DESIGN CONCEPTS OF CONCRETE PAVEMENTS IN EUROPE

Prof. R. Springenschmid
Munich/Vienna
Chairman: Technical Committee on Concrete Roads
P.I.A.R.C.

1. Present Practice in Europe

Concrete Pavements are constructed to a considerable amount in many European countries such as Austria, Belgium, Czechoslovakia, France, Germany, Great Britain, Spain and Switzerland. The percentage of concrete pavements on new motorways in these countries is somewhere between 20 and 80 %. For airport runways the percentage of concrete pavements amounts to the same in almost all European countries.

For many decades concrete pavements have been built with slabs between 7,5 m (25 ft) and 12 m (39 ft) long, usually reinforced with steel mats. Since the early sixties almost all countries have adopted a design with slabs, between 4,5 m (15 ft) and 6,0 m (20 ft) long, without reinforcement and without expansion joints. Slipformpavers are used for the majority of motorway and runway projects, except in Germany, Austria and Switzerland. Many countries such as Germany use dowels in transversal joints, others such as France do not.

Considerable research was done on prestressed pavements especially in France. For motorways prestressed pavements seem to be too complicated as a routine construction. On many runways with heavy wheel loads however pavements post-tensioned in longitudinal and transverse direction showed excellent behaviour during the past 10 or 20 years.

As early as 1946 continously reinforced pavements were already built on experimental sections in Belgium and 1949 in Germany. These pavements, using 0,85 % steel as longitudinal reinforcement were built in Belgium on many motorways during the past years. In Spain a larger section will be constructed in the near future. A pavement, using a new system with "controlled" formation of cracks, was applied on top of an old pre-war concrete highway in northern Germany. The distance of the transverse joints of 4,0 to 4,5 m (13 to 15 ft) allowed a concrete thickness of 16 cm instead of 22 cm ($6\frac{1}{4}$ "instead of $8\frac{1}{2}$") and a reduction in the percentage of steel to about 0,4 %.

2. Design Practice

Many European states have specifications for concrete pavements, which contain all important design features such as concrete quality, slab dimensions, joints and subbase requirements. Usually several alternatives are permitted for the construction of the subbase. In countries with a smaller number of paving jobs or less attitude to strict specifications more freedom and responsibility is given to the designing engineer and new findings are therefore often adopted earlier in these countries.

There is no common European specification or recommendation for concrete pavements (and it will take some years until a cement standard of the European Community will be finished). But it would be very difficult to set up such common recommendations since the climatic conditions and the traffic frequencies differ considerably in different parts of Europe.

Furthermore it is necessary to observe that the maximum permissible axle-load is specified in Belgium, France and Spain with 13 tons (28 600 lbs), and in many other European countries with 10 tons (22 000 lbs).

Design charts or fomulas where the required thickness of the concrete pavement is given as a function of the modulus of rupture of the concrete, the maximum axle-load and the modulus of subgrade reaction (similar to the wellknown charts of P. Fordyce and R. G. Packard) are not in general use in Europe. Usually the concrete thickness is specified as a function of the traffic frequency and of the importance of the road. Table 1 is taken from the German specification "TV-beton 72".

Class	Vehicles in 24 hours (ADT) 1)		Pavement Thickness
	commercial vehicles 2)	Total number of vehicles	cm (in)
V	... 10	... 500	16 ($6\frac{1}{4}$)
IV	10 ... 100	500 ... 2000	16 ($6\frac{1}{4}$)
III	100 ... 500	2000 ... 5000	18 (7)
II	500 ... 1000	5000 ... 10000	20 ($7\frac{7}{8}$)
I	1000 ...	10000 ...	22 ($8\frac{3}{4}$)

1) on two lanes in one or both directions
2) more than 5 tons load

Table 1: Thickness of concrete pavements according to TV-beton 72 (concrete road specification of 1972 of the German Federal Republic)

In areas with poor soil conditions a thick subbase construction is necessary in order to achieve the specified modulus of subgrade reaction.

It may be interesting to note, that the thickness of the concrete slabs of new Autobahn (motorway) pavements in Austria and Germany has been kept constant over the past 40 years. It is still 22 cm ($8\frac{3}{4}$").

3. Influence of Research

The present concrete pavement design is a result of

(a) practical experience
(b) measurements on test roads
(c) laboratory investigations and
(d) theoretical considerations and calculations.

The great amount of research work done in the past decade has shown, that theoretical work should always be confirmed by measurements in practice and that a wise combination of both can still improve our concrete pavement design.

The research work in various European countries is not coordinated - it is more a "free competition". The exchange of research results therefore plays an important role. Two Symposia on Concrete Roads 1969 in Paris and 1973 in Berne (Switzerland) have served this purpose. Furthermore, the meetings of the Technical Committee on Concrete Roads of the P.I.A.R.C., where experts of almost all European countries are represented, are a very valuable place for the exchange of information.

4. Theoretical Basis for Design Concepts

At the XVth World Road Congress in Mexico City in October 1975 the Technical Committee on Concrete Roads has presented a report on the "Theoretical Design of Pavements with Concrete Surfacings" /‾1_7. This report contains contributions by experts of seven different countries and was coordinated by J. Verstraeten. Most contributions show methods for the calculation of the different stresses in a concrete slab.

It is necessary to mention the work done in the Centre de Recherches Routières in Bruxelles, Belgium by J. Romain and coworkers. The finite element method is used in order to calculate the displacements of the slabs and the stresses in the stratified structure supporting the slab. Another promising work is going on at the Laboratorie Central des Ponts et Chaussees in Paris by M. Fremond and G. Rouques: a theoretical model was set up which made it possible to calculate - using the finite element method - the displacements, the restraint and the deformation of a slab including the influence of the surface of contact with the underlaying layer.

Both models take the finite geometry of the slab into account. With the French model the temperature distribution in the slabs is taken into consideration.

The work done at the French and Belgium road research institutes is still going on. The methods are up to now not used in other countries, where traditional procedures for the calculation of the stresses are still in use:

(a) Stresses due to Traffic Loads

The stresses due to traffic loads are mostly calculated using the Westergaard formulas for a wheel load at a corner, at the edge and at some distance from the edge of the slab. These formulas have been improved by Teller and Sutherland respectively Kelley. Fig. 1 shows that edge loading results in tensile stresses almost twice as high as interior loading. Corner loading causes the highest tensile stresses on the upper surface of the slab, Fig. 2. Stresses due to edge and corner loading can be reduced, if care is taken for an effective load transfer across the joints. As shown in Fig. 1 the slab thickness has a considerable influence on the stresses. The effects of changes of the modulus of subgrade reaction and of changes of the modulus of elasticity of the concrete are comparatively small.

Several attempts have been made to calculate the stresses in a multilayer system with e. g. a concrete surface and a soil cement subbase. Using the formulas by D. M. Burmister and L. Fox it can be shown, that a cement-bound subbase can reduce the stresses in the slab and in the subgrade.

Wheel loads usually pass road pavements with high speeds and act on a specific part of the slab for only a very short time of about 0,01 sec. The influence of this very short time of this dynamic loading is usually neglected, although it is known that for instance the modulus of elasticity is much higher for fast application of the load.

(b) Thermal Stresses

When discussing thermal stresses one has to distinguish between uniform longitudinal stresses over the cross-section of the concrete due to high or low temperatures and warping stresses due to temperature changes resulting in temperature gradients.

Longitudinal tensile stresses develop, when the concrete is cooled down and its contraction is prevented by the friction between concrete and subbase. Stresses are greatest in the center of the slab. They increase with longer slabs as used for prestressed pavements. Longitudinal compressive forces occur mainly in pavements placed at low temperatures during hot period .They can reach a considerable value and can overcome all tensile stresses.Warping stresses are the result of an uneven temperature distribution over the cross-section of the slab. If the top surface of a slab is warmer than the bottom surface the slab tends to become spherical. High bending stresses occur, if the center of a slab is removed from the supporting layer. These bending stresses are caused by the own weight of the slab and increase with the square of the length of the slab.

J. Eisenmann [3] has shown, that highest warping stresses develop, when the slab reaches a critical length l_{crit}. At this length the deflection due to the own weight is so large that the slab touches with its center again the underlaying layer, Fig. 3. For quadratical slabs the critical length is $l_{crit} = 37\ h$ (h = thickness). Using slab lengths of 25 h - as recommended in the conclusion of the XV World Road Congress - the warping stresses are reduced to about 40 %. They are however still so high e. g. 1,75 N/mm^2 (250 psi) for a 5 m (16,4 ft) long and 22 cm thick slab, that they have to be considered in all stress calculations.

The thermal gradient has been measured at several places in Europe. It is assumed that it reaches usually a value of less 0,4^{o}C/cm, the maximum value - during a short time of the year - 0,9^{o}C/cm (20^{o}C for a 22 cm slab). Negative gradients are usually assumed to ammount to only half of the magnitude of the positive ones. Recent measurements during a thunder shower after a very hot day however showed, that negative gradients can ammount to almost twice as much as the positive ones.

(c) Stresses due to Shrinkage

Stresses due to shrinkage have been studied by L. Pfeifer [4] on large models and are of similar kind but smaller magnitude as warping stresses. Following measurements by G. Weil it has to be assumed, that - under European climatic conditions - deformations due to drying of the concrete are negligible.

(d) Differences in the settlement

Differences in the settlement of the subgrade result in considerable stresses in the concrete and very often cause cracks. In order to keep such different settlements small a high compaction of the subsoil is usually specified. At bridge abutments the fill material is sometimes stabilized with cement in order to prevent larger settlements.

Subbase erosion along the joints occured on many older roads specially if the joints were undowelled and the traffic frequency was high during rainfalls. A similar effect has even been found with absolutely stable subbases: fine sand was transferred from unstable shoulders under the concrete slabs [5].

There is no doubt that high stresses result from all disturbances in the evenness of the layer under the slab. In many cases however faulty joints effect the riding quality more than transverse cracks due to stresses exceeding the concrete strength.

(e) Stress Accumulation

Thermal stresses last at least for several hours, whereas stresses due to high speed traffic occur with very high frequences but usually act for less than 0,02 sec. Little is known about the fatigue flexural strength of concrete. The Smith diagram is often used for the accumulation of repeated loads. The fatigue strength of concrete in flexure is usually assumed to be between 50 and 60 % of the modulus of rupture. Since thermal stresses have a low frequency it seems to be possible to assume the maximum permissible flexural stresses being between 60 and 70 % of the modulus of rupture. The influence of the dimensions of a flexural test beam and of the shrinkage stresses on the test results are often neglected.

5. Design Concepts

Theoretical calculations and their confirmation in laboratory or field investigations have influenced modern design concepts to a large extent. There are however additional factors such as the action of water penetration along the edges of a pavement, or the impact of fast moving wheel loads, or the dynamic behaviour of the concrete slabs, which are difficult to study in theory or in laboratory tests.

Therefore we are at present not able to base our new design solely on theory. We have however learned from theory how to reduce the stresses in the concrete and thus improve the lifetime of a road and to make more economic designs.

5.1 Slab Dimensions

High warping stresses can be prevented, if the slabs are more or less quadratic and the slab length is not more than 25 times the slab thickness. Since trucks usually drive rather close to the right edge of the traffic lane, at new pavements the right slab also includes the right side strip, thus preventing edge and corner loads. The slab width is usually 3,75 + 50 cm = 4,25 m (14 ft) for the right slab and 3,75 m (12 ft) for the other slabs, the length varies between 4,50 and 6 m (15 and 20 ft). The dimensions of slabs of airport runways having a concrete thickness between 30 cm (12") (Zürich) and 40 cm (16") (Paris Roissy) are usually 7,50 by 7,50 m (25 ft).

5.2 Load Transfer at Joints

Up to now, no better system for load transfer has been found than dowels. The disadvantage of dowels are the high costs and the required accuracy of placement. In the past years heavy dowel placing machines have been developed using powerful vibrators.

The efficiency of dowels is not very high. Only about 30 % of the vertical load is transfered across the joint. The subbase and - for small joint openings - the aggregate interlock also plays an important role. Some new motorways are going to be built without dowels. Faults at the transverse joints are prevented by a stable base construction and hard shoulders, which do not allow any fine material to penetrate underneath the concrete slab of the pavement.

Small joint openings can only be obtained, when the joints open regularly. It was found in Germany /6/ that joint openings are more uniform, if soil-cement subbases are used resulting in high friction values between subbase and slabs. Therefore soil-cement is now preferred as a subbase material. The joints are sawn somewhat deeper than before in order to secure early and regular cracking under the saw cut.

Short slabs reduce joint openings and therefore improve the load transfer. A further reduction of slab length to 2 or 3 m (7 or 10 ft) would increase the total costs. It is not known, whether dynamic loading or other effects can lower the lifetime of such a pavement.

Longitudinal joints are usually anchored with tie bars to prevent opening of the joints, which would occur when the pavement cools down after a hot period. If any hard material can penetrate into untied longitudinal joints the opening would increase every winter.

5.3 Subbases

Bonded subbases of usually 15 cm (6") thickness are placed under almost all heavy trafficked concrete pavements. The purpose of this subbase is to prevent any erosion and to take care that the "abutment" of the concrete slab does not make any excessive or different changes in its height. Bonded subbases have a considerable strength and load bearing capacity. It can be shown by theoretical calculations, that they would permit a small reduction of the slab thickness. There are also proposals /¯7_7 to increase the thickness of the cement-bonded base to 30 cm (12") and place on top of it a 14 cm (7") continously reinforced pavement. A good bond between pavement and subbase can reduce the bending stresses in the concrete slabs considerably.

5.4 Thickness of the Concrete Pavement

A number of sections of the prewar German Autobahn are still in use. These Autobahns did not have any subbase and were designed at a time when todays high traffic frequencies were unknown. The studded tire used between 1965 and 1975 have worn off the slabs to a thickness of 20 cm or less. If now a concrete pavement is built according to new standards, the same lifetime of about 40 years should be considered as a time with unpredictable influences to our road pavements. As a concrete pavement is difficult to strengthen when it is already laid, the thickness design should contain a "sound" amount of safety.

There are several factors we do not know well enough for exact computations of pavement thickness such as the reduction of flexural strength caused by small shrinkage cracks or the effect of hydration of the cement during long time on the fatigue modulus of rupture of concrete.

It has been shown by theoretical means, that the right lane - where usually almost all heavy trucks are driven-should be equipped with a thicker concrete slab then the left lanes. The French motorway is built with trapecoidal cross-sections having a thickness of 28 cm (9 ") at the right and 18 cm (7 ") at the left edge. We do believe, that the factor of safety - although it is not exactly known - will be the same for all this traffic lanes.

5.5 Safety Against "Blow-ups"

From May to mid-July 1976 the weather in Central-Europe has been extreemly hot and dry - highest recorded temperatures for the past 120 years. Long lasting high air temperatures caused extrem high longitudinal forces in the concrete pavements. As far as it is known until how (end of July 1976), several "blow-ups" occured in many European countries, but fortunately nobody was injured. Expansion joints, as they were used in older pavements, have been no suitable means to prevent high longitudinal stresses, because the transfer of longitudinal forces is often concentrated on small parts of the joints. On all modern pavements the "blow-ups" have been caused by faults during the construction (e. g. too thin slabs, no bond between upper and lower layer of the concrete) /¯8_7.

6. New Developments

In the past years many new proposals have been made for the improvement of the design or the construction of concrete pavements.

Many of them have been studied on test sections or are already in general use in one or two countries. In this connection reference should be made to

unsealed joints,

the texturing of road surfaces with chippings or exposure of aggregate by washing methods,

thermal insulating layers as subbase courses,

the use of super liquidizer for the concrete and

the use of thick soil-cement subbases and thin concrete pavements.

For the introduction of several of these proposals the risk has been lowered considerably, because stresses due to wheel loads and temperature were calculated according to our present theories.

7. Examples of Some Structures [1]

7.1 GREAT BRITAIN (maximum weight per axle – 10 t)

TRAFFIC	VERY HEAVY	HEAVY	AVERAGE	LIGHT	VERY LIGHT
NUMBER OF STANDARD AXLES (in millions)	40	20	10	2	0 4
POOR SOIL CBR ≤ 2%	28cm / 15cm	26cm / 15cm	24cm / 15cm	20·5cm / 15cm	18·5cm / 15cm
NORMAL SOIL 2%≤CBR≤15%	25·5cm / 8cm	23·5cm / 8cm	21·5cm / 8cm	18cm / 8cm	16cm / 8cm
GOOD SOIL CBR≤15% (foundation)	23cm	21cm	19cm	15·5cm	13·5cm

a) The first course – cement concrete reinforced or not reinforced; in the case of reinforced concrete the thicknesses of the slabs corresponding to a very light traffic are reduced by 1cm.

b) If the soil is frost susceptible, the total thickness of the pavement is 45cm in the case of very heavy traffic.

7.2. GERMAN FEDERAL REPUBLIC (maximum weight per axle: 10t)

TRAFFIC	VERY HEAVY	HEAVY	AVERAGE	LIGHT AND VERY LIGHT
Concrete / Tar stabilised course / Materials non frost susceptible	22cm / 15cm	20cm / 15cm	16cm / 15cm	15cm / 15cm
Concrete / Bituminous course / Materials non frost susceptible	22cm / 10cm	20cm / 10cm	18cm / 8cm	16cm / 8cm
Concrete / Cement stabilised course / Materials non frost susceptible	22cm / 15cm	20cm / 15cm	16cm / 15cm	14cm / 15cm
Concrete / Materials non frost susceptible			18cm	16cm

7.3 FRANCE (maximum weight per axle: 13t)

Concrete (BC). Sand-gravel-cement (GC). Untreated sand-gravel (GNT)

TRAFFIC / SOIL	T_1	T_2	T_3	T_4
S_1 S_2	27cm BC 15cm GC	25cm BC 15cm GC	22cm BC 15cm GC	20cm BC 15cm GC
S_3 S_4	25cm BC 15cm GC	23cm BC 15cm GC	20cm BC 15cm GNT (1)	18cm BC 10cm GNT (1)

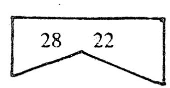
REMARKS ON THE CROSS-SECTIONAL PROFILE

For dual carriageway roads it is recommended that the thickness of the concrete slab should be varied linearly:

--from 28cm, at the extremity of the slab on the heavy traffic lane side, to 22cm, at the other extremity in the case of T_1 S_3 S_4;
--from 26cm to 20cm in the case of T_1 S_3 S_4;
--from 26cm to 22cm in the case of T_2 S_1 S_2;
--from 24cm to 20cm in the case of T_2 S_3 S_4;
--from 23cm to 20cm in the case of T_3 S_1 S_2;
--from 21cm to 18cm in the case of T_3 S_3 S_4.

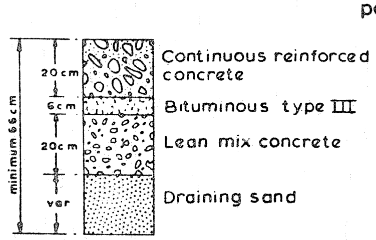
This arrangement allows the thickness of the concrete under the different traffic lanes to be differentiated and therefore a greater thickness to be provided under the heavy traffic lane.

It can advantageously be extended for use in certain cases to non-separated carriageways, the section conforming to the diagram shown here (cases T_1 S_1 S_2).



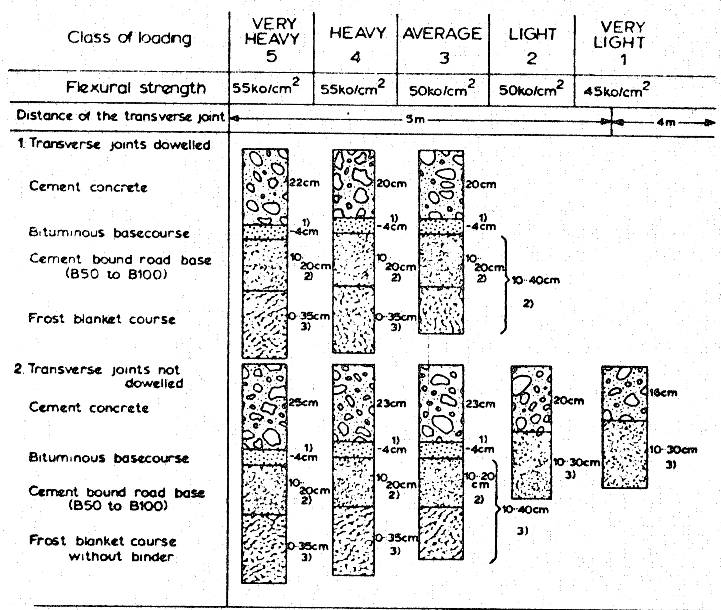
Extract from the catalogue of structures: Pavement Cross-Sectional profile, LCPC 1973.

7.4 BELGIUM (standardisation of motorways maximum weight per axle 13 t)



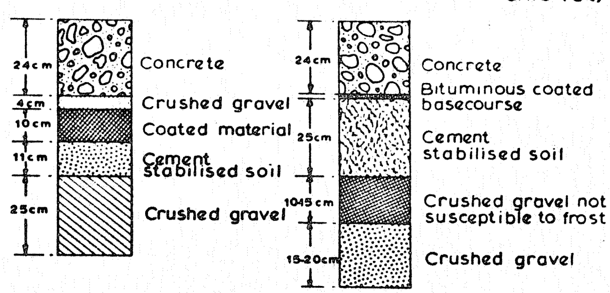
Extract from the BRA 725 Ministry of Public Works Road Administration

7.5 GERMAN DEMOCRATIC REPUBLIC (maximum axle load; 10t)



1) sometimes omitted
2) depending on the working site traffic when laying the surfacing
3) depending on the class of soil and the hydrologic conditions
4) can be replaced by a road base without binder the constructions conform to

7.6 CZECHOSLOVAKIA (motorways maximum weight per axle 10t)



Extract from Roads in Czechoslovakia published on the occasion of the XIVth World Road Congress of PIARC Prague 1971.

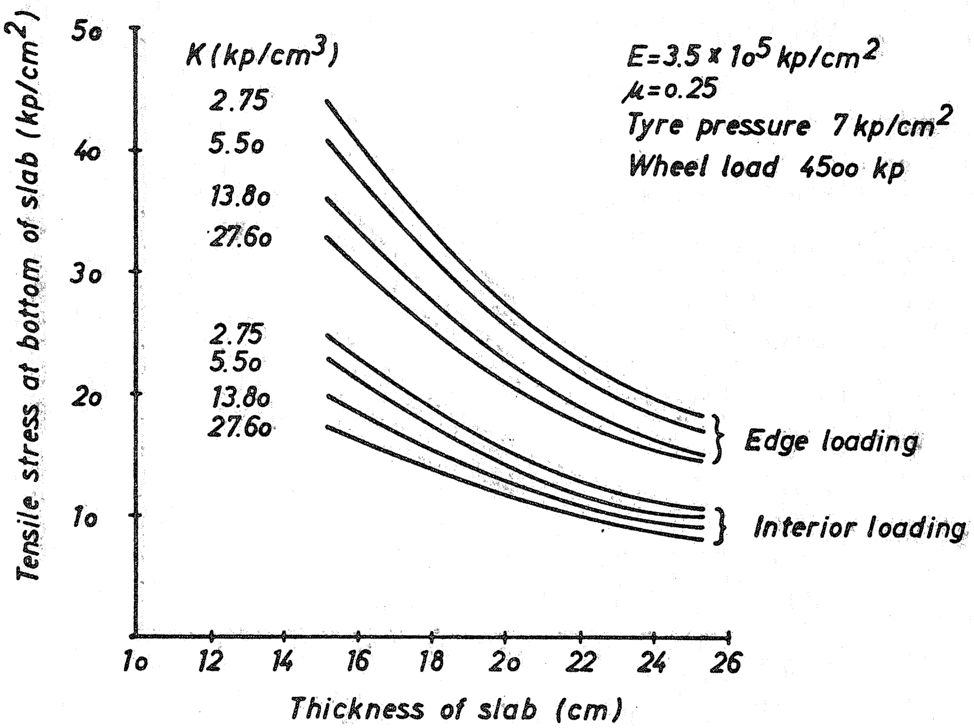


Figure 1: Tensile stresses due to interior and edge loading (modified Westergaard formular) /‾2_7

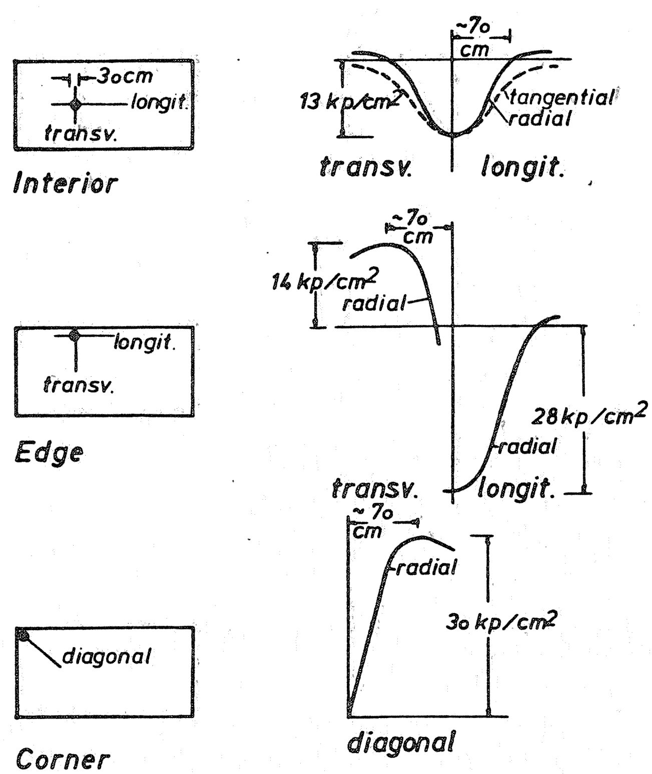


Figure 2: Bending stresses for interior-, edge- and corner loading (slab thickness: 18 cm, load: 5 t, contact pressure 7 kp/cm^2 (100 psi), K = 24 kp/cm^3 ~867 (lb/in^2/in) /‾3_7

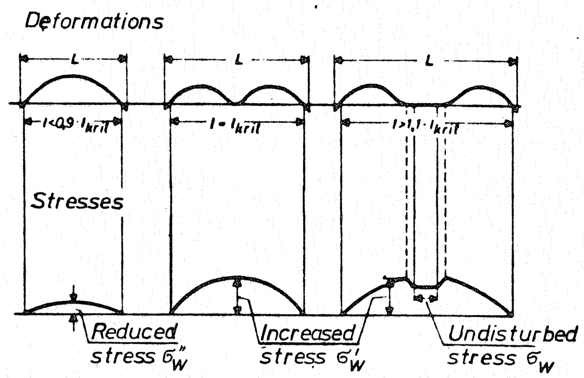


Figure 3: Deformations and stresses due to temperature increase at the top surface of a concrete pavement /‾3_7

8. References

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