# PARAMETER STUDY ON THE DESIGN OF CONCRETE BLOCK PAVEMENTS

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## ABSTRACT

The concrete block pavement is a versatile pavement structure that can be used for various applications, e.g., city streets, traffic crossings, bus stops, harbours, industrial pavements, and airports. The concrete block pavement has a load distribution ability that is of the same magnitude as the asphalt pavement's. In Sweden, the use of concrete block pavements is less than in other comparable countries. One reason is that concrete block pavements are designed according to old and unfashionable guidelines that lead to an unnecessarily thick pavement system. Currently, a research project is carried out in Sweden to improve the design procedure. One part of the project is to optimise the pavement system through conducting a parameter study. Several factors, e.g., paver layer stiffness, base layer stiffness, material in the subbase layer, alternative failure criteria, and season lengths have been considered. Computations of the load carrying capacity, defined as the number of possible standard axes, show that stiffness of the paver layer and the use of crushed aggregate in the subbase have a major influence on the load carrying capacity. New design charts using the optimised pavement system show that concrete block pavements are competitive to asphalt pavements.

## 1. INTRODUCTION

The concrete block pavement is a pavement system with several advantages: good load distribution ability both for short time and long-term loading, high resistance to settlements, high durability, good reparability, high light reflection, and aesthetic potential. By combining colours, paver shapes, and laying patterns in a clever way, the use of concrete block pavements may enhance both the traffic safety and the architectural values in an urban environment. In addition to city streets, traffic crossings, and bus stops, concrete block pavements are laid on harbours, industrial pavements, and airports.

In Sweden, approximately 2 million square metres of concrete block pavements are laid annually, see [1], Despite a small increase during the last decade, the Swedish use per capita is only 1/3 of those in some comparable European countries. One reason may be the current Swedish design praxis that leads to a concrete block pavement system that is thicker than corresponding asphalt pavement system despite similar load carrying capacities. In other words, the current Swedish design praxis for concrete block pavements may be too conservative. Another reason may be that too few pavements designers are familiar with concrete block pavements, maybe due to the lack of a solid Swedish design guide. In order to develop such a guideline, some major concrete paver producers, the Swedish major cement producer, and the Royal Institute of Technology have started a research project on the design

and behaviour of concrete block pavements. The project consists of three parts: (i) investigation of structural performance of more than 20 concrete block pavements in various parts of Sweden, (ii) construction, instrumentation, and evaluation of five test sections outside a paver factory in Uppsala, and (iii) a parameter study on the design of concrete block pavements. The first two parts are dealt with in a companion paper [2], This paper summarises the parameter study.

## 2. CURRENT SWEDISH DESIGN PRAXIS

The current Swedish design praxis consists of the following steps:

1) Determine appropriate climate zone.
2) Divide the year into seasons (winter, frost heave period, spring, summer, and autumn) with lengths depending on climate zone.
3) Estimate the magnitude of the design axle load, usually the Swedish 100 kN standard axle can be used.
4) Estimate the number of standard axles by multiplying the number of heavy vehicles per day and the intended service life of the pavement.
5) Estimate the material in the subgrade.
6) Select material and thickness for each layer in subbase, roadbase, bedding sand, and pavers.
7) Estimate moduli of elasticity for the layers in subgrade, subbase, roadbase, bedding sand, and paver for each season.
8) Compute vertical strain in the top layer of the subbase and horizontal strain in the bottom layer of the stabilised roadbase, if any, for each season by using a computer program for an elastic multilayer pavement system (Figure 1).
9) Compute the number of allowable load repetitions for each computed strain value using equations (1) - (3).
10) Compute the total number of allowable load repetitions by using Miner-Palmgren's law.
11) If the total number of allowable load repetitions is less than the estimated number of standard axles, increase at least one layer thickness and return to step No. 8.

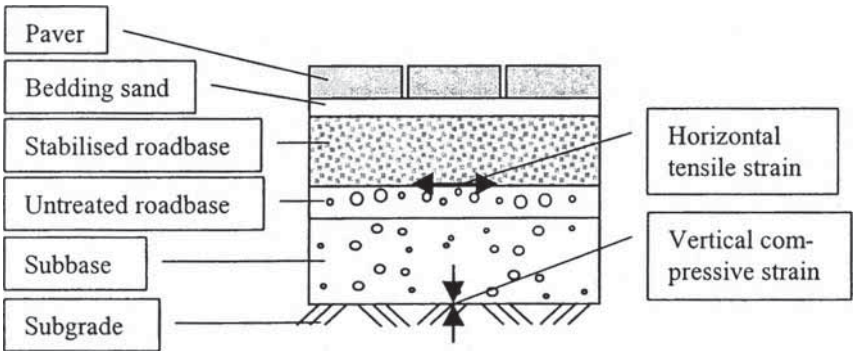



**Figure 1 Failure criteria are given for vertical strain in the top layer of the subgrade and for horizontal strain in the bottom layer of the stabilised roadbase (if any).**

The following failure criteria are used for asphalt stabilised roadbase, cement stabilised roadbase, and the subgrade, respectively:

$$N = \frac{2.37 \cdot 10^{-12} \cdot 1{,}16^{(1.8 \cdot T+32)}}{\varepsilon_y^{\,4}} \quad (1)$$

$$N = \frac{1.06 \cdot 10^{-10}}{\varepsilon_y^{\,4}} \quad (2)$$

$$N = \frac{8.06 \cdot 10^{-8}}{\varepsilon_z^{\,4}} \quad (3)$$

where,

$N$ = number of load repetitions (standard axles) at failure,
$T$ = the temperature (°C) in the bituminous layer,
$\varepsilon_y$ = horizontal tensile strain in the bottom layer of the stabilised roadbase (if any),
$\varepsilon_z$ = vertical compressive strain in the top layer of the subgrade.

The moduli of elasticity for various materials in the subgrade and in the pavement system are based on falling weight deflectometer (FWD) measurements and are tabled in the Swedish pavement code [3]. The values vary from one season to another with a maximum during winter and a minimum during the frost heave period.

The interaction between pavers, joint sand, and bedding sand implies that the concrete block pavement may be approximated with an elastic layer with equal thickness and load distribution ability. FWD measurements reported in Shackel [4] indicate that this layer may have a modulus of elasticity between 500 and 7 000 MPa. In Swedish design praxis, an intermediate value of 3 000 MPa has been used.

## 3. PARAMETER STUDY

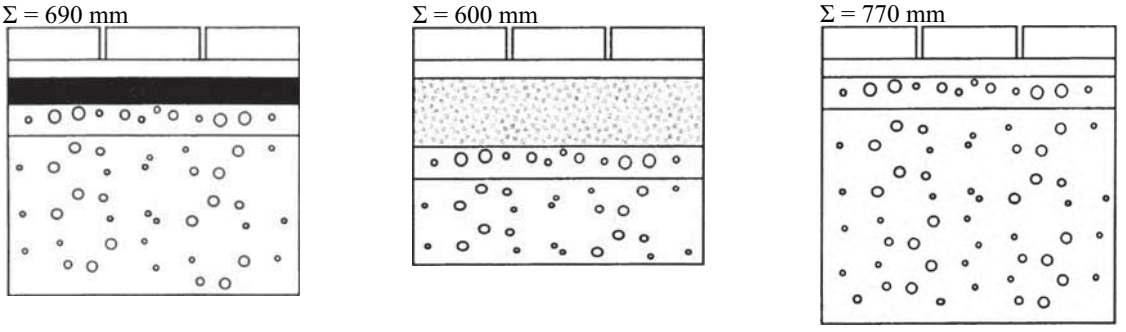
### 3.1 General

A parameter study was conducted in order to investigate how variations of some of the major parameters influence the pavement design. The following items were investigated in the study:

- The stiffness (modulus of elasticity) of the paver layer.
- The stiffness of stabilised roadbases.
- The temperature in the asphalt stabilised roadbase.
- The failure criteria for asphalt or cement stabilised roadbases and the subgrade.
- The thickness relationship between an untreated roadbase and the subbase.
- The use of crushed aggregate instead of natural aggregate in the untreated roadbase and the subbase.
- The introduction of a new failure criterion for the entire concrete block pavement system.
- The season lengths.
- The computer program for determining strain values.

The parameter study has been based on a concrete block pavement located in the south of Sweden (climate zone 1 of 6 in Sweden), resting on a subgrade of silty sand (material type 3 of 6), and designed for 2.5 million standard axles (traffic class 3 of 7). Three alternatives with and without stabilised roadbase have been investigated (Figure 2).

| Alternative 1 - with asphalt stabilised roadbase | Alternative 2 - with cement stabilised roadbase | Alternative 3 - without stabilised roadbase |
|---|---|---|
| 80 mm paver | 80 mm paver | 80 mm paver |
| 40 mm bedding sand* | 40 mm bedding sand* | 40 mm bedding sand* |
| 70 mm asphalt stabilised roadbase | 180 mm cement stabilised roadbase | |
| 80 mm untreated roadbase | 80 mm untreated roadbase | 80 mm untreated roadbase |
| 420 mm untreated subbase | 220 mm untreated subbase | 570 mm untreated subbase |
| Σ = 690 mm | Σ = 600 mm | Σ = 770 mm |



Note. * 40 mm was selected to facilitate the computations, but ought to be read 30 mm.

**Figure 2 Selected pavement systems.**

The effects of changing the selected parameter values were investigated by computing the load carrying capacity of the three selected pavement systems (Figure 2) before and after alteration of the parameter values. The load carrying capacity was defined as the number of allowable standard axles. In the following sections, the variations of the parameter values are described. Their influence on the load carrying capacity is summarised in Section 3.8.

### 3.2 Variation of the stiffness of the paver layer

The stiffness of the concrete block pavement increases with time and number of vehicles trafficking the pavement (Figure 3). According to Shackel [4], an increased stiffness is achieved after 10 000 to 15 000 passages (Figure 4). The effect of a doubled stiffness of the paver layer was investigated. The first 10 000 to 15 000 standard axles constitute only 0.5 percent of the design traffic of the selected pavement system. Computations with Miner-Palmgren's law show that the 0.5 percent of the standard axles trafficking the soft paver layer (*E* = 3 000 MPa) may be ignored compared to the 99.5 percent trafficking the stiff paver layer (*E = 6 000* MPa). Consequently, we may use *E* = 6000 MPa for the entire service life.

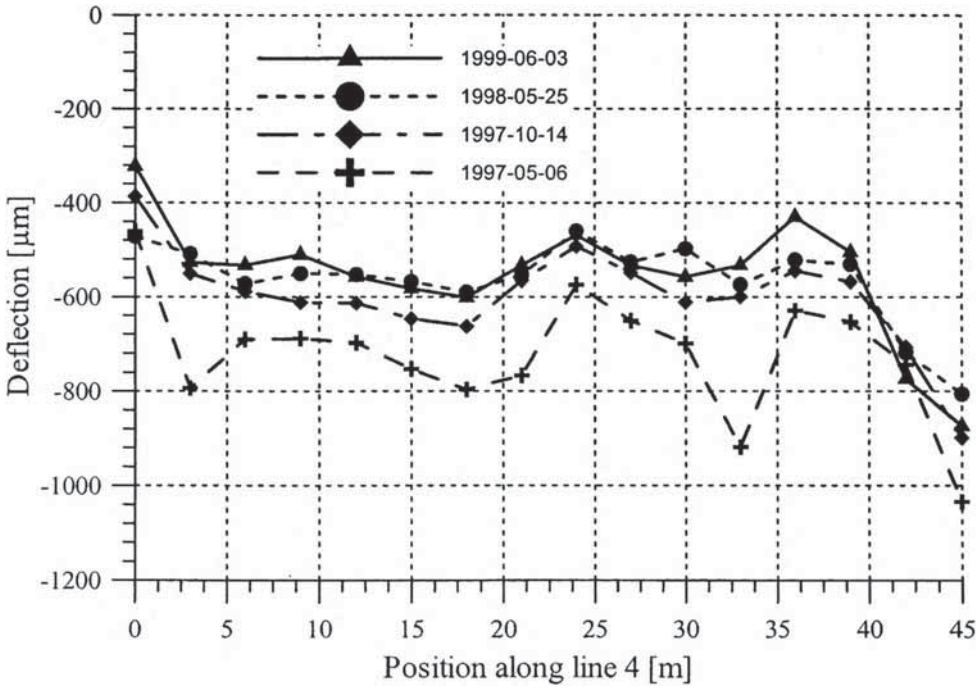



**Figure 3 FWD measurements showing an increased stiffness (decreased deflection) with time on a bus terminal in Goteborg, Sweden. The concrete block pavement was completed in April 1997.**

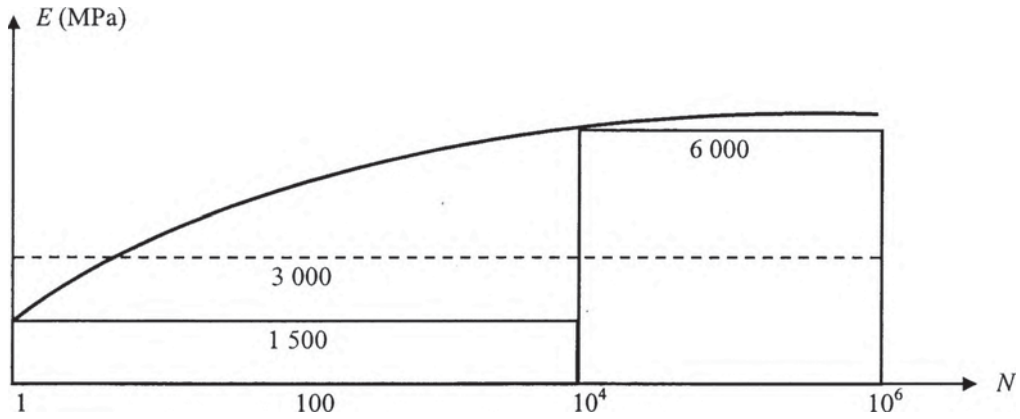



**Figure 4 Schematic description of the stiffness increase of the paver layer.**

### 3.3 Variation of the properties of the stabilised roadbase

The modulus of elasticity *E* of the cement stabilised roadbase is set to 17 000 MPa according to Swedish design praxis for concrete block pavements and asphalt pavements. If a cement stabilised roadbase is used under a concrete pavement, the stiffness is reduced to *E* = 8 000 MPa. The reduced value is based on an assumption that the cement stabilised roadbase is cracked under concrete pavements, but uncracked under more flexible asphalt and concrete block pavements. Thermal movements of the rigid concrete pavement will cause the cement stabilised roadbase to crack. In the parameter study, the influence of a cracked cement stabilised roadbase *(E* = 8 000 MPa) on the load carrying capacity was investigated, see Section 3.8.

The temperature *T* in the asphalt stabilised roadbase influences both the modulus of elasticity and the failure criterion for asphalt (equation (1)). Compared to an asphalt pavement, the asphalt stabilised roadbase is insulated from extreme temperatures both during summer and winter. Effects of a winter increase of 2°C and a summer decrease of 2°C of the asphalt temperature were investigated.

### 3.4 Variation of the properties of the untreated roadbase and the subbase

hi the original pavement systems (Figure 2), natural aggregate was used both in the untreated roadbase and in the subbase. Alternative 3 consists of 80 mm untreated roadbase and 570 mm subbase. Since the assumed stiffness of the roadbase (E = 450 MPa during summer/ 300 MPa during frost heave) is approximately twice the stiffness of the subbase (E - 240/ 160 MPa), an increase of the roadbase at the expense of the subbase thickness might be successful.

According to the Swedish pavement design praxis, the stiffness of untreated roadbases and subbases composed by crushed aggregate is not assumed to vary with the seasons (E - constant = 450 MPa for both roadbase and subbase) contrary to the stiffness of layers composed by natural aggregate. The effect of replacing the natural aggregate with crushed aggregate in both the roadbase and the subbase was investigated in the parameter study.

### 3.5 Other failure criterion for the subgrade

In most applications, the concrete block pavement system does not include a stabilised roadbase. In these cases, the failure criterion for the subgrade is the only design criterion. Consequently, the used failure criterion will have a very large impact on the load carrying capacity. The Swedish failure criterion for the subgrade (equation (3)) was originally based on measurements and experiences by the Swedish Road and Transport Research Institute (VTI). Based on long-term measurements on test roads, VTI has proposed a new failure criterion [5]:

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

In [5], comparisons are also made with Shell's failure criterion that has the following expression:

$$N = 10^{\log(0{,}028/\varepsilon_z)/0{,}25} \qquad (5)$$

Both equations (4) and (5) lead to an increased load carrying capacity for the pavement system without stabilised roadbase, see Section 3.8. The alteration did not influence the systems with stabilised roadbase since the failure criterion for the subgrade was not the design criterion for these cases (the failure criterion for the roadbase constituted the design criterion).

### 3.6 Variation of the season lengths

In [5], Djärv et al also propose new season lengths. The proposal is both an adjustment to improved climate data and a simplification. In stead of five or six seasons, only three need to be considered in the design: frost heave period, summer, and autumn. The winter period is

omitted since the traffic damage on the pavement during the frost period is negligible. The spring period has been omitted due to improved climate data.

### 3.7 Exchange of computer program

The first author has used van Cauwelaert's computer program GIPI [6] for computation of strain values. This program has previously been used extensively in Sweden for design of both concrete pavements and concrete block pavements. VTI uses Shell's program BISAR for design of asphalt pavements. It was, e.g., used to develop the design charts in the Swedish pavement code [3]. Both programs use a model based on a multilayer elastic semi-infinite solid. They can both deal with several, arbitrarily placed loads. It is outside the scope of this paper to analyse the differences between the programs, but the strain values computed by BISAR is only 75 to 85 percent of the corresponding GIPI strain values. The fact that different computer programs lead to different strain values and, hence, different load carrying capacities or pavement thickness is not solely valid for concrete block pavements. A similar result has been obtained for asphalt pavement, see the COST report by the European Commission [7].

### 3.8 Summary of computation results

The influence of the parameter value variations on the load carrying capacity of the selected pavement systems is summarised in Table 1. The assumption of an increased stiffness of the paver layer, the use of crushed aggregate in untreated roadbase and subbase, and the change of computer program have the largest beneficial impact on the load carrying capacity. An introduction of VTI's new failure criterion for the subgrade will also lead to a major increase of the load carrying capacity of the pavement system without stabilised roadbase.

**Table 1 Influence of parameter value variations on the load carrying capacity of the selected pavement systems.**

| Case No. | Sec-tion | Description of the alteration | Relationship between allowable load repetitions after and before alteration | | |
|---|---|---|---|---|---|
| | | | Alt. 1 - with asphalt stab, base | Alt. 2 - with cement stab, base | Alt 3 - without stab, base |
| 1 | 3.2 | Stiffness increase of paver layer | 2.6 | 1.3 | 1.3 |
| 2 | 3.3 | Stiffness decrease of cement stabilised roadbase | N/A | 0.14 | N/A |
| 3 | 3.3 | Limitation of thermal variation in asphalt stabilised roadbase | 1.1 | N/A | N/A |
| 4 | 3.4 | 200 mm roadbase + 430 mm subbase instead of 80 + 570 | N/A | N/A | 1.0 |
| 5 | 3.4 | Crushed aggregate in untreated roadbase and subbase | 1.2 | 1.2 | 3.2 |
| 6 | 3.5 | VTI's failure criterion for the subgrade, Eq. (4) | 1 | 1 | 1.7 |
| 7 | 3.5 | Shell's failure criterion for the subgrade, Eq. (5) | 1 | 1 | 7.6 |
| 8 | 3.6 | New season lengths | 1.25 | 1.1 | 1.15 |
| 9 | 3.7 | Computer program BISAR instead of GIPI | 3.0 | 2.0 | 2.2 |

In addition to the nine cases in Table 1, the alteration of the failure criteria for stabilised roadbases was investigated. The use of a couple of other failure criteria, tentatively used in Swedish pavement design, did not lead to any improvements. Other criteria that may be found in the international literature have not been adopted since they may not be appropriate for Swedish cement and asphalt stabilised materials. For more details, see the complete report [8].

If we limit our discussion to the most important case, the concrete block pavement system without stabilised roadbase, we may ask if a subgrade failure criterion, developed from measurements on asphalt pavements, is suitable for design of the concrete block pavement. We might need a modified subgrade criterion for this case. Furthermore, it may be argued that the concrete block pavement has a different structural behaviour than the asphalt pavement. Contrary to asphalt and concrete pavements, the concrete block pavement might resist damages in the subgrade (or cracks in the stabilised roadbase). Efforts to find a new design criterion ought to start from the user, the car, bus or truck driver. Such an attitude might result in a criterion that origins from a limited rutting depth. Further research is needed in this area.

## 4. NEW SWEDISH DESIGN CHARTS FOR CONCRETE BLOCK PAVEMENTS

Based on the parameter study, summarised above, the first author has developed a new design chart for Swedish concrete block pavements (Table 2). The design chart has also been included in the new Swedish design guide for concrete block pavements [1], The design is based on the Swedish pavement code [3], but new findings concerning stiffness of the paver layer, subgrade failure criterion (equation (4)) and season lengths have been adopted. Table 2 is valid for crushed aggregate in untreated roadbase and subbase. The computer program BISAR, also used for the asphalt pavement systems in [3], was used for computation of strain values.

**Table 2 Concrete block pavements without stabilised road base. Measurements in mm.**

| Climate zones 1-6. Crushed aggregate in roadbase and subbase. | | Traffic class (number of standard axles, millions) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0 (0.05) | | 1 (0.5) | 2(1.0) | 3 (2.5) | 4(5.0 |
| Paver | | 80 | 80 | 80 | 80 | 80 | 80 |
| Bedding sand | | 30 | 30 | 30 | 30 | 30 | 30 |
| Untreated roadbase | | 80 | 150 | 150 | 150 | 150 | 150 |
| Total pavement system for subgrade material type (with example) | 1 (crushed rock) | 190 | | 260 | 290 | 380 | 440 |
| | 2 (sand) | | 260 | 340 | 400 | 480 | 540 |
| | 3 (silty sand) | | 260 | 430 | 480 | 540 | 590 |
| | 4 (clay) | | 260 | 460 | 520 | 600 | 660 |
| | 5 (silt) | | 360 | 590 | 650 | 770 | 870 |

Returning to the conditions behind the selected pavement systems (Figure 2), we may redraw the pavement system for climate zone 1, material type 3, and traffic class 3 (Figure 5). The thickness of the pavement system has decreased from 770 to 540 mm. The major causes behind the decrease is the use of crushed aggregate, the increased stiffness of the paver layer, the new subgrade failure criterion, and the change of computer program. This pavement system is also competitive to asphalt pavements. According to the Swedish pavement code [3], corresponding asphalt pavement ought to be slightly thicker, or 610 mm.

Alternative 3 - without stabilised roadbase
80 mm paver
30 mm bedding sand
150 mm untreated roadbase
280 mm untreated subbase
$\Sigma$ = 540 mm

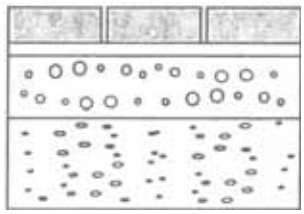


**Figure 5 Selected pavement system according to the new design chart**

## 5. CONCLUSIONS

(1) The parameter study show that assumption of an increased stiffness of the paver layer, the use of crushed aggregate in untreated roadbase and subbase, the introduction of a new subgrade failure criterion, and the change of computer program have the largest beneficial impact on the load carrying capacity.
(2) Based on the parameter study, a new design chart for Swedish concrete block pavements has been developed. The use of the new design chart lead to concrete block pavements that are competitive to asphalt pavements.
(3) Further research is needed in order to find improved design criteria for concrete block pavements. These criteria ought to be based on the specific characteristic of the structural behaviour of the concrete block pavement.

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