

New Swedish Design Method for Concrete Pavements

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Abstract

A new concrete pavement design method is currently introduced in Sweden. It consists of two parts: (i) computations of subgrade and base distresses and (ii) computations of concrete pavement distresses. To eliminate the difference between concrete and asphalt pavement design, the first part is carried out with equal requirements, in the same manner, and with the very same computer program. The computer run also provides a coefficient of subgrade reaction that is used as input in the second part. For this part, the American FE program ISLAB2000 is used to compute stresses – both traffic and thermal stresses, simultaneously – in various locations of the concrete pavement slab. Contrary to previous Swedish tradition, both bottom-up and top-down cracking are considered in the analysis of the computations. For the pavement designer, the division into two parts will not be visible. She will use the same user-friendly computer program (that previously has only been used for flexible pavement design) for both pavement alternatives. It is the authors' hope that the selection of pavement solution for a certain case will be dependent solely on technical and economical factors and not on tradition and intensive advertising. The new design method includes a novelty concerning safety philosophy. The safety margin should be obvious and transparent and determined by the client in co-operation with the designer by selecting an appropriate safety class that is dependent on the economical consequences of a pavement failure but independent of material in the wear layer.

1. Introduction

The current Swedish design method for concrete pavements is based on German design methods from the 1970s. Traffic and thermal stresses are calculated separately and superimposed. The thickness design is based on a comparison of the superimposed flexural stress and the flexural strength taking into account fatigue compiled according to Tepfers' criterion (Tepfers, 1979). Traffic stresses are computed by using a one-dimensional, linear multi-layer elastic half-space model. Thermal stresses are computed by using a modification of Eisenmann's beam equations (Eisenmann, 1979). In Sweden, concrete pavements have difficulties competing with flexible pavements. One reason is that the design methods are not compatible. For flexural pavements, more modern design tools are available and reliability issues are considered differentially.

The current Swedish concrete pavement design method was developed by Petersson (1990) and applied to highways. It has later been further developed for additional applications such as concrete pavements in tunnels (Silfwerbrand, 1993) and industrial concrete pavements (Silfwerbrand, 1994, & Silfwerbrand, 2001). The experience of concrete pavements designed with this design method is satisfactory, but concrete pavements still have difficult competing with flexible pavements. One reason might be that the current design is either too complicated, too conservative, or both.

2. Research Significance

The current Swedish design method for concrete pavements has its origin in the 1970s. In order to make concrete pavement comparable with flexible pavements, for which modern design methods exist, there is urgent need of a new concrete pavement design method that can be used under Swedish conditions. This paper describes work in developing a new Swedish concrete pavement design method. The proposed method to consider security levels will facilitate an objective material selection.

3. Starting Points

In Sweden, more than 99 percent of the highway network consists of asphalt pavements while the total length of concrete pavements is less than 100 km (87 km of concrete pavements were constructed between 1972 and 2006). There are several reasons for this predominance:

- (i) low construction cost,
- (ii) good traffic comfort,
- (iii) popularity among contractors and the highway authorities,
- (iv) well-known tools to accommodate for poor subgrade and materials sensitive to frost-heave,
- (v) strong bitumen industry,
- (vi) comparable ease to repair, and
- (vii) simple and well-known design tools.

The concrete pavement has several advantages, e.g., load-carrying capacity, stiffness, wear resistance, insensibility to heat, incombustibility, and brightness, but several of these factors influence only the long-term costs. In order to let the concrete compete in a comparable way, long-term costs have to be considered in the design (by performing life-cycle cost analyses) and the design tools have to be as simple and well-known as the ones used for flexible pavements.

In Sweden, the Swedish Road Administration (SRA) had developed a powerful, straightforward, and user-friendly software for designing highway pavements. It is called PMS Object and is based on SRA's technical guidelines for pavements (SRA, 2005). The design contains the following steps:

1. Computation of traffic volumes
2. Determination of the pavement structure
3. Computation of load-carrying capacity
4. Computation of security against frost heave

The design process is iterative. The user selects layer sequences and layer thicknesses, the program computes the load-carrying capacity. If the load-carrying capacity (measured in number of 100-kN axle passages) is greater than the design traffic loading (also measured in number of 100-kN passages), the user receives a "green light". If not, the computer screen shows a "red light". If the load-carrying capacity is close (within 10 %) of the design traffic loading, there is a yellow warning signal. Usually, the user increases the thickness of one or more layers to increase the load-carrying capacity and turn off the

red or yellow light. For economic design, unnecessary layer thickness should be reduced to approach the yellow light. As with all user-friendly programs, PMS Object appears as a “black box”. However, one subroutine is used to compute strains at various levels in the pavement system while another one compares the obtained strains with the Swedish design criteria for bound bases (asphalt-treated or cement-treated) and subgrade. The model used for strain computation is a multi-layer elastic half-space.

PMS Object also contains a concrete pavement module. However, here the user has a much more limited possibility to alter the solutions. No strain or stress computation is made when running the program. The program just interpolates between previously determined concrete pavement solutions for three traffic classes, three concrete strength classes, and alternatives with asphalt- or cement-treated base (Silfwerbrand, 2003).

Concerning concrete pavements and PMS Object, the following shortcomings have been identified:

- The program is limited to interpolation between very few pre-calculated solutions.
- It is impossible to consider improvements or any alterations in concrete quality, base layers, slab width, joint spacing, dowel bars, and reinforcement.
- New loads (e.g., increased axle loads and super single wheels) cannot be taken into account.
- Only traditional loading cases are considered, i.e., “bottom up cracking” while not “top down cracking”.
- The failure (fatigue) criterion for cement-treated base, that is old and too rigorous, cannot be exchanged.
- Intensity and frequency of thermal gradients, causing thermal loading, are incorrectly assumed to be equal throughout all of Sweden, which measures 1700 km from north to south.
- The design method originated in Germany in the 1970s (Eisenmann, 1979). Further design method development and local circumstances are not considered.
- Security against failure and cracking is not visualized.

4. Old Swedish Design Method for Concrete Pavements

The old Swedish concrete pavement design method was originally developed by Petersson (1990). It was based on the German design method according to Eisenmann (1979). The design is based on the following items:

1. The traffic loading is represented by a number of 100-kN standard axle passages. There are simplified methods to transfer the mixed car and lorry traffic to standard axles and to count the average number of standard axles per heavy vehicle (usually 1.3 standard axles per vehicles weighing more than 3.5 metric tonnes). This computation does not differentiate between concrete and asphalt pavements.
2. Material (modulus of elasticity and Poisson’s ratio) and geometrical (thickness) data for each layer in the pavement system are selected from values that can be found in SRA tables (SRA, 2005). The stiffness (i.e., modulus of elasticity) for

- asphalt-treated base, unbound base, unbound subbase, and subgrade varies from season to season due to temperature, frost, and frost heave.
3. Traffic stresses and strains are calculated by using a computer program (Gipi, developed by van Cauwelaert [1986]) that is based on a multi-layer elastic half-space (Figure 1).
 4. Traffic stresses at or close to edges and joints are magnified by a certain factor that has been determined by using a program for slabs on a Winkler foundation and analyzing its result.
 5. Thermal stresses are computed by using Eisenmann's beam model (Figure 2) and thermal gradients (Δt) with magnitudes and frequencies based on limited Swedish temperature measurements in Swedish concrete pavements (5 % of the year: $\Delta t = 60^{\circ}\text{C/m}$, for 20 %: $\Delta t = 40^{\circ}\text{C/m}$, and for 75 %: $\Delta t = 0$, [Silfwerbrand, 1995]).
 6. For concrete, traffic and thermal stresses are superimposed and compared with the fatigue strength using Tepfers's fatigue criterion (Tepfers, 1979).
 7. For bound bases and for the subgrade, traffic strains are compared with SRA's fatigue criteria for cement-treated base, asphalt-treated base, and subgrade, respectively (SRA, 2005).
 8. Items 3-7 have to be computed for each season and, for the concrete layer, the summer seasons have to be divided into parts with and without thermal gradient (thermal stress). In practice, the partial damage (defined as the number of load repetitions during the season or seasonal part divided by the allowable load repetitions during the same period) is computed for each season or seasonal part.
 9. The effects from all seasons are combined by using Miner-Palmgren's partial damage hypothesis.

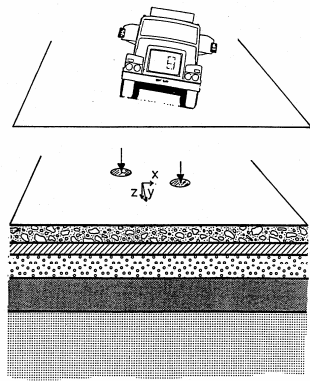


Figure 1. Computation of traffic stresses and strains by adapting a multi-layer elastic half-space.

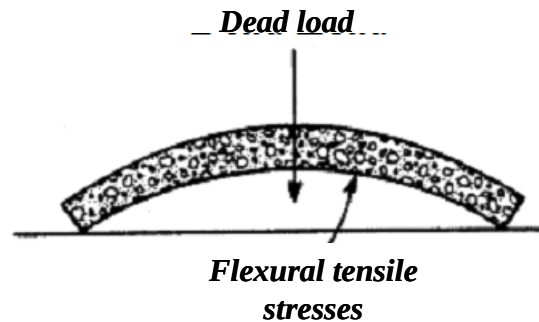


Figure 2. Temperature stresses develop as the curling due to a positive thermal gradient (heated top-side) is counteracted by dead load.

5. New Swedish Design Method for Concrete Pavements

The aim of the new Swedish concrete pavement design method has been (i) to place the concrete pavement design method on equality with the asphalt pavement design method and (ii) to make it fully competitive in the available software PMS Object. In the past, the layers beneath the pavement, i.e., base, subbase, and subgrade, have been designed by using different computer programs. However, the partial damage that is caused in the subgrade by the overpass of a heavy vehicle must be dependent solely on the magnitude and duration of the strain that is developed. If the strain is the same for two pavement systems, the material in the wear layer cannot have any influence. Therefore, the very same software should be used to compute strains in the subgrade for both concrete and asphalt pavements. Consequently, the PMS Object's subroutine (BISAR) for computing subgrade strains is used also in the new concrete pavement design method. As a by-product, we are able to take the high stiffness and high load-spreading capacity of the concrete pavement into account.

The new design method consists of the following items (Figure 3):

1. The traffic loading is represented by a number of 100-kN standard axle passages (see item 1 for the old method in Section 4).
2. Material (modulus of elasticity and Poisson's ratio) and geometrical (thickness) data for each layer in the pavement system are selected from values that can be found in the PMS Object package. The stiffness (= modulus of elasticity) for asphalt-treated base, unbound base, unbound subbase, and subgrade varies as for the old method.
3. Traffic stresses and strains are calculated by using a subroutine (BISAR) that is based on a multi-layer elastic half-space. The strain values obtained for the subgrade and for the asphalt-treated base (ATB), if any, are used in the design.

4. Underneath the wheel load, the vertical stress σ_z and the vertical displacement w on the bottom side of the ATB or the cement-treated base (CTB) are used to estimate a value of the subgrade reaction k by setting $k = \sigma_z / w$.
5. Stresses due to combined traffic and thermal loading in the concrete pavement and in the CTB, if any, are computed by using a slab-on-Winkler foundation model, the previously obtained k value, and a FEM program (ISLAB2000, ERES Consultants, 2000).
6. For concrete, stresses at four different locations in both the top and bottom of the concrete slab, are compared with the fatigue strength using Tepfers's fatigue criterion (Tepfers, 1979).
7. For bound bases and for the subgrade, traffic stresses are compared with SRA's fatigue criteria for CTB, ATB, and subgrade, respectively (SRA, 2005).
8. Items 3-7 have to be computed for each season and for the concrete layer, the summer seasons have to be divided into parts with and without thermal gradients (see item 8 for the old method in Section 4).
9. The effects from all seasons are combined by using Miner-Palmgren's partial damage hypothesis.

This process will not be practically possible to conduct. Including a subroutine that consists of a FEM program will lead to unacceptably long computing times. Consequently, these computations have to be run in advance. A database containing the solutions to 48,600 cases has been developed. The cases are the result of combinations of three concrete strength classes, five concrete thicknesses, three values of joint spacing, two slab widths, two types of bases (ATB and CTB), three subgrade materials, six seasons, five thermal gradients, and three loading locations. When running the PMS Object software, a subroutine will call the database and by interpolation found solutions to any case that is inside the multi-axial space that is limited by the variations of the six parameters strength class, concrete thickness, joint spacing, slab width, base type, and subgrade material. However, the database can easily be expanded to cover broader variations, as well as alterations in other parameters, e.g., axle load, load transfer efficiency at joints, and base layer thickness.

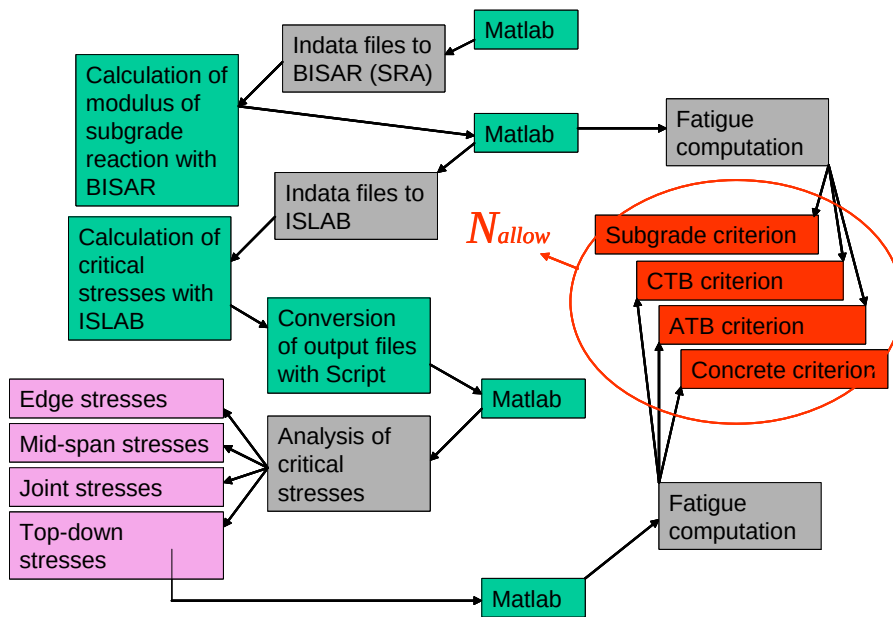


Figure 3. Flow chart showing the new Swedish concrete pavement design method.

6. Safety Levels

In modern design codes, the security philosophy is based on probabilistic methods. The risk of a failure must not exceed a certain limit, e.g., 0.01 % during the entire service life (Figure 4). Consequently, the load-carrying capacity has to be significantly higher than the maximum load. In practical design, this philosophy is simplified to the following principle equation:

$$\frac{\text{Load carrying capacity}}{\text{Partial factor for strength}} \geq \text{Load} \times \text{Partial factor for load} \quad (1)$$

where, the partial factors have to be ≥ 1.0 .

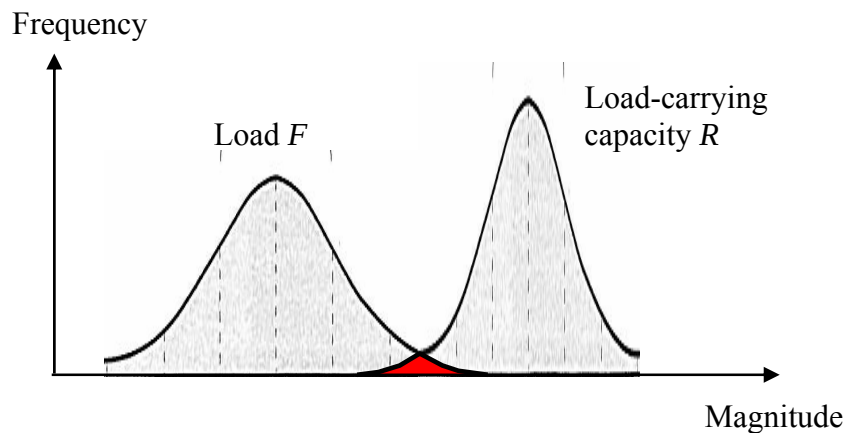


Figure 4. The probability of failure, expressed as the load exceeding the load-carrying capacity, has to be sufficiently small (cf. overlapping area with total area of load-carrying capacity).

In contrast to bridge and building design, conventional pavement design does not deal with partial factors for strength. Usually, they are understood to have the value of 1.0. However, there might still be an implicit safety. The Swedish concrete pavement design method is one example. This design is based on the characteristic flexural strength. It means that the actual strength in 95 % of the cases, e.g., in 95 % of the pavement slabs, exceed the design value. Consequently, failures are rare. However, for concrete structures, usually the characteristic strength is divided by partial factors (> 1.0) for strength. This provides additional safety and additionally diminished failure probability.

Pavements are usually designed for fatigue loading. It usually means that the wide spectrum of traffic loads is converted to a number of standard axle loads. However, the standard axle load is rarely the anticipated maximum axle load. Consequently, the concept of partial factors for loads is not only unused, but also irrelevant. In Swedish pavement design, the default value is that all vehicles weighing more than 3.5 metric tonnes is considered to be converted to 1.3 passages of a 100-kN standard axle.

The original Swedish design tables for concrete pavements (SRA, 1994) have been analyzed in detail to determine the implicit safety margin. A safety factor was determined by dividing the number of possible standard axles with the number of allowable standard axles for the various tabled values. The possible numbers were calculated as the number of load repetitions at cracking by using the procedure described in Section 4. It varies between 0.7 and 10 with a gravity center at 2 (Silfwerbrand, 2003). This is an example of an implicit safety margin that is invisible for both the designer and the client. It is the authors' opinion that all safety margins should be obvious and transparent.

There are several measures to consider the safety problem:

1. The concrete strength and the available strain levels in the base and subgrade might be divided by a partial factor for strength $\gamma_n > 1$.
2. The design traffic load may be multiplied by a partial factor for loads $\gamma_f > 1$.
3. The design criteria for the various layers may be provided by an inbound safety factor.
4. The measures 1, 2, and 3 may be combined.
5. Minimum thickness values may be stipulated for the wear layer, base layer, and other layers in the pavement system.
6. Probabilistic measures taking into account probability values and scatter in all important parameters.

The measures contain two partial factors frequently used in Swedish and European design of concrete structures: γ_n = partial factor that considers the safety class, γ_f = partial factor that considers type of loading. The value of γ_n increases with decreasing failure probability. High values are used for more complicated buildings and civil engineering structures and for buildings and structures whose failure might lead to high risks of injuries. The value of γ_f reflects the uncertainty of the load.

In the new Swedish concrete pavement design method, we have focused on a combination of measures 1 and 5. Since we know that Swedish concrete pavements designed according to the old method perform well, we neither want to make them thinner with less crack and failure risks nor want to make them thicker with unnecessary increases in material resources and costs. The intention is not to reduce the safety margin but to make it visible and transparent. In the new Swedish concrete pavement design method, the safety margins have been made transparent by inserting partial factors in the failure criteria. This is exemplified by the criteria for concrete and subgrade:

$$\frac{\sigma_{\max}}{f_{\text{cfl}} / \gamma_n} = 1 - 0.0685 \cdot \left(1 - \frac{\sigma_{\min}}{\sigma_{\max}} \right) \cdot \log N \quad (2)$$

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

where, $\sigma_{\min}$ = minimum concrete stress during the load cycle (usually $\sigma_{\min} = \sigma_{\text{temp}}$ = thermal stress), $\sigma_{\max}$ = maximum concrete stress during the load cycle ($\sigma_{\max} = \sigma_{\text{temp}} + \sigma_{\text{traffic}}$, σ_{traffic} = traffic stress), f_{cfl} = concrete flexural strength, γ_n = partial factor for safety class, N = number of load repetitions at failure, and ε_z = vertical strain at the top surface of the subgrade. Equations 2 and 3 are illustrated in Figures 5 and 6.

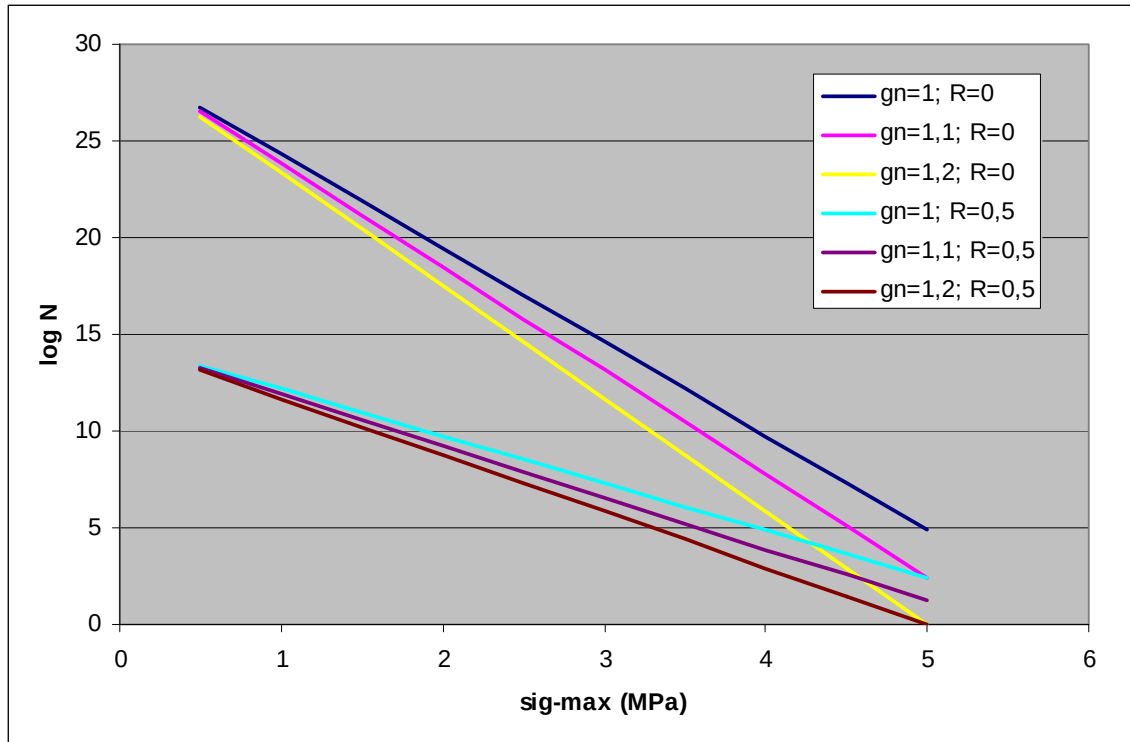


Figure 5. The concrete failure criterion. The logarithm for the number of load repetitions at failure for varying values of the maximum stress $\sigma_{\max}$, the partial factor γ_n , and the ratio R between minimum and maximum stress. Concrete flexural strength $f_{\text{cfl}} = 6.0$ MPa.

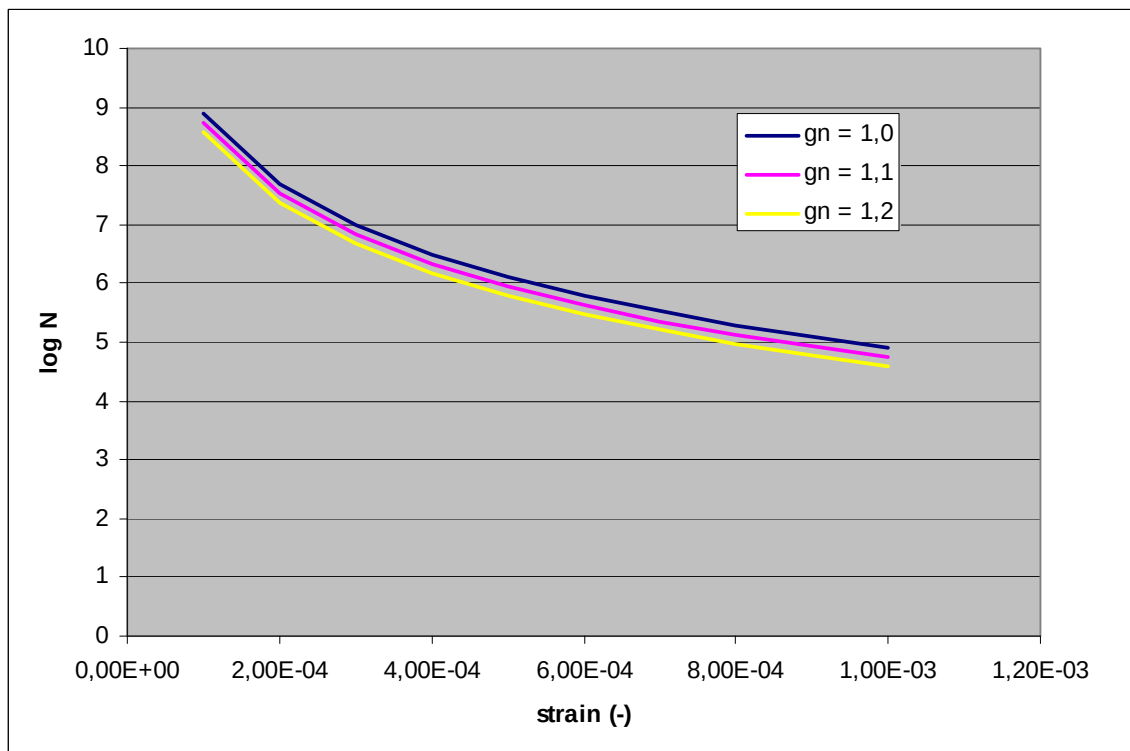


Figure 6. The subgrade failure criterion. The logarithm for the number of load repetitions at failure for varying values of the partial factor γ_n ,

In Sweden, safety classes (reliability classes) are used when designing buildings, bridges, and civil engineering structures, i.e., all load-carrying structures (slabs-on-grade and pavements are not considered as load-carrying structures since they have a zero span length). There are three safety classes and the selection of safety class is based on the risk of severe injuries. A pavement cannot fall onto the head of human beings, so in that perspective they ought to be classified in the lowest safety class (safety class 1). On the other hand, the consequences of damages, e.g., extensive cracking, joint faulting, and punch-outs, may be severe, leading to an increased risk of traffic accidents and large costs for repair and traffic closing. Consequently, also pavements might be divided into safety classes.

The new Swedish concrete pavement design method contains three safety classes (Table 1). The lowest class is suitable for industrial pavements and other pavements with mostly low-speed vehicles with large wheels. The next class is suitable for highly trafficked highways. The highest safety class is intended for highly trafficked highways that are very difficult to close and repair, e.g., through tunnels. If the new concrete pavement design method would be used without caution, it might lead to very thin concrete pavements at certain conditions, i.e., in tunnels with small thermal gradients and stiff support (rock). However, we have very limited experience with pavements thinner than 180 mm. Consequently, the safety concept also comprises minimum thickness values for the three safety classes (Table 1).

Table 1. Proposed safety classes in the new Swedish concrete pavement design method

Safety class	1	2	3
Economical consequences at failure or severe damage	Minor	Significant	Extensive
Example of application	Industrial pavement	Highway	Highly trafficked road in a tunnel
Partial factor	1.0	1.1	1.2
Minimum concrete thickness (mm)	160	180	180

7. Timetable

The work with the new Swedish concrete pavement design method started in 2002. In 2003, a concrete pavement alternative was introduced in the SRA software PMS Object. This was, however, only based on interpolation of previously tabled values (Silfwerbrand, 2003). The work with improvements was intensified in 2004 and resulted in a licentiate thesis (resulting in licentiate degree used in the Swedish education system for an educational degree between M.Sc. and Ph.D.) in 2006 (Söderqvist, 2006). The database discussed in Section 5 was established in the fall 2007. During the spring 2008, the

software PMS Object will be further developed to include the new concrete pavement method. The ambition is that the updated software should be ready for use in late 2008.

8. Concluding Remarks

A new concrete pavement design method has been developed in Sweden. The aim is that concrete and asphalt pavements will be designed with the same simplicity, safety margins, and software program. Consequently, the design of the subgrade and bound base, if any, is carried out with the same design criteria and the same subroutine. A new safety philosophy has been introduced aiming at making the safety margin visible and transparent. The client and the designer have to select a suitable safety class dependent on the economical consequences of a pavement failure or distress. The authors believe that safety class should be selected independent on the material in the wear layer.

Acknowledgement

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References

- van Cauwelaert, F. (1986). *Computer programs for the determination of stresses and displacements in four layer systems with fixed bottom*. Centre de Recherches de l'Institut Supérieur Industriel Catholique du Hainaut, Mons, Belgium, 1986, 61 pp.
- Eisenmann, J. (1979). *Betonfahrbahnen. Handbuch für Beton-, Stahlbeton und Spannbetonbau*. Verlag von Wilhelm Ernst & Sohn, Berlin, München, Düsseldorf, 305 pp. (In German).
- ERES Consultants (2000). *ISLAB2000 – Finite Element Analysis Program for Rigid and Composite Pavements, USER'S GUIDE*, ERES Consultants, A Division of Applied Research Associates, Inc., 505 W. University Avenue, Champaign, IL 6182.
- Petersson, Ö. (1990). *Design of plain jointed concrete pavements* (Dimensionering av oarmerade betongvägar). CBI Report No. 2:90, Swedish Cement and Concrete Research Institute, Stockholm, Sweden, 29 pp. (In Swedish).
- Silfwerbrand, J. (1994). *Design of concrete pavements* (Dimensionering av betongbeläggningar). Report No. 9, Chair of Structural Mechanics and Engineering, Department of Structural Engineering, Royal Institute of Technology (KTH), Stockholm, Sweden, 73 pp. (In Swedish).
- Silfwerbrand J. (1993). *Concrete pavements in tunnels*. (Betongbeläggningar i tunnlar). CBI Report No. 5:93, Swedish Cement and Concrete Research Institute, Stockholm, Sweden, Sweden, 41 pp. (In Swedish).
- Silfwerbrand J. (1994). *Design of industrial concrete pavements*. (Dimensionering av tungt belastade industriytar). CBI Report No. 1:94, Swedish Cement and Concrete Research Institute, Stockholm, Sweden, 79 pp. (In Swedish).
- Silfwerbrand J. (2001). *Design of industrial cast-in place concrete pavements*. (Dimensionering av platsgjutna industriytar i betong). Report No. 63, Chair of Structural

Design and Bridges, Department of Civil and Architectural Engineering, Royal Institute of Technology (KTH), Stockholm, Sweden, 54 pp. (In Swedish).

Silfwerbrand, J. (2003). *Computation of load-carrying capacity of concrete pavements according to ATB VÄG 2002*. (Beräkning av bärförmåga hos betongöverbyggnad i ATB VÄG 2002). Commission report No. 2003-51, Swedish Cement and Concrete Research Institute, Stockholm, Sweden, 35 pp. (In Swedish).

Söderqvist, J. (2006). *Design of Concrete Pavements – Design Criteria for Plain and Lean Concrete*. Trita-BKN. Bulletin 87, 2006 (Licentiate Thesis), School of Architecture and Built Environment, Structural Design and Bridges, Royal Institute of Technology, Stockholm.

SRA (1994). *General technical requirements for pavements* (Väg 94. Allmän teknisk beskrivning för vägkonstruktioner). Swedish Road Administration, Borlänge, Sweden. (In Swedish).

SRA (2005). *General technical requirements for pavements* (ATB Väg. Allmän teknisk beskrivning för vägkonstruktion). Swedish Road Administration, Borlänge, Sweden. (In Swedish).

Tepfers, R. (1979). "Tensile Fatigue Strength of Plain Concrete". *ACI J., Proceedings* 76(8), 919-933.