DESIGN OF INDUSTRIAL CONCRETE BLOCK PAVEMENT: SUMMARY OF AN INTERNATIONAL WORKSHOP

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ABSTRACT

Concrete block pavements have been used successfully on industrial pavements, ports, airfields, and other heavy-duty pavements in several countries in the world. Despite the existence of British and Spanish guidelines, there is a need for improved design tools in this area. Loads, climate, subgrade conditions, design methods, and construction tradition may vary extensively from one country to another making the adoption of a specific country's guidelines difficult and maybe erroneous. In order to compare the design methods in various countries and facilitate the development of improved design methods, nine international concrete block pavement specialists were gathered in Stockholm in August 2000.

The basis for the workshop was a hypothetical design of a new concrete block pavement at the port of Helsingborg in the south of Sweden. Loading cases and other prerequisite were distributed to the participating specialists before the workshop. This paper contains a summary of the various specialists' solutions and a comparison of their results and aims at facilitating the development of design methods for industrial concrete block pavements.

Based on the presentations and discussions, the following major conclusions can be drawn:

- Pavement solutions for the selected loading case with an axle load of 900 kN are available for cases with untreated (unbound) roadbase, asphalt stabilised roadbase, and cement stabilised 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 experiences.

The total pavement thickness for cases with cement stabilised 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 stabilised roadbase.

1. INTRODUCTION

Concrete block pavements have been used successfully on industrial pavements, ports, airfields, and other heavy-duty pavements in several countries in the world (Figure 1). Despite the existence of British and Spanish guidelines, both of which are also used in other countries, the organisers of the 2000 International Workshop on design of industrial concrete pavements had the opinion that there was a need for improved design tools in this area. Loads, climate, subgrade conditions, design methods, and construction tradition may vary extensively from one country to another making the adoption of a specific country's guidelines difficult and maybe erroneous.

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In order to compare the design methods in various countries and facilitate the development of improved design methods, nine international concrete block pavement specialists from Europe, North America, and Australia were gathered in Stockholm in August 2000. The workshop was organised by the Royal Institute of Technology (KTH) and the Swedish Concrete Block Paving Association (Svensk Markbetong). The basis for the workshop was a hypothetical design of a new concrete block pavement at the port of Helsingborg in the south of Sweden. The design vehicle had an axle load of 900 kN and it was anticipated to traffic the pavement 20 times a day during 20 years. Details of the loading cases and other prerequisites are given in Appendix A. The various specialists' solutions are given in Chapters 1-9 of the workshop proceedings (Silfwerbrand, 2000). This paper contains a summary of their findings and a comparison of their results.

Figure 1. Heavily loaded industrial concrete block pavement.

2. SUMMARIES OF THE SPECIALISTS' CONTRIBUTIONS

Eight international concrete block pavement specialists participated in the workshop. They were Professor Brian Shackel (AUS), Professor Carlos Kraemer (ES), Professor Frohmut Wellner (DE), Dr. Raymond Rollings (USA), Professor Anthony Beaty (CA), Professor Ian Cook (UK), Dr. Rien Huurman (NL), and Professor Johan Silfwerbrand (SE). A ninth specialist, Mr. Haldor Grayston (NO), was not able to attend the workshop, but his contribution was summarised at the workshop and included in the proceedings. The following table contains a summary of the various specialists' methodologies and the results obtained.

Table 1. Summaries of the specialists' contributions to the workshop.

Expert	Methodology	Results and comments
Prof. Brian Shackel (AUS)	Professor Shackel's methodology is based on experience and tests on concrete block paving conducted over more than 20 years in Australia, South Africa and North America. It is described in detail in Shackel (1990). Shackel's computer program LOCKPAVE, that contains a fully automated design procedure, is used in the design. Unbound layers are designed according to the Shell rutting criterion for the vertical compressive strain at the top of the subgrade. Bound layers are designed according to PCA's and Shell's criteria for the horizontal strain at the bottom of the cement roadbase or asphalt roadbase, respectively.	Shackel studies 54 different cases for Loading Case 1 (900 kN axle load) and recommends four main alternatives. Drainage is dealt with by a drainage factor that is influencing the required total depth of the pavement system. He states that the used design method does not claim to be universal, but that it has shown to yield thicknesses that are slightly greater than those implemented in a range of industrial pavements performing successfully.

Table 1. continued

Expert	Methodology	Results and comments
Prof. Carlos Kraemer (ES)	Professor Kraemer bases his design on the Spanish Pavement Design for Ports (1994). It is in turn based on experience and computations. The design guide covers several pavement alternatives including concrete block pavements. The port traffic is categorised into four groups dependent on load and use rate. With known traffic category (A) and use (commercial), design tables provide required thicknesses.	Since the subgrade at Helsingborg consists of clay, a capping layer of 1 m is needed for subgrade improvement. The design guide does not allow untreated (unbound) roadbases for traffic category A, but Kraemer suggests substituting an untreated gravel layer.
Prof. Frohmut Wellner (DE)	Professor Wellner states that there is no established and uniform design method for civilian pavement for axle loads of 900 kN in Germany. Therefore, Wellner's design is based on strain computations based on the multi-layer computer program BISAR. Computed strain values are compared with design equations given in the German pavement literature. A safety factor of 1.5 is used for granular materials since strain limits for water permeable base courses are unknown.	Wellner computes stresses, strains, and deflections and finds that the deflection in cases with granular base courses is too high. Thus, a stabilised roadbase is needed. Wellner's solutions contain asphalt or cement treated roadbases. He states that interlocking blocks with a thickness equal to or greater than 100 mm should be used.
Dr. Raymond Rollings & Dr. Marian Rollings (USA)	Due to the magnitude of exposed loads and tire pressures, Dr. Rollings and Dr. Rollings suggest that the design and construction of a port pavement should be drawn from heavy-load pavements such as airfields rather than more lightly loaded highway pavements. Concrete block pavements distribute loads through underlying layers rather than rigid pavements that distribute loads through bending. Consequently, Rollings and Rollings select the U. S. Army Corps of Engineers' flexible airfield design approach as the design method for this specific problem. Two design approaches are available: the traditional CBR flexible pavement design method and a layered elastic approach. They decide to use the latter method since the pavement system contains bound layers. The Corps of Engineers' subgrade criterion is used.	A cement stabilised roadbase is used. The Corps of Engineers uses an effective cracked modulus with a rather low value (in this case E = 814 MPa) due to shrinkage and load-induced cracking. Rollings and Rollings describe thoroughly how the Corps of Engineers deals with frost issues, but they conclude that the frost penetration depth is less than the total pavement thickness, which is why no special frost provisions are needed.
Prof. Anthony Beaty (CA)	Professor Beaty states that the dominant factor in the specific problem is the magnitude of the front axle load (900 kN) that is more than ten times the value of the standard highway axle load (80 kN). He uses the British Port Association manual (1989). This method is semi-empirical. The pavement structure is divided into two parts; the foundation (subbase) whose thickness is dependent on subgrade strength and the structure (roadbase) whose thickness is dependent on traffic loading.	The manual distinguishes between cases with traffic loads running free without any dynamic effects and cases where dynamic effects have to be taken into account, e.g., braking and cornering. Braking is assumed to increase the load by 30 %, cornering by 40 %, and simultaneous braking and cornering by 70 %.

Table 1. continued

Expert	Methodology	Results and comments
Prof. Ian Cook (UK)	Professor Cook is also using the British Port Association manual (1989) for the design. In addtition , he describes the design of the Port of Santos in Brazil. This case study is very interesting since the Port of Santos case has several similarities with the hypothetical design of the port of Helsingborg. The Santos project comprised a 132 000 m^2 container handling facility. The subgrade consisted of soft clay. The surface was engineered to allow percolation of water. The surface was designed for wheel loads exceeding 500 kN. The concrete block pavement at Port of Santos has been built and functions well.	By using the British Port Association manual, the following pavement system was selected: 80 mm pavers, 50 mm bedding sand, 500 mm cement stabilised gravel, and 1500 mm sand (according to pre-compaction settlement). Instead of drilling 50 mm holes, c/c 2 m, a cement stabilised gravel with no fines was used to allow percolation. It had a permeability of 1 mm/s. The pavers had 6 mm radius spacers to provide a 6 mm gap and to allow the free water flow into the bedding sand. Whilst the pavement system will not permit the immediate percolation of rainwater in severe storms, it will ensure that standing water percolates quickly.
Dr. Rien Huurman (NL)	Dr. Huurman basis his design on a FE model that was developed in Delft in the late 90s (Huurman, 1990). The structural model uses axial symmetry and comprises all the various layers in the pavement system. The concrete blocks are able to translate and rotate without the development of stresses. The joints between the blocks are represented by sets of springs that are active under compression but inactive under tension. The value of the spring stiffness is based on FWD measurements on concrete block pavements. In his analysis, Huurman considers that the pavement materials are showing stress-dependent behaviour and various relationships between resilient modulus and stress are given in his paper.	He analyses 15 pavement structures and uses failure criteria for shear stresses and permanent rutting as well as fatigue and crushing in the cement treated roadbase to determine required thicknesses. He concludes that pavements without bound roadbases are not able to resist current traffic load.
Prof. Johan Silfwerbrand (SE)	Professor Silfwerbrand uses a semi-empirical design method. Stresses and strains in the pavement system's various layers are computed with the computer program BISAR. Moduli of elasticity of the pavement layers are based on FWD measurements on Swedish pavements. The paver layer has been given a relatively high modulus of elasticity (E = 6 000 MPa) considering the stiffness increase that occurs during the first 10 000 to 15 000 passages that only comprise less than 10 % of the total number of passages (146 000). Computed strain values are compared with available strain values determined from failure criteria given in the Swedish road pavement code (1994) and subsequent improvements.	Silfwerbrand proposes two solutions; one with an untreated roadbase and one with an asphalt stabilised roadbase (Figure 2). No solutions with cement stabilised roadbases are given due to the current Swedish failure criterion, which would lead to a uneconomical design.

Table 1. continued

Hr. Haldor Grayston (NO)	Referring to the successful experience of the old concrete block pavement in Helsingborg, climatic conditions, and access to high quality aggregates, Mr. Grayston selects a mechanically stabilised roadbase.	Subbase and roadbase should be made of crushed rock 0-80 and 0-64 mm, respectively. Both materials ought to be reinforced using Geogrid Tensar SS 2 (or equivalent). The bedding sand ought to be comprised of crushed rock 0-8 mm with maximum 5 % fines to ensure drainage. Grayston prescribes that the blocks should be mechanically laid.

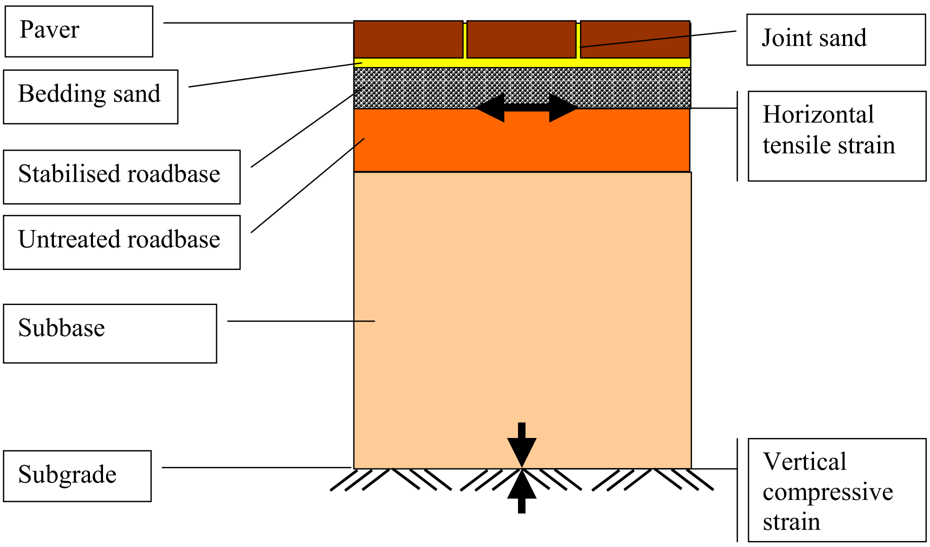

Figure 2. Principle drawing showing Silfwerbrand's solution and the failure criteria used in Swedish design.

3. DESIGN RESULTS

The design results have been summarised in Tables 2-4. They are dealing with pavement systems with untreated (unbound) roadbase, asphalt stabilised roadbase, and cement stabilised roadbase, respectively. The tables show total thicknesses and thicknesses for each layer. Furthermore, recommended paver shapes and laying patterns are given. "Dentated" stands for the Australian paver Category A (pavers which key into their neighbours on all sides) and "Rect." means rectangular ones. "Herringb." stands for herringbone pattern. If these data are missing, the authors did not state any recommendations concerning paver shape and laying pattern. Finally, the design type has been indicated in the tables. "Multi-lay." means that the design is based on a strain computation for an elastic multi-layer pavement system. "Manual" indicates that the design is carried out using design charts in a manual or guideline, that in turn may be based on computations. "Experience" means that the design is based on experience from similar cases that in turn may be based on either computations, manuals, or success stories. "FEM" stands for the Finite Element Method and that this method has been used in the design procedure.

Table 2. Design of concrete block pavement on untreated (unbound) roadbase.

	Thicknesses (mm)					Pavers		Design type
Name	Total	Paver	Bedding sand	Roadbase	Subbase	Shape	Laying pattern	
Shackel	1480	80	25	150	1225	Dentated	Herringb.	Multi-lay.
Kraemer	1750	120	30	250	1350†	Rect.	Herringb.	Manual
Rollings	1255	80	25	1000	150**			Multi-lay.
Beaty	1170	80	30	660	400	Rect.	Herringb.	Manual
Cook	1910	80	30	1500	300	Rect.	Herringb.	Manual
Silfwerbr.	1330	100	30	150	1050		Herringb.	Multi-lay.
Grayston	660	80	30	250††	300††			Experience
Wellner					Not possible.			
Huurman					Not possible.			

†Including 1 m capping layer. **Drainage layer. ††Reinforced road- and subbase.

Table 3. Design of concrete block pavement on asphalt stabilised roadbase.

	Thicknesses (mm)					Pavers		Design type
Name	Total	Paver	Bedding sand	Roadbase	Subbase	Shape	Laying pattern	
Shackel	765	80	25	100	560*	Dentated	Herringb.	Multi-lay.
Silfwerbr.	1230	100	30	200	900		Herringb.	Multi-lay.
Wellner	1050	100	50	500	400	Dentated		Multi-lay.
Kraemer					Not treated.			
Rollings					Not treated.			
Beaty					Not treated.			
Cook					Not treated.			
Huurman					Not treated.			
Grayston					Not treated.			

* Cement stabilised subbase.

Table 4. Design of concrete block pavement on cement stabilised roadbase.

	Thicknesses (mm)					Pavers		Design type
Name	Total	Paver	Bedding sand	Roadbase	Subbase	Shape	Laying pattern	
Shackel	765	80	25	300	360*	Dentated	Herringb.	Multi-lay.
Kraemer	1700	120	30	200	1350†	Rect.	Herringb.	Guide
Wellner	1050	100	50	600	300	Dentated		Multi-lay.
Rollings	980	80	25	725	150**			Multi-lay.
Beaty	950	80	30	440	400	Rect.	Herringb.	Manual
Cook	960	80	30	550	300	Rect.	Herringb.	Manual
Huurman	1550	100	50	400	1000	Rect.		FEM
Silfwerbr.	Not economical due to Swedish failure criterion for cement stabilised base.							
Grayston					Not treated.			

* Cement stabilised subbase. †Including 1 m capping layer. **Drainage layer.

As shown in Table 2, the concrete block pavements with untreated roadbase have suggested thicknesses varying between 660 and 1910 mm. It ought to be mentioned that Grayston prescribes reinforced roadbase and subbase.

One explanation for the remaining thickness difference (1170 to 1910 mm) is varying properties and demands of the granular materials used for roadbase and subbase. Silfwerbrand requires crushed aggregates whereas the material in Kraemer's capping layer might need to fulfil other demands. It is worth mentioning that Wellner and Huurman do not think that pavements without stabilised roadbase are able to carry the 900 kN axle load. Beaty and Cook are using the same manual, but draw different conclusions. Their solutions for the case with cement stabilised roadbase are similar (Table 4), but they make different assumptions when substituting the cement base with crushed rock.

Only three specialists have made any solutions for the case with an asphalt stabilised roadbase (Table 3). If you consider that Shackel is using a cement stabilised subbase, the thickness difference between the other two solutions is rather small.

At first sight, the thickness differences are large for the case with a cement stabilised roadbase. However, if you omit Shackel's solution, also in this case containing a cement stabilised subbase, Kraemer's solution that demands a thick capping layer, and Huurman's numerical solution, the remaining four solutions have total pavement thicknesses between 950 and 1050 mm, i.e., they are quite similar.

4. LOADING CASE 2

The Loading Case 2 (LC2) comprises a container load as detailed in Appendix A. The loading case was selected by the organising committee after discussions with Swedish port engineers. However, as shown by Professor Beaty for example, the load is dependent on how the containers are stacked, i.e., if there is a single, row, or block arrangement (if one, two or four feet are in proximity). LC2, as it was defined originally (Appendix A), does not constitute the design case. Required pavement thickness to fulfil the demands of LC2 is roughly only 50 % of what is needed for Loading Case 1.

5. MEASURES TO ENSURE DRAINAGE

There are two conflicts when ensuring drainage on an industrial pavement carrying heavy loading:

- Heavy loads lead often require a stabilised roadbase and stabilised materials are less permeable than untreated materials.
- In order to stack containers high, the user requires a zero slope, whereas the pavement engineer wants 2 to 2.5 % or even more, to secure drainage.

During the workshop's final discussion (Chapter 10), drainage was thoroughly discussed. Professor Cook referred to the recently completed Port of Santos in Brazil and concluded that it is possible to make a permeable cement stabilised roadbase by prohibiting the fines. Others asserted that the problem is exaggerated; after some months most of the water flows on the concrete block pavers' surface. The important things are to maintain a slope demand of 1 % in discussions with the user and to select a suitable grading of the bedding sand. The amount of fines (< 0.065 mm) should be less than 3 %, preferably less.

6. MEASURES TO PREVENT FROST HEAVE

In order to prevent frost heave of unacceptable magnitude, the pavement system need to have a sufficient thickness. The thickness increases with increased susceptibility to frost heave within the subgrade and with increased frost amount (in Sweden, the frost amount is estimated as the product of number of days with temperature below 0°C and the average temperature during these days). Clay is more susceptible to frost heave than sand and gravel, but less than silt.

According to the Swedish guidelines for concrete block pavements (1999, 2002), the total thickness of the pavement system must exceed 275 mm in climate zone 1 (south of Sweden) if the subgrade consists of clay. The required pavement thickness for carrying the load is, however, much greater.

7. MEASURES TO ENSURE EVENNESS

In order to ensure evenness, the level of subbase, roadbase, and bedding sand must be controlled carefully. The roadbase should have a level tolerance less than ±10 mm. The bedding sand must have a uniform thickness. The paver thickness should not vary more than ±1 mm. A close inspection during laying is needed. The pavers are initially vibrated and compacted. Subsequently, the joints should be filled and a second compaction applied. Any excess sand should be removed.

8. CONCLUSIONS

A workshop on industrial concrete block pavements was held in August 2000 in the Stockholm Archipelago. Nine pavement specialists had designed a hypothetical concrete block pavement for the port of Helsingborg in south of Sweden. Based on the presentations and discussions, the following conclusions can be drawn:

- Field experiences from Australia, Canada, Israel, The Netherlands, and Latin America, show that industrial concrete block pavements perform well and are able to carry heavy loads with high tire pressures.
- Pavement solutions for the selected loading case with an axle load of 900 kN are available for cases with untreated (unbound) roadbase, asphalt stabilised roadbase, and cement stabilised 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 experiences. Generally, these pavement systems are thicker than those with stabilised roadbases.
- The total pavement thickness for cases with cement stabilised 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 stabilised roadbase.
- The drainage of industrial pavements ought to be ensured by selecting a proper bedding sand grading with minimum fines and a minimum slope of 1 %.
- The container loading case and the frost heave prevention are not critical for the hypothetical design of the Helsingborg port pavement.
- The paver thickness does not seem to be conclusive for providing load carrying capacity. However, a minimum thickness of 80 mm seems to be appropriate.
- Various failure criteria are used in various countries, even if some have the same origin. Beside failure criteria for the vertical strain in the subgrade and horizontal strain in stabilised roadbases, failure criteria concerning permanent deformation (rutting) and shear strength are used by some specialists.
- Finding new failure criteria, that are developed and adjusted solely for concrete block pavements with their specific characteristics, would be interesting, but is at present probably too expensive.
- With a lack of specific design criteria for horizontal loading like braking, acceleration and turning operations, some manuals use a load magnification of 20 to 30 %. Increases due to dynamic loads may be compensated by strength increases due to the high loading rate. The real behaviour under such loading ought to be considered in the future research on concrete block pavements.

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APPENDIX A

DESCRIPTION OF THE LOAD CASES

A.1 Design case
The design case is defined in the following table:

Table 5. Description of the load cases used in the workshop.

Factor	1 DESCRIPTION
Location	Helsingborg along the south-west coast of Sweden. As an average, Helsingborg has yearly 45 days with temperatures below zero. The average temperature during this period is ~2°C.
Climate	Coastal with fairly warm summers and mild winters.
Factor	2 DESCRIPTION
Subgrade	30 m clay on rock. Estimated stiffness of the clay: 40 MPa or CBR 4 %.
Subsoil water table	3 m below surface.
Subbase	Well compacted, crushed aggregate of high quality.
Roadbase	a) untreated, well compacted, crushed aggregate of high quality & b) bound base either cement stabilised or asphalt stabilised.
Loading Case 1 (LC1)	100-ton truck carrying 90 tons on its front axle and 10 tons on the rear axis in fully loaded condition, see Figure 3 (left). This vehicle is the only vehicle trafficking the pavement. It is assumed that it is always fully loaded. Estimated number of daily passages: 20. The pavement is trafficked 7 days a week, or 365 days a year. There is no traffic growth. For simplicity, the traffic is assumed to be fully channelised. In the basic case, only vertical loading is considered. If there was time, the participants were welcome to consider other kinds of vehicle operations, e.g., turning, braking, acceleration or operating on an uneven surface.
Loading Case 2 (LC2)	Container foot carrying 5.5 tons, see Figure 3 (right). Estimated average load duration: 3 months.
Intended service life	20 years.

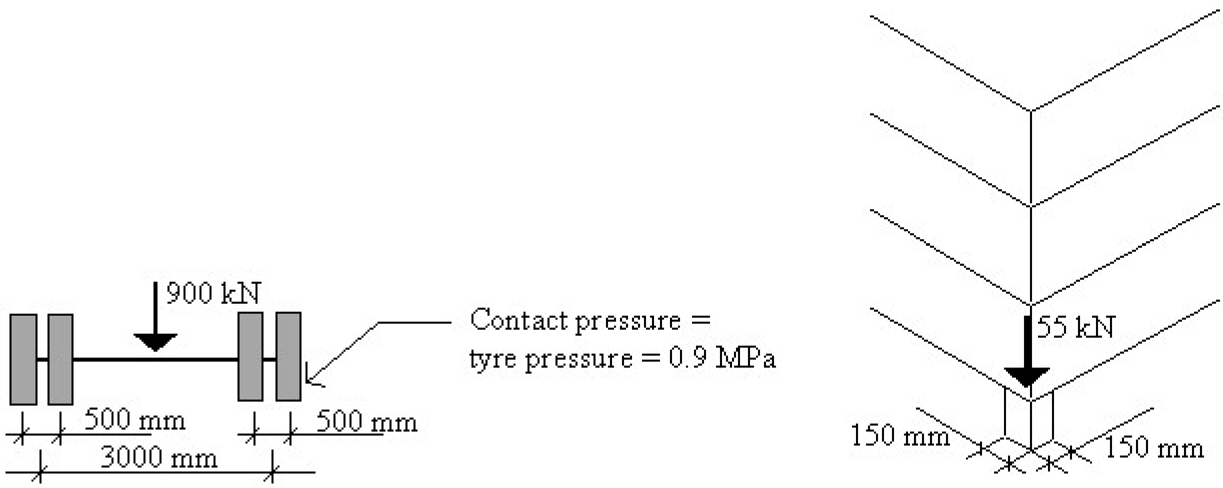

Figure 3. Geometry for Loading Case 1 (LC1) [left] and 2 (LC2) [right].

A.2 Participant's Report

The participants were encouraged to cover the following items:

- type of design (empirical, analytical or mechanistic, semi-empirical),
- physical model or empirical base,
- failure criterion (if any),
- reference literature and/or reference objects,
- pavement system including layer thickness, layer material, and material characteristics,
- type of paver, paver thickness, and laying pattern,
- demands on bedding and joint sand,
- measures to secure drainage,
- measures to prevent frost heave,
- measures to secure evenness, and
- any alterations from the design case data given above.

Both cases with and without treated roadbase ought to be covered by each participant.

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SWEDISH CEMENT AND CO BIOGRAPHY
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