DESIGN OF INDUSTRIAL CONCRETE BLOCK PAVEMENT

Dr. Johan Silfwerbrand, Professor & President
Swedish Cement and Concrete Research Institute (CBI)
SE-100 44 Stockholm, Sweden
Tel: +46 8 696 1100, Fax: +46 8 24 31 37, E-mail: johan.silfwerbrand@cbi.se

SUMMARY

Swedish and international experience shows that the concrete block pavement (CBP) is an excellent pavement system for harbors, industrial pavements, and other pavements carrying heavy trucks and stacked containers. Up to now there has been a lack of Swedish design guides and the designer has been referred to international design guides – not developed for Swedish conditions – or to a solely empirical design.

The *Swedish Concrete Block Paving Association* has launched a new CBP design guide (Simonsen & Silfwerbrand, 2006) containing twelve design tables for three different axle loads (10, 30, and 90 metric tons) and 15 container load cases. Solutions are given for three pavement alternatives: (i) with untreated roadbase and subbase, (ii) with asphalt stabilized roadbase, and (iii) with a subbase composed by crushed recycled concrete.

This paper summarizes the prerequisite for the Swedish design and provides examples of design diagrams. It is shown that recycled and crushed concrete is a suitable subbase material giving thickness reductions. Finally, the design values are compared with British ones and needs for further R&D are identified.

1. INTRODUCTION

Experience shows that concrete block pavement (CBP) is excellent for industrial pavements carrying heavy trucks and stacked containers. Up to now there has been a lack of Swedish design guides and the designer has been referred to international design guides – that regard materials, geology, climate, traffic loads, and construction traditions differently than in Sweden – or to a solely empirical design. The *Swedish Concrete Block Paving Association* (SCBPA) works continuously to develop design tools for concrete block pavements. Some years ago, the Association published a handbook on design and construction of concrete block pavements for urban traffic (SCBPA, 1999). This book has also been updated (SCBPA, 2002). Parallel to this work, the Association has supported R&D on industrial CBP. An early step was the organization of an international workshop on this topic in 2000 on the Lidingö island outside Stockholm, Sweden. Eight international experts discussed a hypothetic design case and exchanged information. The workshop was summarized at the 7th International CBP Conference in 2003 in Sun City, South Africa (Silfwerbrand, 2003). Based on the presentations and discussions, the following major conclusions were drawn:

- Pavement solutions for the selected loading case with an axle load of 900 kN are available for cases with untreated (unbound) roadbase, asphalt stabilized roadbase, and cement stabilized roadbase. The solutions are based on existing manuals, computations for multi-layer systems, or success stories.

- The total pavement thickness for cases with untreated roadbase varies markedly from one specialist's solution to the next one's. One probable reason is use of different materials in roadbase and subbase due to local geology and experiences.
- The total pavement thickness for cases with cement stabilized roadbase is relatively consistent if solutions containing changes from the mainstream are not considered in the comparison. The same conclusion is valid for cases with asphalt stabilized roadbase.

Sweden participated in the international workshop. Since Swedish design practice was within the mainstream of the various design methods presented, we were satisfied and confident to further develop our design concept.

2. LITERATURE SURVEY

A literature survey has been conducted (Silfwerbrand, 2005). It is obvious that British Port Association's recommendations (Knapton & Melitiou, 1996) have a prominent role. It doesn't solely deal with concrete block pavements, but also cast-in-place concrete, precast concrete, and asphalt pavements. Both truck loads and loads from stacked containers are covered. At the 6th International CBP Conference in 2000 in Tokyo, seven of 63 papers dealt with harbor and industrial pavement. Four large projects were presented: Rotterdam (NL) (Van Hees & Luidens, 2000), Helsingborg (SE) (Hammarskjöld, 2000), Bogotá (CO) (Madrid & Vesga, 2000), and Santos (BR) (Knapton & Cook). At the successive conference in 2003 in South Africa, four of 46 papers dealt with industrial pavements. Experiences form Oakland (US) (Smith, 2003) and Killarney (SA) (Pretorius & Logan, 2003) were presented as well as four major industrial concrete block pavements (CBP) in Australia (Shackel et al., 2003). The latter authors define settlements close to connections and edge restraints, settlement of the CBP, and rutting as the most severe damages dependent on their impact on the pavement's function or maintenance costs.

Table 1. Stiffness relation between long-term and short-term loading and design criteria found in the literature

Reference	Stiffness relation between long-term and short-term loading					Design criteria	
	Concrete paver	Untreated roadbase and subbase	Cement stabilized roadbase	Asphalt stabilized roadbase	Subgrade	Deformation (mm)	Subgrade strain (μstrain)
Silfwerbrand (2000)	1/3	1/3		1/3	1/3	(1,4)	2500
Shackel (2000)						2	
Wellner (2000)	1	1/3	1	1	1	1	
Visser (2000)						2,5	800
Paterson (1976)						10	
Towers (1983)						25	

Based on the literature survey, the following conclusions can be drawn:

- It ought to be possible to develop design tables or design diagrams for industrial CBP loaded with containers.
- The loading case punching shear does not seem to be relevant.
- The design tables ought to be based on (i) experience from successful cases with relevant loading, (ii) deformation computations, and (iii) BPA's handbook method.
- Material data to be used for computing long-term deformations should be selected carefully.

- Computations described in the literature indicate that reduced stiffness values may be used in an elastic multi-layer model and that allowable deformation ought to be put in an interval between 1 and 3 mm. Older references use lower demands and allow 10 to 25 mm, see Table 1.

3. PREREQUISITE OF THE SWEDISH DESIGN METHOD

The pavement system consists of the following alternatives: (a) concrete block pavement (CBP) on untreated roadbase and subbase, (b) CBP on asphalt stabilized roadbase, and (c) CBP on untreated roadbase and subbase of recycled and crushed concrete (Figure 1). The thickness of the asphalt stabilized roadbase for case b varied between the different traffic loads. It was 100 mm for the 10 ton axle, 150 mm for the 30 ton axle, and 200 mm for the 90 ton axle. Five different subgrade materials spanning from 1 (crushed rock) to 5 (silt) according to the Swedish Road Administration (2002) have been investigated.

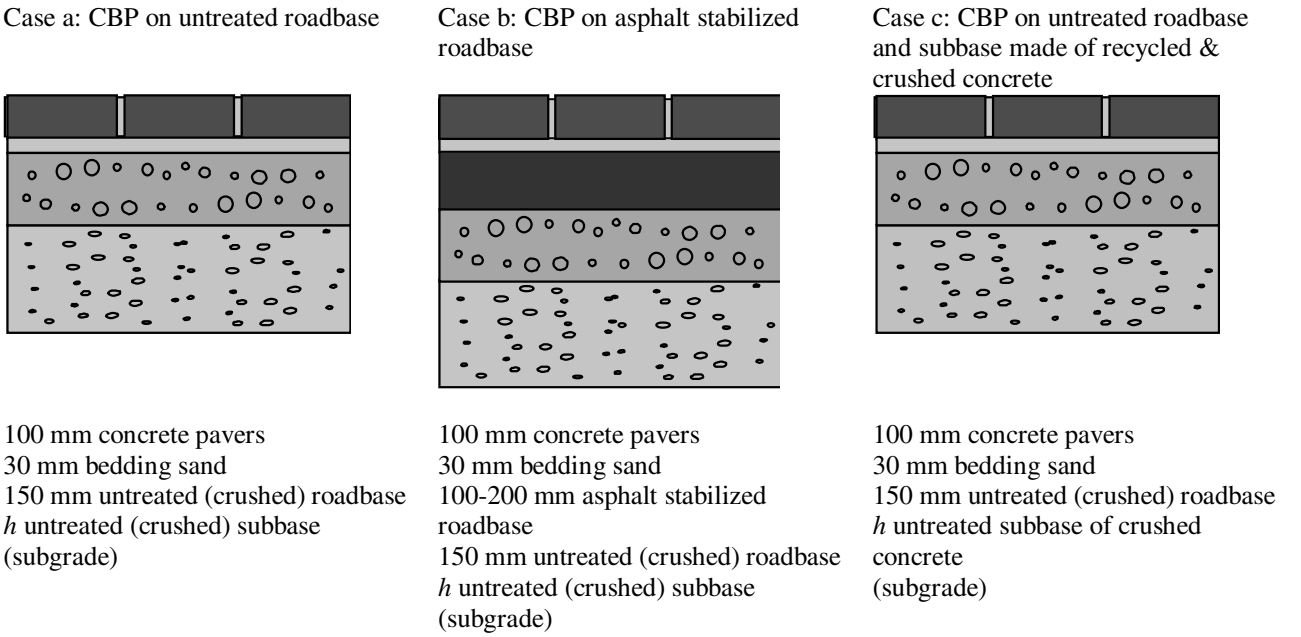


Figure 1. The three alternative pavement systems.

Both traffic and container loading have been studied through computations. The computations cover three different axle loads (Figure 2) and containers stacked 1 to 5 stories high singly, in rows, and in blocks (Figure 3). The top row in Figure 3 (right) shows real load distributions. Container support size: $l_1 \cdot l_2 = 178 \times 162$ mm^2. The bottom row shows used load distributions in the computations. Arrangements: singly (left), rows (center), and blocks (right). The radius of the circle a is chosen so that the circle area is of the same size as the rectangle above, i.e.,

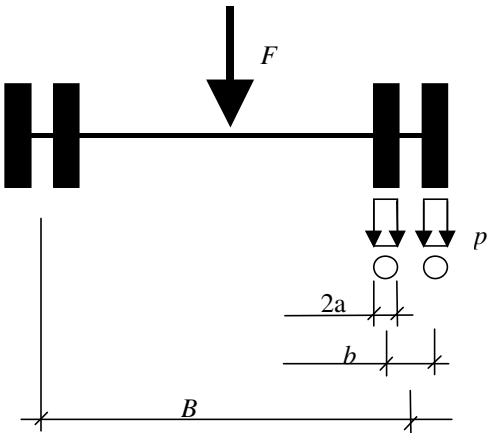
$$A = l_1 \cdot l_2, \; a = \sqrt{l_1 \cdot l_2 / \pi} = \sqrt{178 \cdot 162 / \pi} = 95.8 \text{ mm}.$$

The container loading follows BPA's recommendations (Knapton & Melitiou, 1996). That means that the corner load goes from 76 (1 story, singly stacked) to 914 kN (5 stories, block arrangement).

The Swedish Road Administration divides Sweden into five climate zones from south to north. The computations were all carried out for climate zone 2 which cover most of the densely populated parts

of Sweden. Single computations show also that the climate zone does not have any marked influence on required pavement thickness. Consequently, the limitation to one climate zone is motivated.

Material data for the pavement systems and the five subgrade materials are given in Table 2. Moduli of elasticity and Poisson's ratios are based on Swedish practice for designing CBP and concrete pavements. Appropriate references are given in the right column of Table 2.



Axle load (metric tons)	10	30	90
Axle load *F* (kN)	100	294	896
Number of wheels on the axle	4	2	4
Track width *B* (mm)	1 800	2 360	3 000
Wheel distance *b* (mm)	300	N/A	500
Tire pressure = contact pressure *p* (MPa)	0,80	0,45	0,93
Loading radius *a* (mm)	50	322	277

Figure 2. Definition of the axle load and parameter values for the three traffic loads.

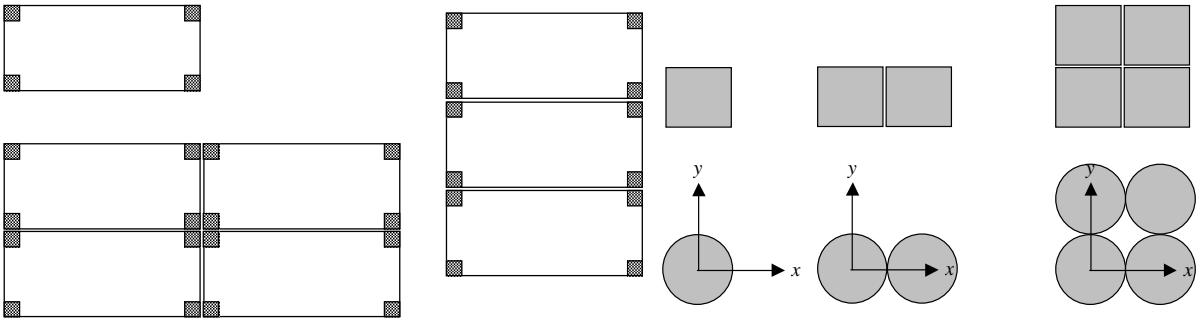


Figure 3. Left: Container stacking arrangements: singly (top left), rows (right), and blocks (bottom left). Right: Load groups for computing the container load cases.

The computations of stresses, strains, and deformations for the various pavement systems subjected to traffic and container loading are based on an elastic multi-layer model. It contains five to seven layers: (1) concrete paver, (2) bedding sand, (3) asphalt stabilized roadbase (if any), (4) untreated roadbase, (5) subbase, (6) frost-influenced zone of the subbase (during spring), and (7) frost-independent zone of the subgrade. The Swedish National Road and Transport Research Institute (VTI) has carried out the traffic load computations using the elastic multi-layer computer program BISAR (1998), while the Swedish Cement and Concrete Research Institute (CBI) has carried out the container load computations using Cauwelaert's similar program Gipi (van Cauwelaert, 1986).

Table 2. Material data

	Climate period							Reference
	Spring	Summer	Fall	> frost depth	Long-term spring	Long-term > frost depth	All	
Material	Modulus of elasticity (MPa)						Poisson's ratio	
Concrete paver	6 000	6 000	6 000	—	2 000	—	0,35	*Silfwerbrand (1999)*
Bedding sand	70	100	100	—	23	—	0,35	*Silfwerbrand (1999)*
Asphalt stabilized roadbase	10 000	3 000	9 000	—	150	—	0,35	*SRA (2002)*
Untreated roadbase (crushed)	450	450	450	—	150	—	0,35	*Djärv et al. (1996)*
Untreated subbase (crushed)	350	350	350	350	117	117	0,35	*Djärv et al. (1996)*
Untreated subbase (crushed concrete), year 1	450	450	450	450	150	150	0,35	*Farhang (2004)*
Untreated subbase (crushed concrete), year 2 and cont.	900	900	900	900	300	300	0,35	*Farhang (2004)*
Material type 1	150	150	150	150	50	50	0,35	*Djärv et al. (1996)*
Material type 2	70	100	100	100	23	33	0,35	*SRA (2002)*
Material type 3	35	100	100	100	12	33	0,35	*SRA (2002)*
Material type 4	30	50	50	50	10	17	0,35	*SRA (2002)*
Material type 5	10	45	45	45	3,3	15	0,35	*SRA (2002)*

In the traffic load computations, VTI's design criterion for the subgrade (Djärv et al., 1996) and Swedish Road Administration's design criterion for the asphalt stabilized roadbase (2002) have been used. They have the following expressions:

$$N = \frac{14 \cdot 10^{-8}}{\varepsilon_z^{\,4}} \qquad \text{(subgrade)} \qquad (1)$$

$$N = \frac{2.37 \cdot 10^{-12} \cdot 1{,}16^{(1.8 \cdot T + 32)}}{\varepsilon_y^{\,4}} \qquad \text{(asphalt stabilized roadbase)} \qquad (2)$$

where,

N = number of load repetitions (axles) at failure,
T = temperature (°C) in the asphalt stabilized roadbase (2,3, 18,1 and 3,8°C for spring, summer and fall in climate zone 2, respectively),
ε_y = horizontal tensile strain (real value, not µstrain) in the lowermost fiber of the stabilized roadbase, and
ε_z = vertical compressive strain (real value, not µstrain) in the top of the subgrade.

Since separate computations must be conducted for each season, the total number of possible load repetitions has been computed by using Miner-Palmgren's partial damage hypothesis.

The container loading is a long-term loading. Here, Swedish Road Administration's criterion has been used. It states that the maximum vertical strain in the top of the subgrade must be limited to 2400 μstrain.

Finally, it has to be stated the design is solely based on load-carrying capacity (but both for short-term and long-term loading). In countries with winter temperatures below 0°C, e.g. Sweden, a complete design must also cover prevention against frost heave. This has been neglected here. However, in heavily loaded industrial CBP, the pavement system thickness has to have such a thickness due to structural reasons that the required thickness for preventing frost heave usually is not decisive.

4. COMPUTATION RESULTS

The complete report (Silfwerbrand, 2005) contains nine design tables for traffic loads (3 axle loads times 3 pavement systems) and three design tables for computer loading (3 pavement systems). As shown in Figure 1, the dependent design variable is the subbase thickness *h*. All other layer thicknesses are kept constant. Figure 4 shows a comparison between the three pavement systems subjected to the smallest truck (10 ton axle load). The different lines correspond to subgrade materials 1-5 according to Table 2. The stiffest material (mtrl 1) is always the bottom line, the others follow in anticipated order. Using recycled and crushed concrete leads to substantial thickness reductions and material savings. The reason is that the stiffness increases (Table 2) due to late cement hydratation when previously unhydrated cement surfaces are coming into contact with moisture. Crushed concrete in the subbase is almost as efficient as an asphalt stabilized roadbase. Figure 4 (bottom right) shows also that the untreated subbase has to be increased several times if the traffic load increases to 90 tons.

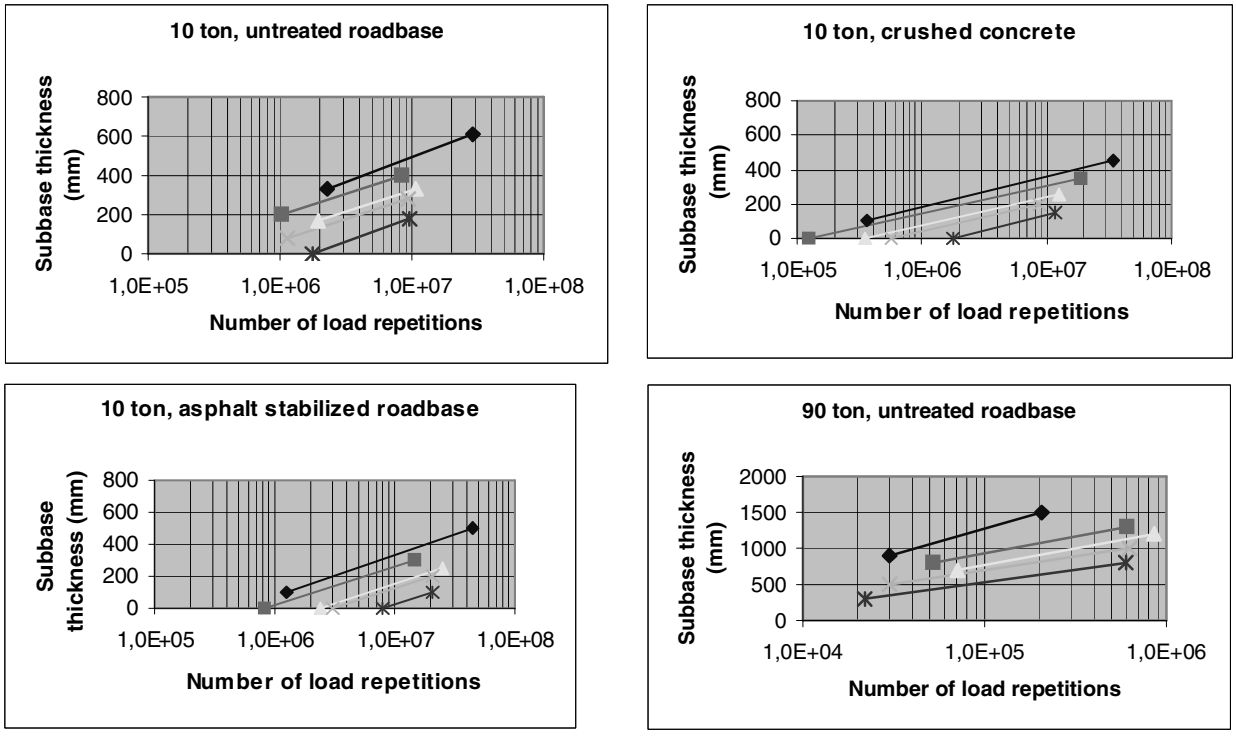


Figure 4. Required subbase thickness for three different pavement systems.

Figure 5 shows required subbase thickness for the container loading. Two examples of computation results are shown. They cover pavement systems a (untreated roadbase) and c (recycled and crushed concrete in the subbase). Only containers stacked in 1 to 3 stories are shown here. As shown in Figures 5 and 6, the use of recycled and crushed concrete leads to substantial thickness reductions.

The thickness values in Figure 5 are based on SRA's design criterion maximizing the vertical subgrade strain to 2400 μstrain. In Section 2, also deformation criteria are discussed. Figure 7 shows the computed long-term deformations for the pavements in Figure 5 (left). As shown, the maximum deformation approaches 18 mm already for containers stacked in three stories. Containers stacked in four and five stories are not rare. This will lead to even larger deformations. However, experience from case studies shows that the CBP loaded in such a way often perform excellently without any problematic deformations. Consequently, we have repudiated deformation criteria in the Swedish design and maintained the strain criterion instead.

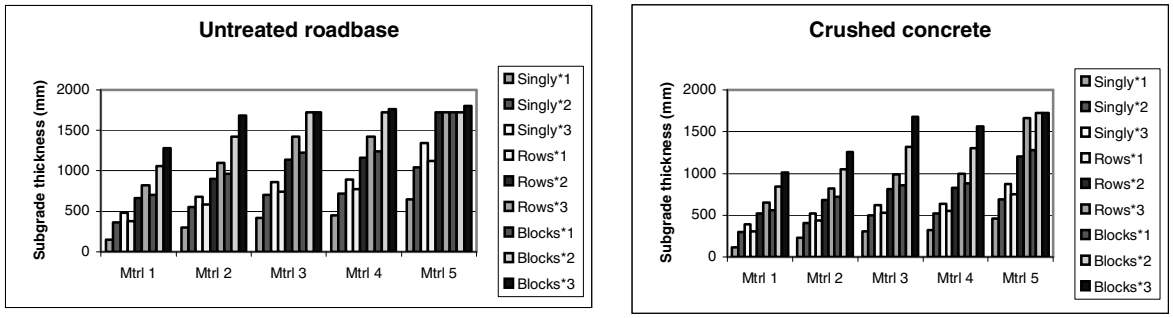


Figure 5. Required subbase thickness for two different pavement systems subjected to container loading.

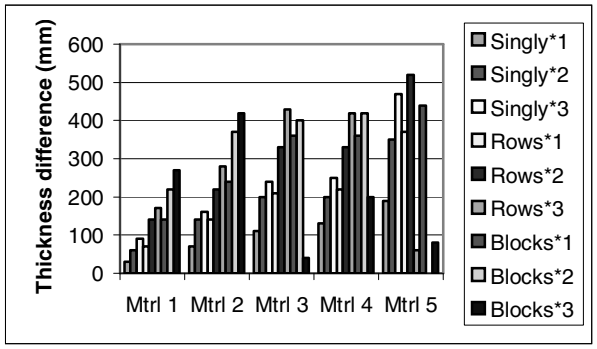


Figure 6. Difference in required subbase thickness between untreated subbase and subbase of recycled and crushed concrete in Figure 5.

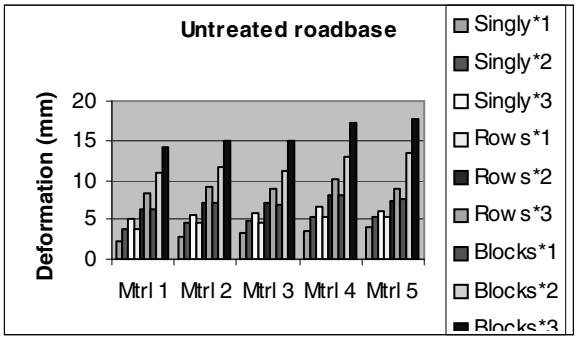


Figure 7. Computed long-term deformations for the different pavements shown in Figure 5 (left).

Finally, the Swedish design has been compared with the design according to British Port Association (Knapton & Melitiou, 1996). Figure 8 shows a comparison between pavement systems according to Swedish method (required thickness of untreated subbase) and BPA (sum of required thickness of subbase of crushed rock and capping). Since the thicknesses of pavers, bedding sand, and untreated roadbase are considered to be the same in the two methods, the dotted line marked "identity" implies that both design methods give identical solutions. As shown in Figure 7, the required subbase thickness is similar for the two design methods. The British method is more conservative for stiff subgrade

materials whereas the opposite is valid for soft materials. The probable explanation is that the necessary conversion from British to Swedish materials is not completely correct.

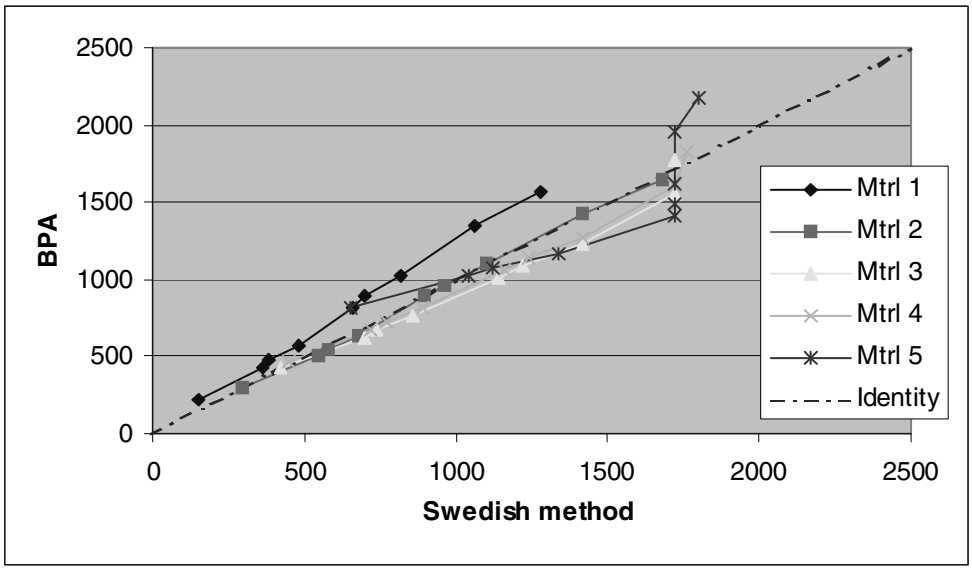


Figure 8. Comparison between pavement systems according to Swedish method and BPA.

5. FURTHER RESEARCH AND DEVELOPMENT

The design diagrams shown in this paper are based on current design practice for Swedish CBP. International comparisons show that CBP systems designed according to these diagrams will have approximately the same thickness as those designed according to BPA. Since the Swedish practice is semi-empirical and the empery mainly deals with the design criteria that are based on asphalt pavements there is a need of further development, not least for cases outside the mainstream. It may contain heavier loads, new pavement materials, new geotechnical conditions, and colder or moister climates. Further R&D ought to cover the following items:

- New design criteria for CBP. Here maximum vertical strain in the top of the subgrade is used. Internationally, deformations and deformation differences have been proposed. How can you define the end of the good function of a CBP?
- Security philosophy. How large probability for failure or function loss can be accepted? For buildings and civil engineering structures, both loads and materials are provided with partial coefficients. May such a security philosophy be used in highway engineering (not only for CBP)?
- Material models. For computing stresses, strains, and deformations, an elastic, multi-layer, mechanical model is used despite that the comprising road materials are far from linear-elastic. Is it time to leave linear elasticity and replace it by better material models? How is the model changed when going from short-term (traffic loading) to long-term loading (container stacking)? Which test methods may be used or need to be developed in order to determine the many new parameter values that will be needed in more sophisticated, non-linear models?
- Cement stabilized materials. In this investigation, no cementitious materials have been used in the roadbase. The reason is that the current Swedish design criterion for the cement stabilized

roadbase leads to very thick layers. New tests indicate (Söderqvist & Silfwerbrand, 2006) that this design criterion is very rigorous. Here, research is needed to develop new criteria, maybe various dependent on the use of the cement stabilized roadbase (in concrete pavements, asphalt pavements, or CBP).

- Field tests. Outside Uppsala, 70 km north of the Swedish capitol Stockholm, there is a well-documented and instrumented test section with varying roadbases, edge restraints, and camber (Wäppling, 2000). Here, there is an unique possibility to carry out full-scale tests using the HVS simulator and gain new, valuable, empirical data to be used for comparisons with computations.
- Frost heave design. In Sweden, the frost heave design of CBP is done in the same manner as for asphalt pavements despite that the CBP and the asphalt pavement have different thermal properties and that the consequences due to frost heave are likely to be different. Here, more research is anxious for enabling differentiating.

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