concrete are specified by the design of concrete pavement structure. Standard cement concrete classes used for pavement design according to the *RDO Beton 09* are presented in Table 1. The normal strength concrete is used for construction of road pavements with additional requirements for fatigue, thermal expansion, and resistance to scaling and de-icing mixtures. Typical specifications of paving concrete are (Kosmatka, Kerkhoff, & Panarese, 2002; Tayabji, Ye, & Buch, 2013; *TL Beton-StB 07 Technische Lieferbedingungen für Baustoffe und Baustoffgemische für Tragschichten mit hydraulischen Bindemitteln und Fahrbahndecken aus Beton*;):

- fresh concrete mixture:
  - water-cement ratio (0.37–0.45);
  - air content (minimum air voids in fresh concrete with a maximum 8 mm aggregate size – 5.5%, and with 32 mm or 22–4.0%);
  - aggregate gradation (optimal aggregate gradation results in less need for cement paste);
  - slump for pavements and slabs (75–25 mm).
- hardened concrete:
  - flexural (4.5–5.2 MPa) strength after 28 days;
  - compressive (27.5–40.0 MPa) strength after 28 days;
  - durability (resistance to fatigue, alkali-silica reactivity, the influence of sulphate, D-cracking, scaling).

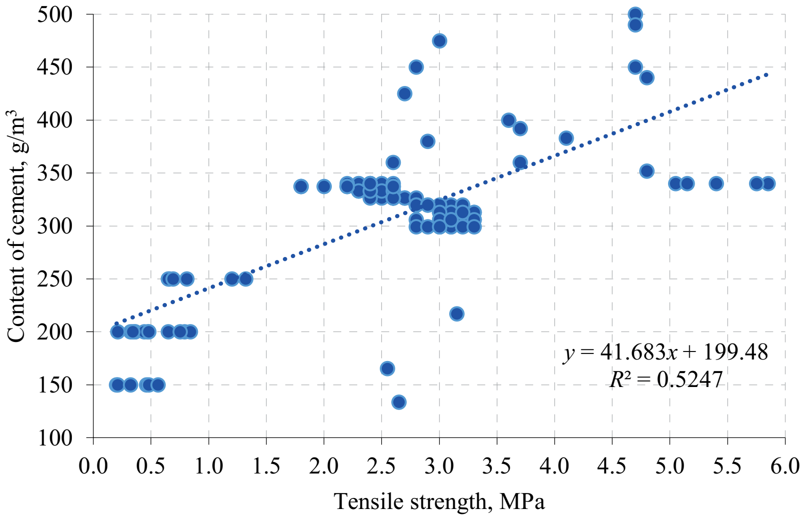
Table 1. Standard cement concrete classes used for pavement design according to the *Richtlinien für die rechnerische Dimensionierung von Betondecken im Oberbau von Verkehrsflächen RDO Beton 09*

Layer of pavement structure	Concrete class for road pavement		Tensile splitting strength, f_{ctk}, N/mm²	Tensile elasticity modulus, E_{ctm}, MPa
	Class of			
	environmental properties	mechanical properties	*EN 12390-6*[1)]	*STR 2.05.05:2005*[2)]
Concrete wearing (top)	*XM*2 and *XF*4[3)]	StC 30/37 – 3.0	3.0	37 000
		StC 30/37 – 3.3	3.3	39 000
		StC 30/37 – 3.7	3.7	41 000
		StC 35/45 – 3.3	3.3	39 000
		StC 35/45 – 3.7	3.7	41 000
		StC 35/45 – 4.0	4.0	42 000
		StC 40/50 – 4.0	4.0	42 000
		StC 40/50 – 4.3	4.3	43 000
		StC 40/50 – 4.6	4.6	44 000
Concrete base	No requirement	StC 25/30 – 2.4	2.4	34 000
		StC 25/30 – 2.7	2.7	35 000
		StC 25/30 – 3.0	3.0	37 000
		StC 25/30 – 3.3	3.3	39 000

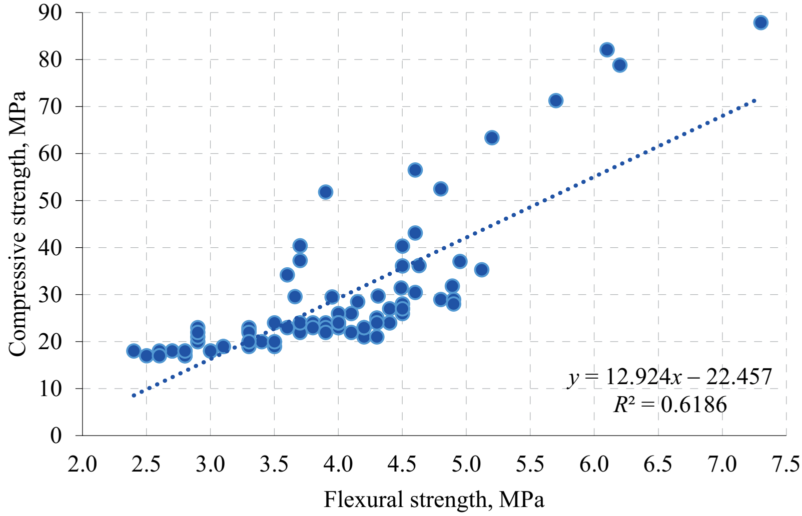
Note: [1)]*EN 12390-6 Testing Hardened Concrete – Part 6: Tensile Splitting Strength of Test Specimens*; [2)]*STR 2.05.05:2005 Design of Concrete and Reinforced Concrete Constructions*; [3)]*EN 206 Concrete – Part 1: Specifications, Performance, Production and Conformity*.



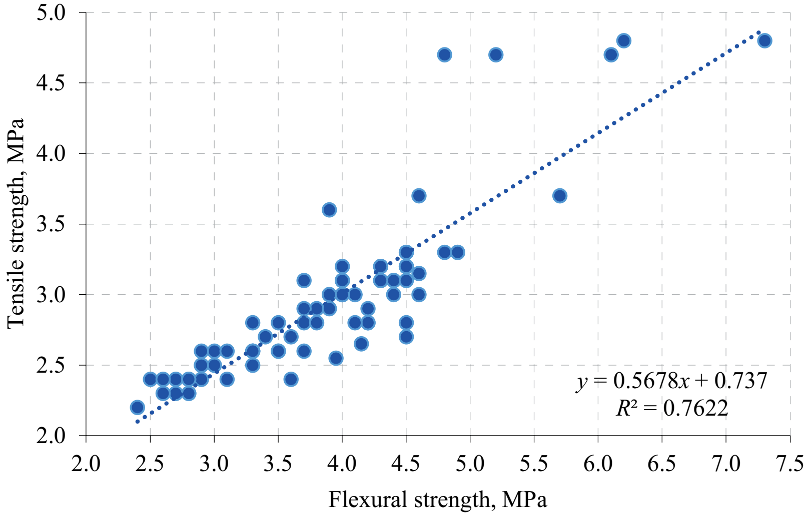
a) comparison of cement content influence on compressive strength



b) comparison of cement content influence on tensile strength



c) comparison of compressive and flexural strength



d) comparison of tensile and flexural strength

Figure 2. Summary of the analysis of concrete mixture influence on mechanical properties (Hesami, Ahmadi, & Nematzadeh, 2014; Huang, Wu, Shu, & Burdette, 2010; Ibrahim, Mahmoud, Yamin, & Patibandla, 2014; Isaia, Gastaldini, & Moraes, 2003; Jalal, Pouladkhan, Harandi, & Jafari, 2015; Naik, Ramme, & Tews, 1994; Nehdi, Pardhan, & Koshowski, 2004; Phoo-ngernkham, Chindaprasirt, Sata, Hanjitsuwan, & Hatanaka, 2014; Rangelov, Nassiri, Haselbach, & Englund, 2016; Shannag, 2000)

Flexural strength (or modulus of rupture) of concrete is the basic input in the design of concrete pavements and slabs (Kosmatka, Kerkhoff, & Panarese, 2002). Since the compressive strength test is easier to perform, the flexural strength assumed from the index and empirical relationship. Wood (1992) stated that the flexural strength of normal-weight concrete could be approximated to 0.7–0.8 times the square root of the compressive strength in MPa. An extended review of the studies of several researchers allowed for determining correlations between the content of cement and mechanical properties (Figure 2 and Table 2). The measurements of other researchers show that there is a weak relation between cement content and compressive and tensile strength. However, with a cement content of 340–360 kg/m^3, optimal composition and additives the improve mechanical properties significantly (compressive strength above 78 MPa, and tensile strength above 4.8 MPa. Nazari and Riahi (2012) determined that adding nano SiO_2 increases concrete compressive, split tensile and flexural strength up to 4% compared to the concrete mixture without additives (Nazari & Riahi, 2012). Goel, Singh, S. P., & Singh, P. (2012) investigated the influence of steel fibre on the fatigue properties of concrete and determined that adding 1.0 % of steel fibre allows increasing fatigue strength by 76% and static flexural strength by 73% (Goel, Singh, S. P., & Singh, P. (2012). Klcriber (1982) stated that the water-cement ratio in concrete affects the flexural fatigue behaviour of unreinforced concrete. Naik, Ramme, Kraus, & Siddique (2003) and Naik, Ramme, & Tews (1994) investigated the performance of high-volume fly ash cast-in-place plane concrete pavement after 14 years of service (Naik, Ramme, & Tews, 1994). Researchers stated a good performance of fly ash used in concrete pavement in terms of density, compressive strength, resistance to chloride penetration and salt scaling (Naik, Ramme, Kraus, & Siddique, 2003). Thus, the use of the concrete mixture with improved mechanical properties will allow to increase durability and performance of pavement or to assure the same performance with a thinner layer of concrete pavement.

1.3. Joints, dimensions and reinforcement of concrete pavement

Concrete pavement joint function includes control of cracking, provision of load transfer, isolation of structures that behave differently, and provision of the lane delineation (Federal Highway Administration, 2019). Jointing of precast concrete panels has to be designed in longitudinal and transversal directions, thus assuring that percentage of the load to be transferred across the joint is 100%.

The spacing of transverse and longitudinal contraction joints depends on material and environmental conditions. Joint spacing selected from empirical data or calculated evaluating the relationship between the maximum panel length (L) and the radius of relative stiffness (l). The recommended ratio between slab length, pavement thickness and Effective Modulus of Subgrade Reaction (k value) is presented in Figure 3. Smith, Peshkin, Darter, Mueller, & Carpenter (1990) stated that joint faulting and transverse cracking appear more frequently when joint spacing is above 5.5 m (Smith, Peshkin, Darter, Mueller, & Carpenter, 1990). In *ZTV Beton-StB 07 Zusätzliche Technische Vertragsbedingungen und Richtlinien für den Bau von Tragschichten mit hydraulischen Bindemitteln und Fahrbahndecken aus Beton*, transversal contraction joints are constructed in the same locations as a notch in the hydraulically bound base layer (HBBL) with not greater than 5 m spacing. Federal Highway Administration (2019) stated good performance practice of JPCR with panels of 4.6 m in length and 3.7 m in width. The ratio between the slab width and length, according to American Association of State... (1993) should not exceed 1.25, and according to Federal Highway Administration (2019) should not exceed 1.5.

Properly designed and maintained contraction joints eliminated the need for expansion joints except at connections with structures and around manholes (*ZTV Beton-StB 07*; Mallick & El-Korchi, 2013). The ratio between maximum dimension and thickness of the slab according to *ZTV-Beton StB 07* should be less than 25 times and according to Federal Highway Administration (2019) within 18–24 times, and if this ratio is not assured the reinforcement has to used. According to Smith and Snyder (2017), precast panels should be reinforced to ensure the handling and transportation conditions. During the production of the slab and concrete hardening, it is necessary to assure the precast concrete slab resistance to warping.

The dowel bars or dowel-type elements are required for the joint plane concrete pavement to ensure the load transfer across the transversal joint. Dowel bars reduce slab deflection by nearly 50%

Table 2. Summary of the analysed improved cement concrete mixtures

Reference	Concrete	Composition					Mechanical properties		
		Cement		Water	Superplasticizer	Additives	Strength test		
		Type	Content, kg/m³	Content, ratio	Type, quantity		Compressive,	Tensile,	Flexural,
							MPa (period)		
Naik, Ramme, & Tews (1994)	High volume fly ash concrete	Type I Portland cement	216.0–218.0	0.34–0.40	Melamine-based 3.549 l	Class C fly ash 20%; air-entraining agent 207 ml	27.00–34.00 (28 days)	2.70–3.60 (28 days)	4.40–4.80 (28 days)
Shannag (2000)	Natural pozzolan and silica fume concrete	Pozzolanic Portland cement	340.0	0.35*	Sulfonated naphthalene formaldehyde 7.0–8.0 l	Natural puzzolan 60 kg/m³; silica fume 20.0–80.0 kg/m³	78.00–85.00 (28 days)	5.15–5.85 (28 days)	–
Hesami, Ahmadi, & Nematzadeh (2014)	Rice husk ash and fibres containing pervious concrete	Type II Portland cement	306.0	0.33	Carboxylic ether (Glenium-110P, BASF) 3.50 kg/m³	Polyphenylene sulphide fibre 0.30%; RHA 34.0 kg/m³	~29.00 (28 days)	~3.30 (28 days)	~4.90 (28 days)

Nehdi, Pardhan, & Koshowski (2004)	Self-consolidating concrete	Type 10 Portland cement (CSA3-A5-M93)	215.0	0.38	Naphthalene-sulfonated superplasticizer	High-range water reducer 4.9 l/m^3; polysaccharide welan gum powder 0.2 kg/m^3; class F fly ash 105.0 kg/m^3; ground granulated blast furnace slag 105.0 kg/m^3	36.90 (28 days)	–	–
Isaia, Gastaldini, & Moraes (2003)	High-performance concrete	High-early strength portland cement	367.0	0.35	Naphthalene-based superplasticizer 24.50 kg/m^3	Rice husk ash 122.0 kg/m^3	75.60 (28 days)	–	–
Jalal, Pouladkhan, Harandi, & Jafari (2015)	High-performance self-compacting concrete	ASTM Type II Portland cement	490.0	0.38	Polycarboxylic-ether type superplasticizer 3.12 kg/m^3	Nano silica 10.0 kg/m^3	82.10 (28 days)	4.70 (28 days)	6.10 (28 days)
Huang, Wu, Shu, & Burdette (2010)	Polymer-modified pervious concrete	Type I Portland cement	324.5	0.35	–	Latex binder 32.5 kg/m^3	15.00 (7 days)	1.40 (7 days)	–
Rangelov, Nassiri, Haselbach, & Englund (2016)	Reinforcing previous concrete	Type I/II Portland cement	337.2	0.24	–	Class F fly ash 59.5 kg/m^3	16.60 (7 days)	1.80 (7 days)	–

Note: *c = cement content + silica fume + natural puzzolan.

(Darter, Hall, & Kuo, 1995). Table 3 gives a review of the dimensions and spacing of dowels. Additional considerations for PCP are to analyse of:

1. load transfer at joint;
2. base layer conditions;
3. temperature-related curling/warping and width of the panel (transverse joint spacing);
4. expansion joint width and spacing.

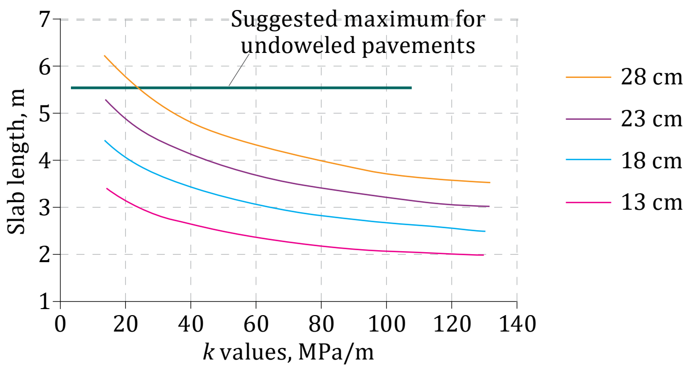


Figure 3. Recommended ratio between slab length and pavement thickness (American Concrete Institute..., 2002)

Table 3. Review of dimensions and spacing of dowels

Thickness of slab, mm	Dowel diameter, mm	Length, mm	Dowel spacing, mm	Reference
152–178	20	460	305	*AC 150/5320-6F Airport Pavement Design and Evaluation*
191–305	25	460	305	
318–406	30	510	380	
419–508	40	510	460	
521–601	50	510	460	
below 200	Dowels are not required			American Concrete Institute... (2002)
200	32	450	300	
250	32	450	300	
280	38	450	300	
300	38	450	300	
350	44	500	300	
no less than 400	50	600	450	
200	25	500	500	*ZTV-Beton StB 07*
230–270	25	500	250	

2. The subject of experiment and methodology

The slab thickness and dimensions were calculated corresponding to the boundary conditions based on the semi-probabilistic analysis detailed in *RDO Beton 09* to evaluate the effect of mechanical properties of the concrete mixture on the PCP. Boundary conditions of the moment used in concrete pavement design are presented in Table 4 and Figure 5. In this study three-pavement performance conditions at two locations in the slab, defined using probabilities to failure models, were evaluated to determine concrete slab dimensions (Table 4):

- boundary conditions of bearing capacity – represent structural failure distress of concrete pavement (transversal cracking and joint faulting);
- the boundary condition of performance – represent surface failure distress of concrete pavement (roughness);
- the boundary condition of fatigue resistance – represent the bearing capacity for the accumulation of stresses occurring in the long term of repetitive loading.

The bending moments are calculated for all boundary conditions at the centre of the longitudinal and transversal joint. Locations for the estimation of bending moment in the slab are presented in Figure 4.

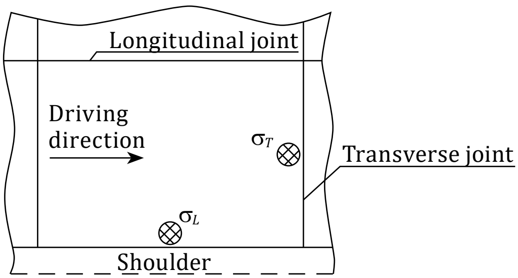


Figure 4. Locations for the estimation of bending moment in the slab

Table 4. Boundary conditions for concrete pavement design

Boundary conditions	Bending moment	
	At longitudinal joint (*L*) at slab centre of the edge	**At transverse joint (*T*) at slab centre**
Bearing capacity (BCBC)	$M_{R,BCBC,L} \geq M_{E,BCBC,L}$	$M_{R,BCBC,T} \geq M_{E,BCBC,T}$
Performance (BCPC)	$M_{R,BCPC,L} \geq M_{E,BCPC,L}$	$M_{R,BCPC,T} \geq M_{E,BCPC,T}$
Fatigue resistance (F)	$M_{R,F,L} \geq M_{E,F,L}$	$M_{R,F,T} \geq M_{E,F,T}$

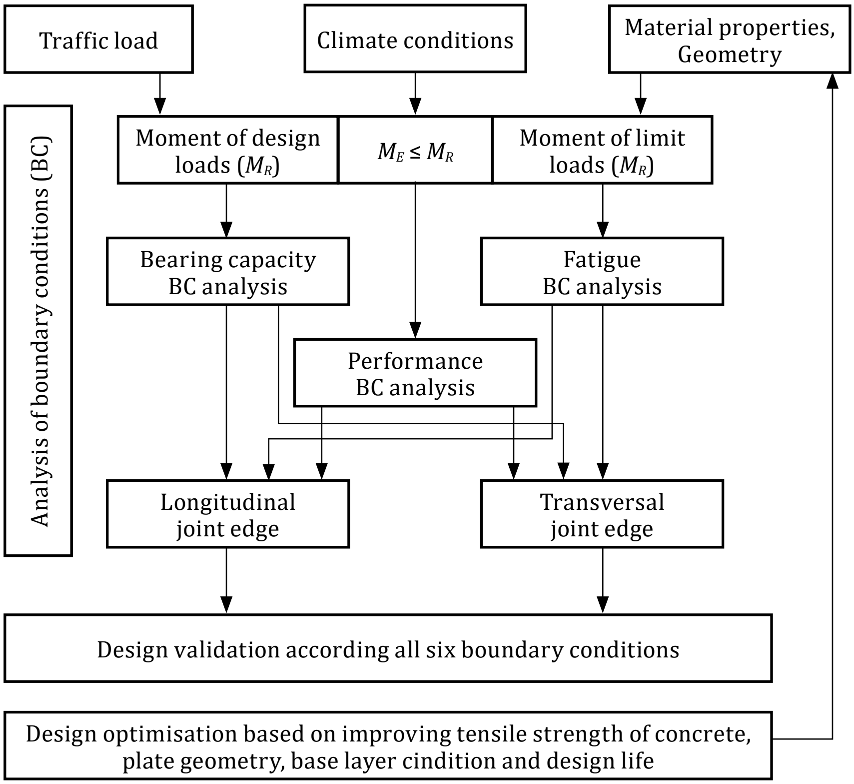


Figure 5. Concrete pavement design based on boundary conditions of design moment M_E and limit moment M_R (Villaret, Kiehne, Riwe, & Villare, 2008)

The basis of concrete pavement design is the assurance that the limit (threshold) bending moments M_R are no less than the design bending moments M_E in all analysis cases. The limit bending moments M_R mainly depending on the slab thickness and strength, which are calculated according to the Eq. (1).

$$M_R = 0.167 h_d^2 f_d, \tag{1}$$

where M_R – limit bending moment, Nmm/mm; h_d – thickness of the concrete surface, mm; f_d – calculated strength, N/mm^2, according to the adjustment factor m_b and primal calculated strength f_d^0.

Based on analysis cases the calculated strength f_d varies depending on analysis type and primal calculated strength f_d^0 (Table 5), which directly corresponds to the characteristic tensile splitting strength f_{ctk} of the concrete and safety coefficients to evaluate reliability. For the limit bending moment estimation under boundary condition of fatigue resistance (longitudinal joint $M_{R,F,L}$ and transverse joint $M_{R,F,T}$) the design load A of equivalent 10 t axles over the design life is evaluated with fatigue coefficient $\gamma_{c,F}$, which depending on the load transfer factor γ_q and is calculated according to the Eq. (2).

$$\gamma_{c,F} = 0.15\log\left(\gamma_q A\right) + 0.748\mathrm{e}^{-0.1365}, \quad (2)$$

where $\gamma_{c,F}$ – fatigue coefficient, which evaluates the design load of equivalent 10 t axles over the design life; A – number of equivalent 10 t weight axial load over the design life, millions of passes; γ_q – load transfer factor, according to Table 6.

Table 5. The factors for calculated strength estimation based on the analysis type of pavement performance conditions

Analysis type of pavement performance conditions	Coefficients	
	m_b	f_d^0
Boundary conditions of bearing capacity and of performance	1.0	$\frac{f_{ctk}}{k_{bt}}$
The boundary condition of fatigue resistance	$\frac{1}{\gamma_{c,F}}$	$\frac{k_{bn} f_{ctk}}{k_{bt}}$

Table 6. Load transfer factors γ_q

Slab width, m	Longitudinal joint $\gamma_{q,L}$	Transverse joint $\gamma_{q,T}$
> 2.00 to 2.50	0.400	0.90
> 2.50 to 3.00	0.180	0.80
> 3.00 to 3.50	0.140	0.70
> 3.50 to 3.75	0.018	0.70
> 3.75 to 4.50	0.008	0.60

The design bending moments M_E that occur in the slab from design load or temperature application, are calculated as a sum of design moments caused by traffic load M_{EV} and by temperature M_{ET}.

$$M_E = M_{EV} + M_{ET}, \quad (3)$$

$$M_{EV} = m_{bL} m_{bd} F_d 1000\left[0.55\lg\left(\frac{I_v}{b}\right) + 0.1\frac{b}{I_v} - 0.011\right], \quad (4)$$

$$M_{ET} = \alpha_{cT}\gamma_{tot}E_{ctm}\frac{h_m^3\, m_{t_1}\, m_{t_2}\, m_{t_3}\, \delta_t}{12}, \quad (5)$$

where factors used for the calculation of M_{EV}, M_{ET} are given in *RDO Beton 09*.

The slab design of PCP for the evaluation of mechanical properties of the concrete mixture was carried out combining *RDO Beton 09* and *KPT SDK 19 Automobilių kelių standartizuotų dangų konstrukcijų projektavimo taisyklės* technical regulations. The design load calculated assuming the annual average daily traffic (AADT, vpd) is 10 000 heavy vehicles per day, the design life of 30 years, with 3% of annual growth of AADT. The design of the national road, where the allowed driving speed of 90 km/h. Thus, the estimated design load *A* for the service life is 76 million of equivalent 10 t weight of standard axle load. The summary of design input data and coefficients are presented in Table 7. The input of variables for concrete pavement design and estimation of slab thickness and dimensions are presented in Table 8. The reinforcement was provided with a diameter of 25 mm and 500 length dowels placed with 250 mm spacing to ensure the load transfer efficiency at PCP slab joints.

Table 7. Summary of design input data and coefficients

Name	Symbol	Unit	Inputs
Design year,	N		30
Annual average daily traffic of heavy vehicles	AADT(SV)	vpd	10 000
Coefficient of axle numbers	f_A	–	3.90
Single axles		axles per day	39 000
Coefficient of axle load	q_{Bm}	–	0.20
Coefficient of lane numbers	f_1	–	0.50
Coefficient of lane width	f_2	–	1.10
Coefficient of longitudinal slope	f_3	–	1.02
Annual traffic growth	p	–	0.03
Coefficient of annual traffic growth	f_z	–	1.586
Design equivalent single axle load (ESAL)	A	mln.	75.986

Table 8. Concrete pavement design variables

Design code	Pavement base layer type	Concrete class	Tensile splitting strength	Tensile elasticity modulus	Concrete slab	
					length	width
			f_{ctk}, N/mm²	E_{ctm}, GPa	L, m	W, m
1-1	Crushed stone	C30/37	3.7	41.0	4.60	4.10
1-2	Crushed stone	C35/45	4.0	42.0	4.60	4.10
1-3	Crushed stone	C40/50	4.6	44.0	4.60	4.10
1-4	Crushed stone	C40/50	4.7	46.0	4.60	4.10
1-5	Crushed stone	C40/50	4.8	48.0	4.60	4.10
2-1	Crushed stone	C40/50	4.6	44.0	5.00	4.10
2-2	Crushed stone	C40/50	4.6	44.0	4.60	4.00
2-3	Crushed stone	C40/50	4.6	44.0	4.40	4.00
2-4	Crushed stone	C40/50	4.6	44.0	4.40	3.80
2-5	Crushed stone	C40/50	4.6	44.0	4.40	3.50
2-6	Crushed stone	C40/50	4.6	44.0	4.20	4.00
2-7	Crushed stone	C40/50	4.6	44.0	4.20	3.80
2-8	Crushed stone	C40/50	4.6	44.0	4.20	3.50
3-1	Hydraulically bound base layer	C30/37	3.7	41.0	4.60	4.10
3-2	Hydraulically bound base layer	C35/45	4.0	42.0	4.60	4.10
3-3	Hydraulically bound base layer	C40/50	4.6	44.0	4.60	4.10
3-4	Hydraulically bound base layer	C40/50	4.7	46.0	4.60	4.10
3-5	Hydraulically bound base layer	C40/50	4.8	48.0	4.60	4.10

Note: 1-1 design inputs of the reference concrete pavement structure used to determine the effect of variables.

3. Result analysis and interpretation

The analysis and application of the *RDO Beton 09* concrete pavement design method allowed comprehending the concrete mechanical properties, the influence of the base layer and slab dimension on the nominal thickness of concrete. The designed concrete slab thickness and the determined M_E and M_R are presented in Tables 9 and 10, respectively. The relation between boundary conditions design and limit (threshold) bending moments are presented in Figure 6. For the comparison of results, the concrete slab of C30/37 with dimensions 4.60×4.10 m (design code No. 1-1) was selected as the reference slab since those slabs are typically used for road pavement.

The first analysis step was to determine the effect of mechanical properties on the concrete slab thickness (design code 1-1...1-5), where the dimensions of the slab were fixed and the tensile splitting strength (f_{ctk}) and tensile elastic modulus (E_{ctm}) were varied. The effect of concrete mechanical properties on slab thickness is presented in Figure 7. The calculation results showed that the increase in f_{ctk} from 3.7 MPa to 4.8 MPa allowed decreasing the nominal slab thickness by 15.5%, from 264 mm to 223 mm.

Then the effect of slab dimensions on the concrete slab thickness was investigated (design code 2-1...2-8), where the length (L) and width (W) of the slab were variable and mechanical properties were fixed (Table 9). The length and width ratio varied from 1.05 to 1.26. The effect of slab dimension on the design slab thickness is presented in Figure 8. The results showed that the change in slab width had the most significant effect on the nominal thickness of concrete slab. The lowest thickness of concrete slab 218 mm was determined for the slabs of 4.4×3.5 m and 4.2×3.5 m, which had the highest L/W ratio of 1.26 and 1.2. The suggested optimal PCP slab dimensions for roads are 4.6 m in length and 4.0 m in width with 227 mm concrete slab thickness.

Also, the base layer influence was analysed by comparing the designed nominal thickness of concrete slab determined under crushed stone aggregate (unbound) base layer (design code 1-1...1-5) and HBBL (design code 3-1...3-5). This analysis was carried out for the fixed dimensions of the slab and varied the tensile splitting strength (f_{ctk}) and elastic modulus (E_{ctm}). The comparison of base layer type with design slab thickness is presented in Figure 9. A positive result of HBBL was only determined for No. 3-1, where the nominal thickness of concrete slab was 2.7% less compared to the crushed stone aggregate base layer. Other design results showed the increased thickness of concrete slab by 1.1–2.3%. According to Bradbury (1938), curling and warping stress analysis, the stiffer base material leads to smaller relative stiffness l, and likewise, a higher L/l ratio for the same joint spacing and higher curling stress. According to the literature and design results, the use of stiffer base layers and thinner concrete slab shall be correspondently adjusted to the joint spacing; otherwise, it may lead to the cracking of HBBL layer due to curling and warping.

Table 9. The limit (threshold) bending moments for design concrete slabs

Design code	Nominal thickness of concrete pavement, mm	Limit (threshold) bending moment M_R, Nmm/mm					
		$M_{E,BCB,L}$	$M_{E,BCBC,T}$	$M_{E,BCPC,L}$	$M_{E,BCPC,T}$	$M_{E,F,L}$	$M_{E,F,T}$
1-1	264	40 023	40 023	43 065	43 065	28 447	24 206
1-2	251	39 112	39 112	42 085	42 085	27 800	23 655
1-3	229	37 440	37 440	40 285	40 285	26 611	22 644
1-4	226	37 258	37 258	40 090	40 090	26 482	22 534
1-5	223	37 047	37 047	39 863	39 863	26 332	22 406
2-1	229	37 440	37 440	40 285	40 285	26 611	22 644
2-2	227	36 789	36 789	39 585	39 585	26 148	22 250
2-3	227	36 789	36 789	39 585	39 585	26 148	22 250
2-4	223	35 504	35 504	38 202	38 202	25 235	21 473
2-5	218	33 929	33 929	36 508	36 508	23 348	20 412
2-6	227	36 789	36 789	39 585	39 585	25 315	22 132
2-7	223	35 504	35 504	38 202	38 202	24 431	21 359
2-8	218	33 929	33 929	36 508	36 508	23 348	20 412
3-1	257	37 929	37 929	40 812	40 812	26 959	22 940
3-2	257	41 004	41 004	44 121	44 121	29 145	24 800
3-3	232	38 427	38 427	41 348	41 348	27 313	23 241
3-4	230	38 588	38 588	41 521	41 521	27 427	23 339
3-5	227	38 388	38 388	41 306	41 306	27 285	23 217

Table 10. The design bending moments for design concrete slabs

Design code	Nominal thickness of concrete pavement, mm	Design bending moment M_E, Nmm/mm					
		$M_{E,BCB,L}$	$M_{E,BCBC,T}$	$M_{E,BCPC,L}$	$M_{E,BCPC,T}$	$M_{E,F,L}$	$M_{E,F,T}$
1-1	264	29 117	29 145	20 411	20 143	23 265	24 114
1-2	251	28 320	28 406	19 910	19 724	22 612	23 541
1-3	229	26 902	27 079	19 030	18 979	21 455	22 514
1-4	226	26 811	27 010	18 987	18 965	21 404	22 454
1-5	223	26 713	26 932	18 938	18 944	21 343	22 387
2-1	229	28 312	27 079	20 440	18 979	22 588	22 514
2-2	227	26 755	26 643	18 938	18 603	21 332	22 111
2-3	227	26 100	26 643	18 283	18 603	20 772	22 111
2-4	223	25 814	25 806	18 109	17 886	20 539	21 341
2-5	218	25 450	24 697	17 888	16 930	20 242	20 317
2-6	227	25 474	26 643	17 657	18 603	20 194	22 111
2-7	223	25 199	25 806	17 494	17 886	19 987	21 341
2-8	218	24 849	24 697	17 287	16 930	19 717	20 317
3-1	257	27 727	27 087	20 375	19 481	20 953	22 861
3-2	257	27 789	27 155	20 420	19 533	21 413	24 766
3-3	232	26 081	25 600	19 240	18 551	19 263	23 231
3-4	230	26 043	25 584	19 219	18 555	19 763	23 257
3-5	227	25 923	25 491	19 141	18 509	20 109	23 200

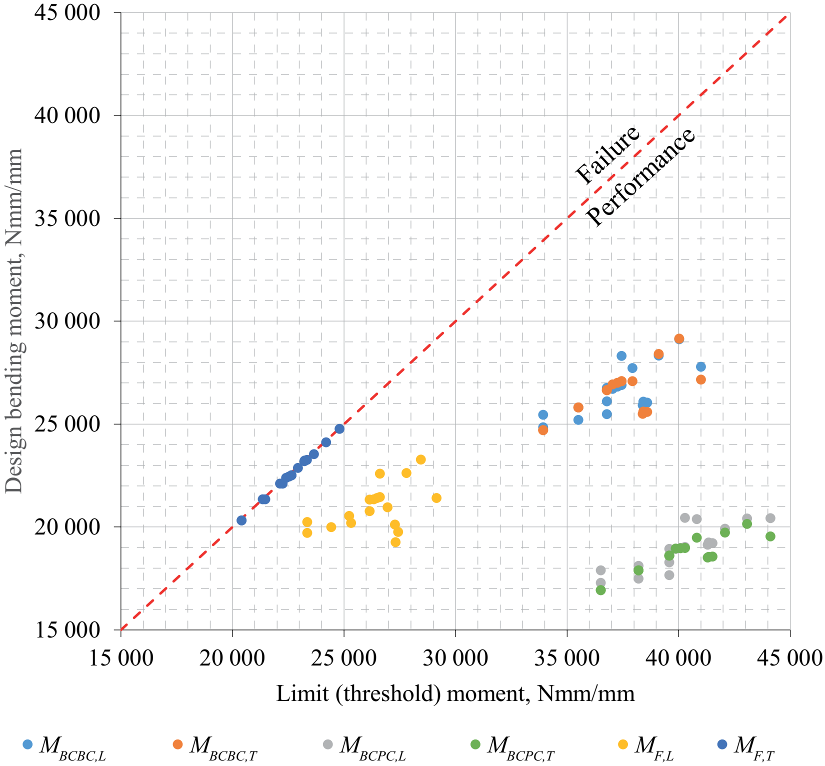


Figure 6. The relation between boundary conditions design and limit (threshold) bending moments

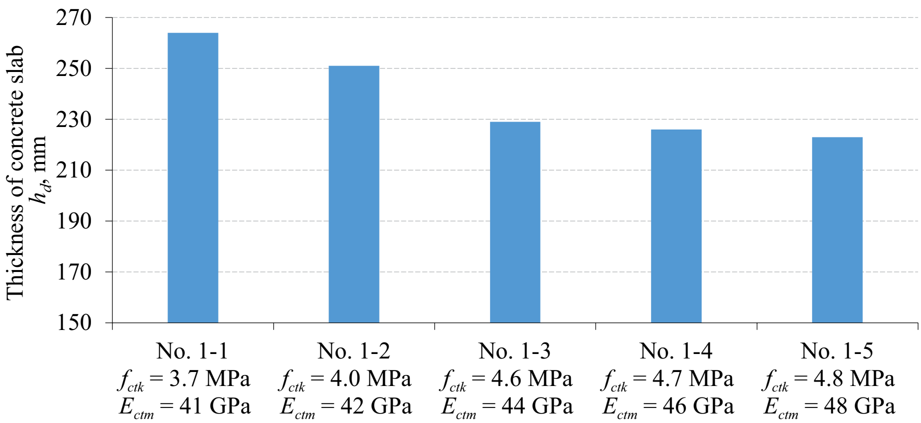
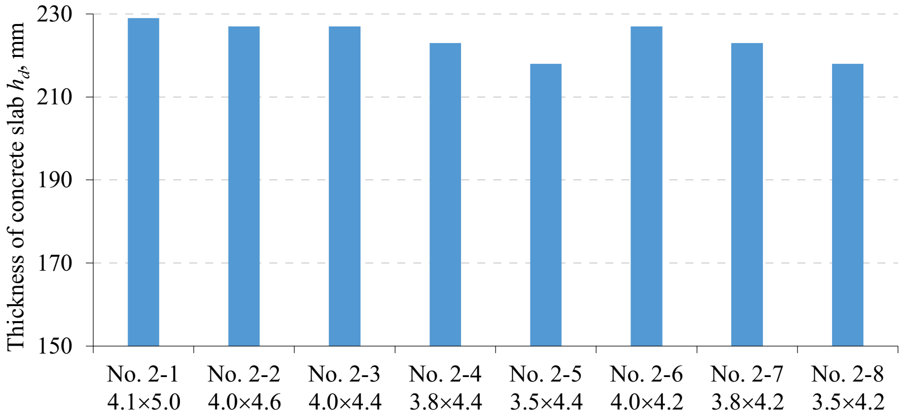


Figure 7. The effect of concrete mechanical properties on slab thickness



Note: length×width, in meters

Figure 8. The effect of slab dimension on design slab thickness

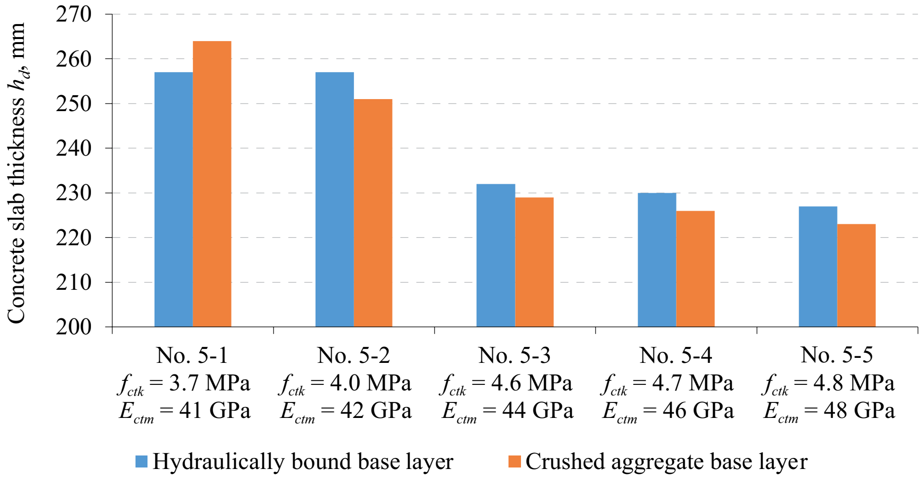


Figure 9. The comparison of base layer type with design slab thickness

Conclusions

Analytical analysis based on semi-probabilistic analysis of bending moments let to define the minimal thickness of precast concrete pavement dependent on slab dimensions and mixture strength. Summarising the results of concrete pavement modelling, the following conclusions were drawn:

1. The fatigue bending moment of the transverse joint is a critical boundary condition evaluating precast concrete pavement structural performance. Depending on precast concrete pavement mixture properties and pavement base layer type the fatigue bending moment in the centre of transverse joint differs from 20 412 Nmm/mm to 24 800 Nmm/mm.

2. The increase of tensile splitting strength from 3.7 MPa to 4.8 MPa lets to reduce the precast concrete pavement concrete slab thickness by 15.5%, from 264 mm to 222 mm, i.e. the difference of 42 mm. However, an increase of tensile splitting strength from 4.6 MPa to 4.8 MPa effect slab thickness very slightly.

3. The minimum thickness of precast concrete pavement slab (218 mm) was determined for the dimensions (length×width) of 4.4×3.5 m and 4.2×3.5 m. Considering standard 3.5 m width of the traffic lane and the impact of the wheel to pavement by distance from joint, the dimensions of the optimal precast concrete pavement slab are 4.6×4.0 m with 227 mm thickness. The cement concrete C40/50 with tensile splitting strength (equal to 4.6 MPa) and the tensile elastic modulus (equal to 44 GPa) can be specified as optimal. Further increase of these mechanical properties does not affect the slab thickness.

4. The thickness of precast concrete pavement slab (4.6×4.1 m and C30/37 class standard concrete) with the hydraulically bound base layer allowed to reduce the nominal thickness of concrete slab by 2.7% (257 mm) compared to the crushed aggregate base. However, stiffer cement concrete mixture of precast concrete pavement has the opposite effect on the slab thickness with the hydraulically bound base layer. The analysis showed that optimal dimensions of precast concrete pavement slab with unbound crushed aggregate base layer provide more reliable performance than with the hydraulically bound base layer.

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