SWEDISH DESIGN OF INDUSTRIAL CONCRETE PAVEMENTS

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ABSTRACT

The use of concrete pavements for industrial purposes has increased in Sweden during recent years. Concrete pavements have high load distribution ability, high wear resistance and can resist long lasting and concentrated loads without permanent deflections. The axle loads may exceed 100 metric tons. Adapting the robust design procedures that are used for highway pavements without changes would lead to very thick and expensive industrial pavements. Consequently, it is mandatory to find possibilities to optimize the design without jeopardizing the good performance. The pavement design covers plain concrete, roller compacted concrete, reinforced concrete, and steel fiber reinforced concrete, both with and without bound bases. The paper also deals with the experience of some industrial pavements that have been constructed based on the new design method.

INTRODUCTION

The use of concrete pavements for industrial purposes like ports, timber stores, and other heavily trafficked surfaces has increased in Sweden during recent years. Concrete pavements have high load distribution ability, high wear resistance and can resist long lasting and concentrated loads without permanent deflections. Axle loads trafficking industrial pavements may exceed 100 metric tons. A concrete pavement for highway is traditionally designed in a very robust manner with means a very low failure probability during the pavement's lifetime. If this pavement design procedure is adapted to industrial pavements they will be very thick and expensive. Consequently, it is mandatory to find possibilities to optimize the design without jeopardizing the good performance. The Department of Structural Engineering at KTH has investigated several concrete pavement alternatives and developed design tables for industrial pavements. This paper is a summary of the complete report (Silfwerbrand /11/).

COMPUTATION ASSUMPTIONS

Pavement Systems

The pavement system consists usually of a wear layer, an unbound base layer of crushed gravel, and a subbase of similar type. The wear layer may consist of plain concrete, roller compacted concrete (RCC), reinforced concrete (RC), steel fiber reinforced concrete (SFRC), or asphalt. In some cases, stabilized bases are inserted between the wear layer and the unbound base layer. Six main cases have been included in this study (Figure 1)

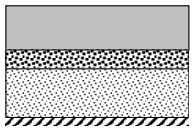
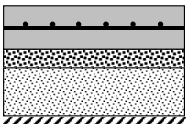
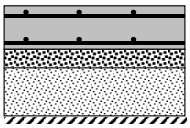
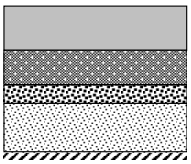
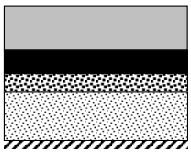
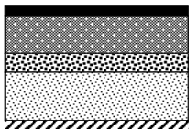
Case a Concrete, RCC, or SFRC	*Case b* RC, centrally placed reinforce-ment	*Case c* RC, reinforce-ment in two layers	*Case d* Concrete + cement bound base or RCC + cement bound base	*Case e* Concrete + asphalt bound or RCC + asphalt bound base	*Case f* Asphalt wear layer + cement bound base
					
• *h* concrete • 80 mm unbound (crushed) base • 220 mm unbound (crushed) subbase • subgrade	• *h* reinforced concrete • 80 mm unbound (crushed) base • 220 mm unbound (crushed) subbase • subgrade	• *h* reinforced concrete • 80 mm unbound (crushed) base • 220 mm unbound (crushed) subbase • subgrade	• *h* concrete • 160 mm cement bound base • 80 mm unbound (crushed) base • 220 mm unbound (crushed) subbase • subgrade	• *h* concrete • 100 mm asphalt bound base • 80 mm unbound (crushed) base • 220 mm unbound (crushed) subbase • subgrade	• 40 mm asphalt • *h* cement bound base • 80 mm unbound (crushed) base • 220 mm unbound (crushed) subbase • subgrade

Figure 1 – Pavement systems considered.

Material Data

Material data used for the various pavement layers are shown in Table 1. The data concern modulus of elasticity, Poisson's ratio, compressive cube strength, and flexural strength. The modulus of elasticity of asphalt materials and subgrade materials is season dependent. The five various subgrade materials that are given represent five subgrade types used in Swedish pavement design (No. 1-5). There is also a group of subgrade materials of type No. 6, but they cannot be used without strengthening (by using a capping layer, e.g.) and have, thus, been omitted.

Table 1 – Material data.

Material	*Climate period*						
	Spring	*Summer*	*Autumn*	*Deeper than frost zone*	*All*	*All*	*All*
	Modulus of elasticity (MPa)				*Poisson's ratio*	*Com-pressive strength (MPa)*	*Flexural strength (MPa)*
Concrete	32 000	32 000	32 000	—	0.20	40	4.8 (5.5[3])
RCC	32 000	32 000	32 000	—	0.20	40	4.8 (5.6[3])
SFRC	32 000	32 000	32 000	—	0.20	40	4.8 (6.0[4])
Asphalt wear layer	15 500	5 000	11 700	—	0.40	—	—
Asphalt base	15 500	5 000	11 700	—	0.40	—	—
Cement base[1]	8 000	8 000	8 000	—	0.25	—	—
Cement base[2]	17 000	17 000	17 000	—	0.25	—	—
Unbound base	450	450	450	450	0.35	—	—
Subbase	350	350	350	350	0.35	—	—
1 Crushed rock	150	150	150	150	0.35	—	—
2 Sand	70	100	100	100	0.35	—	—
3 Silty sand	35	100	100	100	0.35	—	—
4 Clay	30	50	50	50	0.35	—	—
5 Silt	10	45	45	45	0.35	—	—

Notes. [1] Values used if placed below concrete (base supposed to be cracked). [2] Values used if placed below asphalt (base supposed to be uncracked). [3] Strength development is considered. [4] Strength development is considered and increased cracking allowed due to reduced cracking severity.

Climate Conditions

Sweden is 1 700 km long and located between 55° and 70° of latitude. It is divided into six climate zones (Figure 2) according to Swedish National Road Administration /13/. Since the damage that climate and traffic are causing during the winter season is negligible, only spring, summer, and autumn conditions have to be considered in design (Table 2). All calculations behind this paper have been carried out for climate zone 2 (containing, e.g., Stockholm), since the experience show that the differences between the climate zones concerning pavement thickness are negligible, see Silfwerbrand /10/.

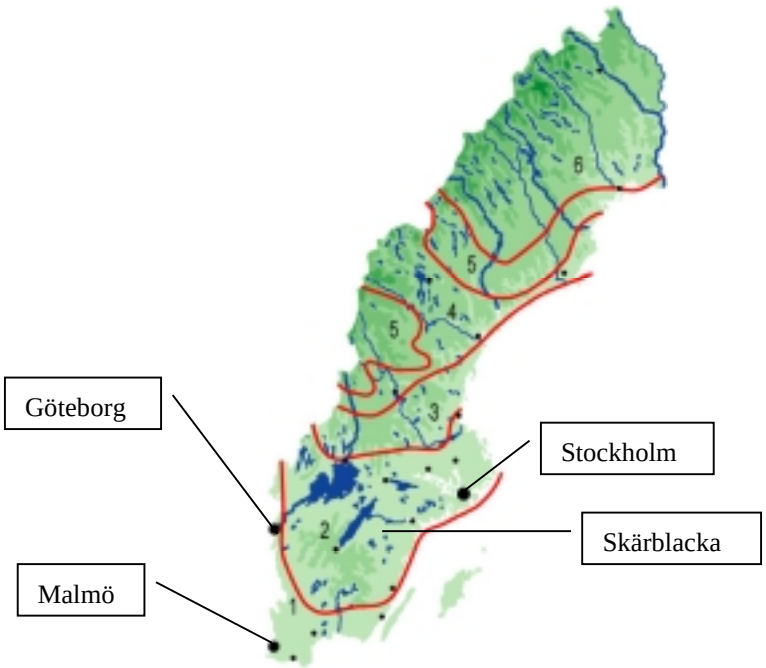


Figure 2 – Sweden is divided into six climate zones.

Table 2 – Sweden's six climate zones with corresponding seasonal lengths (days per year) and frost data.

Season	*Climate zone*					
	1	*2*	*3*	*4*	*5*	*6*
Accumulated negative degrees×days[1]	*0 – 300*	*300 – 600*	*600 – 900*	*900 – 1200*	*1200 – 1500*	*> 1500*
Spring (frost heave)	20	30	40	50	55	55
Summer	170	155	130	100	95	80
Autumn	105	90	90	75	60	50
Depth of frost zone (m)	1.0	2.0	2.5	3.0	3.5	4.0

Note. [1]60 days with an average day temperature of –5°C give 300 negative degrees×days.

Traffic Loads

Five traffic loads have been considered (Figure 3 and Table 3). The smallest load is equal to the Swedish standard axle (Swedish National Road Administration /13/). The largest load is the major axle load of a fork lift truck carrying 90 percent of its load on the front axle. The load data are collected from truck manufacturers selling trucks in Sweden.

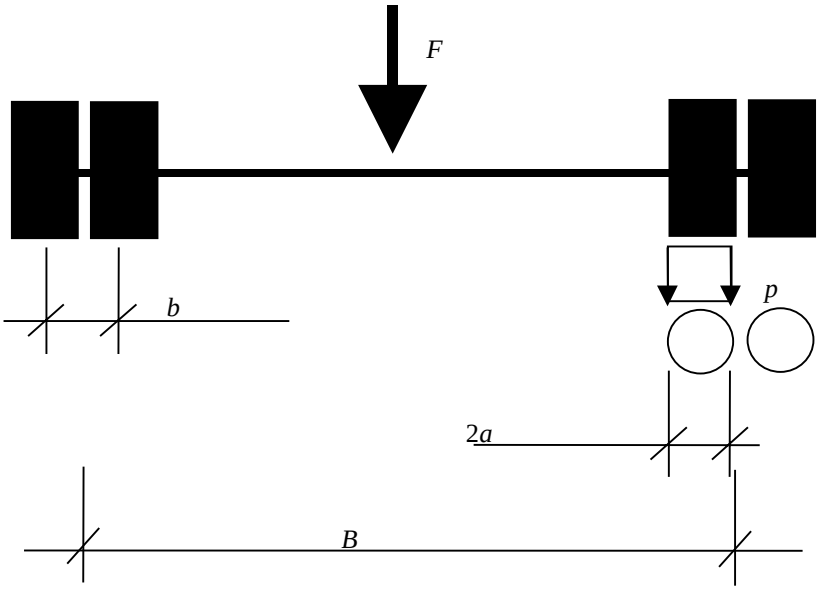


Figure 3 – Schematic presentation of an axle load.

Table 3 – Data for the five traffic loads considered.

Load No.	*Weight (metric tons)*	*Load F (kN)*	*Number of wheels on the main axle*	*Track width B (mm)*	*Distance between dual wheels b (mm)*	*Tire pressure p (MPa)*	*Radius of loaded surface a (mm)*
1	10	100	2	1 800	N/A	0.80	142
2	15	150	2	1 800	N/A	0.80	173
3	30	294	2	2 360	N/A	0.45	322
4	60	613	4	2 438	536	0.90	233
5	90	896	4	3 000	500	0.93	277

Computational Model

Traffic stresses have been computed for an elastic multi-layer pavement system. Cauwelaert's program GIPI has been used /2/. The program can consider several wheel loads and computes stresses and strains at arbitrary levels in a system with maximum five layers. The fifth layer has an infinite depth. The user defines the interface condition between the first and the second layer. Complete slip has been used for concrete, RCC, SFRC, or reinforced concrete on unbound base (case a, b, and c in Figure 1). Complete friction has been used in all other cases.

Solutions to the problem of vertical loads on an elastic multi-layer system are in principle only valid at the interior parts of an infinite slab. Higher stresses appear under the load if it is located at slab edges, slab corners or joints between slabs. Here, such loading cases have been considered in an approximate way by multiplying the stress due to interior loading with a magnification factor dependent on the number of slabs sharing the load and the load transfer efficiency between adjacent slabs. Using Westergaard's equations for slabs on dense liquid foundation, it can be shown that the stress under edge loading is roughly two times larger than the stress under interior loading (Silfwerbrand /11/). According to Swedish concrete pavement design practice, the load transfer efficiency is considered to be 100 percent in dowelled joints between concrete slabs on bound bases. If a vertical load is located close to a dowelled joint, two slabs will equally share the double load effect compared to interior loading. The magnification

factor has been set to unity. Hence, the joint loading case is the same as the interior loading case. Corner loading can be treated in a similar way. Loads close to the pavement edges can be avoided by preventing trafficking of the pavement strip closest to the edge by, e.g., painting lines. Alternatively, haunches can be used.

Joints in RCC are usually not dowelled. Hence, the load transfer efficiency is less than 100 %. It means that a magnification factor larger than unity has been used for loading close to the joint. The value of this factor is based on estimated joint width and relationship between joint width and load transfer efficiency according to PCA /6/. Details are given in Silfwerbrand /11/.

Thermal Loading

Concrete pavements have to be considered for thermal loads. They have an origin in daytime heating due to solar radiation. A linear positive (top surface warmest) thermal gradient with a magnitude of 40°C/m during 25 percent of the loading time and 60°C/m during 0.4 percent and zero during the remaining time have been used. The thermal difference between top and bottom of the concrete pavement has been limited to 10°C for the smaller magnitude and 15°C for the larger one. The limitation is due to concrete's thermal properties prohibiting daily variations to permeate deeper than 0.25 m with any substantial magnitude. The thermal stresses have been computed using Silfwerbrand's slab model /8/, /9/ developed from Eisenmann's beam model /4/ stating that thermal stresses are produced by the dead load of the slab counteracting the thermal curvature. Both models consider the beneficial effects of reducing joint spacing and taking the resilient support into account (Figure 4).

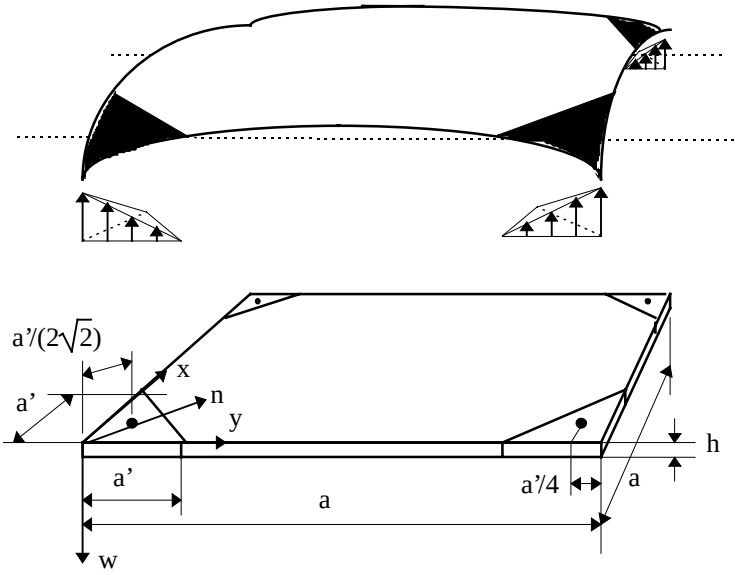


Figure 4 – The slab corners sink down into the subgrade producing pyramidal subgrade reaction distributions. The thermal stress is dependent on the slab weight and the distance between the gravity centers of the subgrade reactions. From Silfwerbrand /9/.

Likelihood of Unloaded Vehicles

On industrial pavements, only half of the truck movements may be assumed to carry load. By using Miner's-Palmgren's partial damage hypothesis, it can be shown that truck movements

without load lead to a negligible partial damage. Consequently, a reduction factor $A = 0.5$ can be introduced in the calculation procedure presented below.

Discrepancy from Complete Channelization

On an industrial pavement, the traffic may be quite irregular. There might be some parts with a traffic pattern that is more like road traffic. However, also on these "roads", the traffic will not follow exactly the same track all the time. In Silfwerbrand /7/, the effect of a discrepancy from complete channelization was studied through a statistical width distribution of ±1 m based on traffic observations. The traffic stresses were computed in nine points along a line through the major axle. The results were put together with Miner's-Palmgren's partial damage hypothesis. An analysis of the results shows that this width distribution indicates a traffic reduction of approximately 50 percent. Thus, a reduction factor $C = 0.5$ is suggested in the calculation procedure presented below.

Design Criteria

Design criteria for concrete, RCC, and SFRC are fatigue criteria based on the maximum flexural stress and Tepfers' fatigue criterion /14/. Design criteria for cement bound base and asphalt bound base are based on the maximum horizontal tensile strain and taken from Swedish National Road Administration /13/ and Djärv et al /3/, respectively. The design criterion for the subgrade is based on the maximum vertical compressive strain and taken from Swedish National Road Administration /13/.

The design of reinforced concrete pavements is based on yield line theory according to Losberg /5/. Based on his discussion, the thermal loads have been omitted in the design. The thermal load is a restrain load causing cracking. After cracking, the restrain vanishes while the reinforcement yields. The design is based on Swedish security class 1 (BBK 94 /1/), Swedish concrete grade K40, and reinforcement grade Ks 500 giving design values for concrete compressive strength of 19 MPa and steel strength at yielding of 435 MPa, respectively.

Security Philosophy

According to Swedish road design praxis, partial coefficients for load, material, and security class are all set to unity. These low values are based on the limited consequences of a damage, if any, the statically indeterminate behavior of the slab enabling stress redistribution after cracking, if any, and the possibilities to repair the damages. Reinforced concrete and SFRC have been dealt with in a slightly different way.

SFRC is assumed to have a crack distribution ability. It is here defined as SFRC having a residual strength factor $R_{10,30} > 50$ percent, see Swedish Concrete Association /12/. Consequently, a higher crack risk may be allowed in SFRC than in plain concrete. The design of plain concrete pavements is based on a characteristic flexural strength (5 % fractile). The design of SFRC pavements may be based on an average flexural strength (50 % fractile) instead. That means that 50 % of the slabs are likely to be cracked at the end of the pavement life instead of 5 %. In the computations, this difference in crack risk has been transferred to a strength difference enhancing the flexural strength of SFRC with 0.5 MPa (Table 1).

Since there is no practical and straightforward design method for reinforced concrete pavements subjected to fatigue, the author has based his design on a quotient equal to three between load carrying capacity and load. The reinforcement ratio is selected to fulfil the Swedish minimum reinforcement according to BBK 94 /1/. For the concrete grade K40 with a design tensile strength (pure tension) of 1.95 MPa and reinforcement grade Ks 500, the reinforcement ratio should be 0.49 percent in both directions.

Strength Development

In Silfwerbrand /7/, the strength development of concrete was considered by a careful computation dividing the pavement's life time in time steps and adopting Miner's-Palmgren's partial damage hypothesis. Based on an analysis of these results, a simplified procedure has been selected by increasing the flexural strength with a certain amount. It has got the value of 0.7 MPa for plain concrete and SFRC of concrete grade K40 (the flexural strength increases from 4.8 to 5.5 MPa, see Table 1) and 0.8 MPa for RCC (4.8 to 5.6 MPa) since it has a faster strength development.

Joints

The computations presume jointed pavements. Saw cuts should be made in both longitudinal and transverse direction. The depth should be 1/3 of the concrete thickness h. The joint spacing is presumed to be 3 m if $h < 0.15$ m, $20 \times h$ if $0.15 \leq h \leq 0.25$ m, and 5 m if $h > 0.25$ m. Plain and SFRC concrete pavement joints should be doweled, e.g., with epoxy coated bars with diameter $\Phi = 25$ mm and spaced 500 mm apart. RCC pavements are usually not doweled due to practical reasons. Since RCC shrinks less than plain concrete, the joint opening width is less and the appurtenant load transfer efficiency is higher than corresponding conditions in plain jointed concrete pavements without dowels. The load transfer efficiency is, of course, not as good as for doweled joints. In the computations, traffic stresses in RCC pavements have been multiplied with a factor larger than one dependent on the joint opening width in turn assumed to be linearly proportional to the joint spacing.

Further Precautions

This paper deals with design for combined traffic and thermal loads. Other issues to consider in pavement design are measures to prevent frost heave deformations and measures to secure drainage. The design tables in this paper do not cover design to limit frost heave deformations. It means that the total pavement thickness in cases with frost sensitive subgrade materials (i.e., subgrade types Nos. 4 and 5) and cold climate (climate zone 3-6) may not be sufficient to prevent frost heave deformations. However, heavily loaded industrial pavements will have such thickness values that the thickness needed to prevent such deformations will be satisfied automatically. Readers interested in drainage issues are referred to highway engineering textbooks since the industrial pavement demands the same drainage precautions as the highway pavement.

DESIGN PROCEDURE

The design procedure consists of the following steps:

1) Determine appropriate climate zone.
2) Determine intended service life *t.*
3) Determine the magnitude of major axle load of the design vehicle (10, 15, 30, 60, or 90 metric tons).
4) Determine the number of movements by using Eq. (1).
5) Estimate the material in the subgrade.
6) Select materials for the wear and base layers.
7) Determine sufficient thickness of the wear layer by using appropriate table.

$$N = t \times m \times n \times A \times B \times C \times D \quad (1)$$

where,

N = number of movements of the design vehicle (= vehicle with the largest axle load),
t = intended service life (year),
m = number of annual days with traffic (m = 200 when trafficked Monday through Friday and interruption during holidays, m = 365 when trafficked during every day),
n = number of daily movements,
A = the share of completely loaded trucks (A = 0.5 may be used if data are missing),
B = number of design axles per vehicle (B = 1.3 may be used as default for lorries and B = 1.0 may be used for trucks with the major part of the load carried by one of the axles),
C = coefficient describing the degree of channelization (C = 0.5 may be used as default for roads), and
D = coefficient characterizing the industrial pavement (D = 1.0 for roads and D < 1,0 for parking lots; in the latter case, D = 0.1 or D = 0.2, e.g., may be used as default).

DESIGN TABLES AND DISCUSSION

The report (Silfwerbrand /11/) contains 40 design tables including a container loading case (Table 4). All pavement alternatives do not provide solutions for all loads. The selected cases are the ones that are considered to have the most economical potential. The tables concerning concrete pavements for various loads are reprinted here (Tables 5-9). Tables 10 to 13 show comparisons between various pavement systems for specific number of movements and subgrade types. For small traffic loads, plain concrete pavements have the smallest thickness. A system composed by an asphalt wear layer on a cement bound base may compete, especially on good subgrades (Tables 10 and 11). For heavy loads, reinforced concrete pavements are thinnest. In cases with few movements, systems composed by plain concrete on cement (Tables 10 and 12) or asphalt bound bases (Table 10) may be competitive. The beneficial structural behavior of these pavements is due to the used design criteria that in turn are based on evaluation of Swedish test roads. The design criterion for the cement bound base is highly fatigue sensitive, i.e., the

load carrying capacity is supposed to decrease rapidly with the number of load repetitions. This is the reason for the need of very thick base layers in cases with large number of traffic movements.

SFRC pavements may be an alternative in cases with heavy and numerous traffic loads (Tables 11 and 13). By improving the properties of the SFRC towards strain hardening, it would be possible to reduce thickness further. RCC pavements are always slightly thicker than corresponding plain concrete pavements. The extra cost for concrete volume may be compensated by reduced costs for dowels and doweling.

Table 4 – Design tables given in the report (Silfwerbrand /11/).

Pavement system	*Axle load (kN)*				
	100	*150*	*300*	*600*	*900*
Concrete	X	X	X	X	X
RCC	X	X	X	X	X
Reinforced concrete				X	X
Concrete + cement bound base				X	X
RCC + cement bound base				X	X
Concrete + asphalt bound base	X			X	X
RCC + asphalt bound base				X	X
SFRC				X	X
Asphalt wear layer + cement bound base	X	X	X		

Table 5 – Required thickness (mm) for jointed and doweled concrete pavements subjected to 100 kN axle loads, for various subgrade materials, and all climate zones.

Subgrade	*Number of movements*						
type (No.)	*10 000*	*30 000*	*100 000*	*300 000*	*1 000 000*	*3 000 000*	*10 000 000*
1	110	115	120	125	130	135	140
2	120	125	130	135	135	140	145
3	120	125	130	135	135	140	145
4	130	135	140	145	145	150	155
5	135	140	140	145	150	155	175

Table 6 – Required thickness (mm) for jointed and doweled concrete pavements subjected to 150 kN axle loads, for various subgrade materials, and all climate zones.

Subgrade	*Number of movements*						
type (No.)	*10 000*	*30 000*	*100 000*	*300 000*	*1 000 000*	*3 000 000*	*10 000 000*
1	135	140	145	150	155	160	165
2	145	150	150	155	160	170	175
3	145	150	155	160	165	170	180
4	155	160	165	175	180	190	200
5	165	170	175	180	190	200	230

Table 7 – Required thickness (mm) for jointed and doweled concrete pavements subjected to 300 kN axle loads, for various subgrade materials, and all climate zones.

Subgrade	*Number of movements*						
type (No.)	*10 000*	*30 000*	*100 000*	*300 000*	*1 000 000*	*3 000 000*	*10 000 000*
1	160	165	175	185	195	200	210
2	180	185	195	200	210	220	230
3	180	185	195	200	210	220	230
4	205	210	220	230	240	250	260
5	210	220	225	235	250	265	330

Table 8 – Required thickness (mm) for jointed and doweled concrete pavements subjected to 600 kN axle loads, for various subgrade materials, and all climate zones.

Subgrade	*Number of movements*						
type (No.)	*10 000*	*30 000*	*100 000*	*300 000*	*1 000 000*	*3 000 000*	*10 000 000*
1	300	310	320	325	335	345	355
2	315	325	330	340	350	360	375
3	315	325	330	340	350	370	385
4	335	345	355	365	375	390	405
5	340	355	365	375	390	450	530

Table 9 – Required thickness (mm) for jointed and doweled concrete pavements subjected to 900 kN axle loads, for various subgrade materials, and all climate zones.

Subgrade	*Number of movements*						
type (No.)	*10 000*	*30 000*	*100 000*	*300 000*	*1 000 000*	*3 000 000*	*10 000 000*
1	370	380	390	400	410	415	440
2	385	395	405	415	430	445	460
3	385	395	405	420	435	450	475
4	410	425	435	450	465	485	505
5	420	435	445	465	485	550	—*

Note. *Unreasonably large value.

Table 10 – Required thickness (mm) for various pavement systems, various loads, 10 000 movements, and subgrade type 1.

Pavement system	*Axle load (kN)*				
	100	*150*	*300*	*600*	*900*
Concrete	110	135	160	300	370
RCC	115	140	170	330	405
Reinforced concrete (centrally placed)				210	250
Concrete + cement bound base				150+160	150+160
RCC + cement bound base				150+160	150+160
Concrete + asphalt bound base	70+100			150+100	290+100
RCC + asphalt bound base				180+100	325+100
SFRC				285	350
Asphalt wear layer + cement bound base	40+100	40+100	40+100		

Table 11 – Required thickness (mm) for various pavement systems, various loads, 1 000 000 movements, and subgrade type 1.

Pavement system	*Axle load (kN)*				
	100	*150*	*300*	*600*	*900*
Concrete	130	155	195	335	410
RCC	135	160	215	365	450
Reinforced concrete (centrally placed)				210	250
Concrete + cement bound base				320+160	420+160
RCC + cement bound base				370+160	480+160
Concrete + asphalt bound base	70+100			235+100	330+100
RCC + asphalt bound base				275+100	380+100
SFRC				315	390
Asphalt wear layer + cement bound base	40+100	40+100	40+100		

Note. *Unreasonably large value.

Table 12 – Required thickness (mm) for various pavement systems, various loads, 10 000 movements, and subgrade type 5.

Pavement system	*Axle load (kN)*				
	100	*150*	*300*	*600*	*900*
Concrete	135	165	210	340	420
RCC	140	170	235	380	465
Reinforced concrete (centrally placed)				270	320
Concrete + cement bound base				150+160	180+160
RCC + cement bound base				150+160	260+160
Concrete + asphalt bound base	70+100			245+100	330+100
RCC + asphalt bound base				285+100	380+100
SFRC				325	395
Asphalt wear layer + cement bound base	40+135	40+185	40+230		

Table 13 – Required thickness (mm) for various pavement systems, various loads, 1 000 000 movements, and subgrade type 5.

Pavement system	*Axle load (kN)*				
	100	*150*	*300*	*600*	*900*
Concrete	150	190	250	390	485
RCC	155	200	275	425	525
Reinforced concrete (centrally placed)				270	320
Concrete + cement bound base				405+160	—*
RCC + cement bound base				—*	—*
Concrete + asphalt bound base	70+100			320+100	440+100
RCC + asphalt bound base				345+100	445+100
SFRC				380	450
Asphalt wear layer + cement bound base	40+160	40+225	40+320		

Note. *Unreasonably large value.

CASE STUDIES

Timber Store in Skärblacka, Sweden

An industrial pavement to be used as a timber store was built in 1998 in Skärblacka close to Linköping about 200 km southwest of Stockholm (climate zone 2, see Figure 2). The pavement totals of 23 000 m^2. The subgrade varies between rock, moraine, clay, and fillings. Two material types were selected: clay (subgrade type No. 4) and gravel (subgrade type No. 1) The pavement was designed for lorries with axle loads of 100 kN and transportation trucks with axle loads of 750 kN. The latter is the design load and the number of load movements was estimated to $t \times m \times n$ = 20×200×20 = 80 000 in the major part of the pavement and 20×200×150 = 600 000 in a minor area in front of what is called a "timber table", where loading, unloading, and reloading are carried out. By introducing the factors A = 0.5, B = 1.0, C = 0.5, and D = 1.0 in Eq. (1), we get N = 20 000 and N = 150 000, respectively. The contractor wanted to use reinforced concrete for the densely trafficked area and plain concrete on unbound or cement bound base for the remaining area. By using the tables in the design report /11/ and interpolation, we arrive at the following solutions:

Densely trafficked area		*Sparsely trafficked area*			
		Alternative 1		*Alternative 2*	
Gravel (sub-grade type 1)	*Clay (subgrade type 4)*	*Gravel (sub-grade type 1)*	*Clay (subgrade type 4)*	*Gravel (sub-grade type 1)*	*Clay (subgrade type 4)*
230 mm reinforced concrete	265 mm reinforced concrete	340 mm concrete, joint spacing = 5 m	380 mm concrete, joint spacing = 5 m	160 mm concrete + 160 mm cement bound base, joint spacing = 3.2 m	180 mm concrete + 160 mm cement bound base, joint spacing = 3.2 m

The original design was based on an older report (Silfwerbrand /7/) with slightly different design values. The subgrade was considered to have properties similar to gravel. The timber store was paved during spring and summer 1998. According to the author's knowledge, the densely trafficked area consists of 250 mm reinforced concrete. The reinforcement is centrally placed and consists of Ks 500 bars with Φ = 16 mm and spaced 160 mm apart in both directions. The sparsely trafficked area consists of 210 mm concrete K40 on a 150 mm cement bound base. The joint spacing is 5.0 m, which is the main reason for increasing the concrete thickness from 160 to 210 mm. After two years of trafficking, the pavement performance is satisfactory.

Älvsborg Port in Göteborg, Sweden

The Älvsborg Port in Göteborg, the second largest Swedish city, located at the west coast (climate zone 1, see Figure 2), was reconstructed in 1999. Prior to reconstruction, the pavement consisted of an 80 mm asphalt layer on an unbound base consisting of 80 mm sand and 1 200 mm tightened blast stone filling. This base was in turn resting either on a 1 m blast stone filling on rock or on a 5 m blast stone filling on clay. Consequently, the entire pavement was supported on a very good subgrade (equivalent to subgrade type No. 1). At the port, goods are transferred from ships to railway. The industrial pavement has a total area of 57 000 m^2. It is divided into three parts depending on the loading: I) one small area close to the railway, II) a large area used as a store, and III) another small area close to the ships. Area I will be loaded by trucks with a total load of 1 700 kN evenly distributed on four axles (axle load = 425 kN). Area II will be loaded by the same truck, by a transportation vehicle (traction vehicle + trailer) having a

maximum axle load equal to 390 kN, and by containers carrying 950 kN distributed on four supports. The transportation vehicle will also load area III. The number of movements ($t \times m \times n$) by the design vehicle have been estimated to 176 000 for area I, 32 000 for area II, and 390 000 for area III. By introducing the factors $A = 1$, $B = 1$ for the transportation vehicle and $B = 4$ for the truck, $C = 0.5$, and $D = 1.0$ in Eq. (1), we get $N = 352\,000$, $N = 64\,000$, and $N = 195\,000$ for areas I, II, and III, respectively.

The contractor wanted to use reinforced concrete for area I and plain concrete on an asphalt bound base on areas II and III. The old asphalt layer was supposed to be included in the new asphalt layer. By using the design tables in the report, we arrive at the following solutions:

Area I	*Area II*	*Area III*
210 mm reinforced concrete	170 mm concrete on 100 mm asphalt bound base, joint spacing = 3.4 m	200 mm concrete on 100 mm asphalt bound base, joint spacing = 4.0 m

According to the author's knowledge, area I was paved with 300 mm of reinforced concrete. It was not designed according to the method described in this paper and the thickness may also have been selected for better correspondence to the existing railway. Area II and III are paved with 200 mm concrete on an 100 mm asphalt bound base. The joint spacing is 5 m. As far as the author knows the pavement performance is good after 18 months of trafficking.

CONCLUSIONS

Concrete pavements have high load distribution ability, high wear resistance, and can resist long lasting and concentrated loads without permanent deflections. They are, therefore, suitable for industrial pavements that are subjected to axle loads exceeding 100 metric tons as well as concentrated loads from container supports. Design tables have been developed for several pavement systems, e.g., plain jointed concrete pavements, RCC pavements, continuously reinforced concrete pavements, and SFRC pavements either with or without bound bases.

Comparisons between various pavement alternatives show that reinforced concrete pavements can be given the smallest thickness on pavements subjected to heavy loads. Plain concrete pavements on bound bases seem to be a competitive alternative in cases with small numbers of traffic movements. The thinnest pavement is, however, not necessarily the most economic solution. Since the joint spacing is dependent on thickness, the costs for saw cuts and dowels have to be compared with the cost for concrete volume. RCC pavements, that ought to be slightly thicker than plain concrete pavements, might be an economic alternative in many cases since it does not demand any dowels.

Two examples of industrial concrete pavements, mainly designed according to the procedure described in this paper, show good performance after two years of trafficking and will be interesting to assess in the future.

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