

Experiences and New Developments in Concrete Road Construction in the Federal Republic of Germany

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1. Introduction

In the Federal Republic of Germany concrete pavements are mainly used on highways with very heavy traffic, for airports and for industrial floors. The traffic load is characterized by a maximum permissible axle-load of 11 Mp and highway sections with up to about 8.000 trucks of more than 2.8 Mp total weight per lane per day. In addition, the climatic conditions are severe with frequent rain fall, air temperatures between +32 °C in the summer and -25 °C in the winter, frequent frost-thaw-cycles and large quantities of anti-freeze salt used on the roads. There is no general speed limit, speeds of more than 200 km/h are frequently found.

In order to withstand such loads for the planned service life of about 30 years a solid and therefore quite expensive concrete pavement construction is necessary. The most important requirements to be met are

- an adequate thickness of the slabs
- a continuous load transfer at the joints
- an adequate protection of the structure against surface and ground water
- a road base with a sufficiently high and evenly distributed load-carrying capacity.

2. Concrete Pavement Structure

2.1 Structural design

In the Federal Republic of Germany concrete pavements consist of short slabs (length $\leq 25 \times$ thickness) with transverse and longitudinal joints /1/. Expansion joints are only made next to bridges. The transverse joints are dowelled by up to 15 plastic-coated steel dowels (diameter 25 mm, length 500 mm) per lane. Studies on test sections have shown that depending on the traffic load steps will form at undowelled joints within three years whereas at dowelled joints no steps developed even after a period of more than ten years under heavy traffic.

All longitudinal joints are fastened by three tie bars per slab in order to prevent the joints from opening and the penetration of surface water. On highways with more than 2 lanes trucks are often crossing the longitudinal joint between the main traffic lane and the first overtaking lane. Therefore, this longitudinal joint should be both anchored and dowelled for load transmission. Transverse joints are usually sawn, longitudinal joints are worked directly into the fresh concrete thus avoiding wild cracks (see section 3.1). The joints are filled with a bituminous joint sealing compound. The longitudinal joints worked into the fresh concrete produce an efficient load transfer. Nowadays concrete pavements are paved in a total width of 15 m including the shoulders.

DESIGN CLASS	SV	I	II	III	IV	V	VI
VEHICLES ¹⁾	>3200	>1800	900-1800	300-900	60-300	10-60	<10
CONCRETE SLAB	26 cm	24	22	22	20	18	16
HBB ²⁾	15 cm	15	15	15	15		
FROST- ³⁾ PROTECTION LAYER							

- 1) TOTAL WEIGHT 2.8 Mp
 2) ALTERNATIVE: 15 CM SOIL-CEMENT (GRAVEL)
 20 CM SOIL-CEMENT (SAND)
 10 CM ASPHALT BASE
 3) TOTAL THICKNESS FOR FROST PROTECTION 50-80 CM

fig. 1: Standard pavement structure

DESIGN CLASS	SV	I	II	III	IV	V	VI
VEHICLES	>3200	>1800	900-1800	300-900	60-300	10-60	<10
CONCRETE SLAB	26	24	22	22	20	18	16
HBB	25	25	23	20	20	15	15
CONCRETE PAVEMENT WITHOUT FROST-PROTECTION LAYER							

- 1) TOTAL WEIGHT 2.8 Mp

fig. 2: Full-depth structure

Figures 1 and 2 show the pavement structures with and without a frost protection layer. Concrete pavements for medium to very heavy truck traffic (class IV to SV in fig. 1) are always built on a bound road base in order to obtain a base with a sufficiently high, durable and evenly distributed load-carrying capacity.

Normally, a 15 to 25 cm thick hydraulically bound base (HBB) with properties as listed in table 1 has been used so far. The objective is to produce a long-lasting and stable bond between the hydraulically bound base and the concrete pavement, because with bond

- the initial restraining stresses rise and the sawn joints will open evenly. The joint width will remain relatively small even in the winter, and the joint sides contribute to the transfer of traffic induced shear stresses. Moreover, the joints can be sealed more effectively
- the traffic-induced bending tensile stress in the concrete slabs will be markedly reduced because it is partly transferred to the underlying HBB. This prolongs the life of the pavement, see fig. 3 /2/
- surface water cannot penetrate between the pavement and the base. Pumping

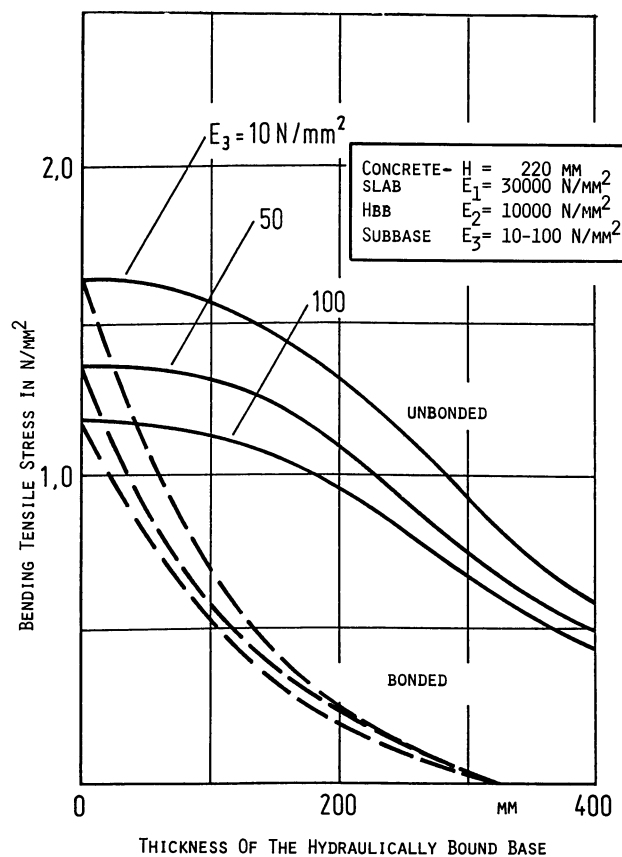


fig. 3: Bending tensile stresses at the underside of concrete slabs with and without bond to the HBB /2/

effects leading to a gradual erosion of the road base surface and the resulting deterioration of the support conditions of the concrete slabs will be avoided, and

- concrete slab displacements due to joint failure at high temperatures, the so-called "blow-up", do not occur.

2.2 Dimensioning

In the Federal Republic of Germany concrete pavements are not dimensioned on a case-to-case basis. According to the German Catalogue of Standardized Pavements /3/ the thickness depends on the expected number of trucks with a total weight of more than 2.8 Mp per lane per day, see figures 1 and 2. The thickness varies from 26 cm for very heavy traffic (3200 trucks per day and more) to 16 cm for very light traffic (10 trucks per day). In addition to the traffic induced stresses the stresses induced by temperature gradients are considered in the centre of the slab. To minimize these stresses, the slab length is reduced to less than 25 x the slab thickness (maximum length of rectangular slabs, e.g. at airports, 30 x the slab thickness but not more than 7.5 m). Relevant for the slab design are the load conditions in the slab center (where they are the most severe) not at the dowelled joints. Even the loading of the slab-edges is not critical, because the first dowel is placed only 12,5 cm from the longitudinal joints and the total slab-width of 4,25 m secures that the trucks normally drive in some distance from the edges. Quantitative studies of moisture-induced stresses have been started. They require more detailed knowledge of the behaviour of concrete under repeated shrinking and swelling.

The thicknesses of concrete pavements given in the Catalogue of Standardized Pavements base on theoretical calculations by Eisenmann /4/ and on decades of experiences. Eisenmann's theory use Westergaard's formulas and Odemark's theory of equivalence /15,16/. Westergaard's formulas are based on the assumption of a swimming slab supported by a dense liquid. The corresponding sub-base reaction is described by the k-modulus. The k-value normally is determined by a loading plate test. On the other side it is possible to calculate the k-value, if the stiffness of the concrete slab and the deformation behaviour of the subbase are known. The formulas are given in table 2 /4/. To use Westergaard's formulas for systems with more than two layers it is necessary to transform the multi layer system in a two layer system of an equivalent bending stiffness. This can be done by Eisenmann's method /5/ which is simple but in a good agreement with the exact multi layer theory if the

range of application will be considered.

In table 2 there is made a distinction between a system with complete friction (bond) and without friction between the concrete slab and the HBB.

System I without friction has the same bearing behaviour as two loosely layered boards. Both layers take part in bearing corresponding to their bending stiffness. This allows the transformation of the three layer system into an equivalent two layer system with the same bending stiffness. In a further step the bending moment (M_I) has to be splitted corresponding to the bending stiffness of the concrete slab and the hydraulically bound base whereby the calculation of the bending stresses of the several layers will be possible.

For system II with complete friction between concrete slab and HBB the calculation of the equivalent two layer system is based on the assumption of uniform deflection. The determination of the equivalent thickness h_{II} is done by Odemark's method /4,5,16/. To calculate h_{II} the ratio of the modulus of elasticity E_2/E_1 is used. The bending moment (M_{II}) of the equivalent system is then calculated with Westergaard's formulas like for system I. To determine the bending stresses of the system the model of a T-beam is used. The real geometry of the cross section requires a transformation of the tensile stresses of the second layer with the factor α .

For the load position "interior" (slab centre) there is distinguished between a system without a crack (column 1 and 6) in the two bound layers and a system with a crack in the concrete slab caused by a joint (column 2 and 5) respectively with a crack in the HBB (column 3 and 4). The effect of the crack on the reduction of the bearing capacity will be determined by a reduction factor. This factor $1/3,46 = 0,29$ corresponds with the increase of the deflection of the free edge of the slab compared with the load position "interior". Otherwise the crack effectiveness caused by aggregate interlock is considered by the factor $(100 + W)/100$. For the system with bond between concrete slab and HBB a wide crack in the HBB ($W = 0$) is critical (column 4 in table 2).

The slab design shown in figures 1 and 2 consider the fact that in 1986 the maximum axle load was raised from 10 to 11 Mp and the maximum total weight of trucks from 38 to 40 Mp in connection with the harmonization trends in Europe. In order to compensate for this increase, concrete pavements today are built 2 cm thicker than in the past in all design classes according to calculations by Eisenmann et

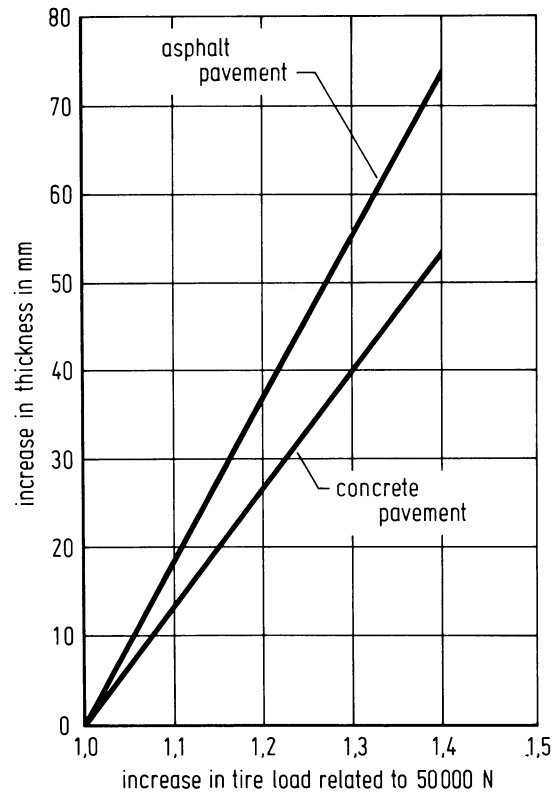


fig. 4: Increase of slab thickness required by an increase of tire-load

al. /6/, see fig. 4. At the same time, in some design classes practical experience was taken into account showing that concrete pavements with medium to heavy traffic and a thickness of only 20 cm on a HBB showed severe traffic induced cracks only after about 7 to 10 years although in theory they had been designed adequately. This can be explained by the fact that in such pavements an insufficient thickness due to thickness variations in the concrete placing process may much more affect the service life of the pavement than it does with thicker slabs. Long-time tests on concrete pavements in the United Kingdom have shown that a thickness only 1 cm, i.e. 5 %, below design thickness will lead to a 10 % reduction in the service life and a thickness 2 cm (10 %) short of design thickness will lead to a reduction in service life of as much as 40 %. Therefore, the current minimum thickness of pavements for medium traffic is 22 cm today. The new design thicknesses of concrete pavements shown in figures 1 and 2 contain an adequate safety margin of about 1 cm.

3. Experiences with concrete pavements bonded to hydraulically bound-base courses

3.1 Crack formation

In the past concrete pavements with two lanes were mostly made by form-riding

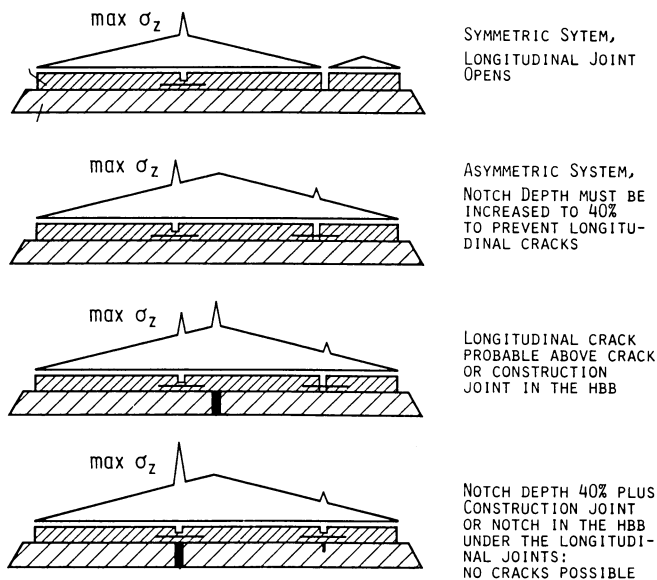


fig. 5: Probability of longitudinal cracks in bonded concrete structures

pavers whereby the shoulder - not tied to the traffic lane - was paved first, and then the two traffic lanes were placed in a separate operation. Therefore, the transverse tensile and warping stresses in the young concrete due to hydration heat, shrinkage and changes in air temperature always had their maximum at the only tied longitudinal joint between the two traffic lanes. That means, the longitudinal "cracks" formed, as desired, in this joint (see fig. 5). Since some years the shoulder is also tied to the two traffic lanes, and the concrete pavement is paved in one operation in its full width of about 15 m by means of slipform pavers. With this procedure an increasing number of longitudinal cracks in the centre of the system, i.e. about 1 to 1.5 m from the central longitudinal joint, was found. These cracks were caused by the fact that the transverse tensile stresses increased as a result of the greater width of the concrete pavement and that the maximum of all temperature and shrinkage induced transverse stresses no longer occurred in the central longitudinal joint [7,8]. As a result, the longitudinal joints with a depth of about 30 to 35 % of the slab thickness did not open but, instead, the severe longitudinal cracks formed. Moreover, in some cases in which the HBB was built with a higher content of hydraulic binder in order to improve its erosion resistance, gaping transverse cracks formed in the base course, and on top of it reflection cracks developed in the fresh concrete. As a result of practical experience and theoretical calculations [9], the hydraulically bound base nowadays is always "notched" immediately after placing. This

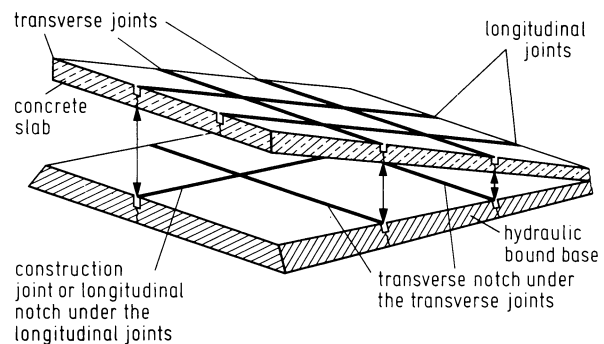


fig. 6: Notches in the HBB to prevent reflection cracking

means that joints are worked into the fresh HBB e.g. using a small vibrating plate with an edge welded to the underside. The depth of the notches is about 30 % of the base thickness and, as fig. 6 shows, they are placed underneath the joints of the concrete pavement which is built in subsequently. By this low-cost and technically simple method wild cracks can be effectively avoided without giving up the advantages of the bond between the concrete slabs and the basecourse.

3.2 Disintegration of the bond and erosion of the base course

In some cases the initial bond between the HBB and the concrete pavement disintegrated or had not existed from the very beginning. Water was able to penetrate between the concrete and the base, and under the impact of traffic this led to an increasing erosion of the base (pumping effects caused by high water pressures), especially near the transverse joints. As a result the traffic induced deformations and bending stresses increased in the joint area followed by the formation and propagation of cracks sometimes after a period of only about 7 to 8 years.

In order to prevent early failure, the following measures have been taken to improve the bond and the erosion resistance of the HBB:

3.2.1 The strength of the bond depends primarily on the strength of the surface of the hydraulically bound base. Studies made by the Research Institute of the German Cement Industry have shown that an adequate surface strength requires a sufficiently high quantity of hydraulic binder in the base and that it can be markedly improved by intensive curing. Fig. 7 shows the bond strength of HBB cured in different ways. The strength was determined by direct shearing tests on 200x200x100 mm slabs. The hydraulically bound base made of well graded gravel-sand 0/32 mm with 3 wt.% of Portland ce-

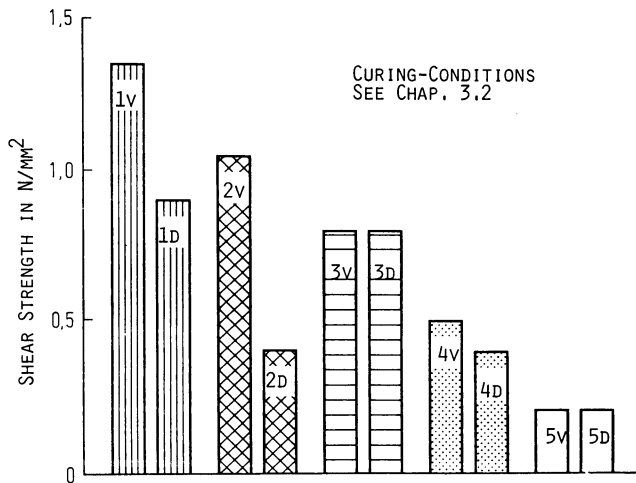


fig. 7: Shear resistance of differently cured HBB surfaces

ment 35 F was either kept moist for three days under wet cloths (1), could dry in laboratory air (2) or was sprayed with a wax based (3) or a thin (< 0.5 mm) (4) or thick (≥ 0.5 mm) (5) bituminous curing agent. After three days the base course specimens were stored either in an air-conditioned room at 20°C and 65 % r.h. (1 D to 5 D in fig. 7) or in a vapour chamber with a humidity of 100 % (1 V to 5 V in fig. 7). At an age of two weeks the concrete ($200 \times 200 \times 100$ mm as well) was placed on the HBB specimens. After another two weeks the shearing test was made. Fig. 7 shows clearly that the hydraulically bound base that had been cured and stored in a permanently moist atmosphere (1 V) developed the highest shear strength of about $\tau_s = 1.35 \text{ N/mm}^2$. In those specimens the fracture occurred in the hydraulically bound base course. The specimens with "poor curing" (2 D) had a shear strength of only $\tau_s = 0.4 \text{ N/mm}^2$. Subsequent moist storage in the vapour chamber, however, led to a substantial "recovery" of the initially inadequate hydration and thus to an increase in shear strength up to $\tau_s = 1.05 \text{ N/mm}^2$ (specimen 2 V).

As expected, the shear strength of the hydraulically bound base treated with curing agents (3 D, V to 5 D, V) was lower than the values obtained for specimens cured in a wet atmosphere. The curing agents, depending on the thickness of their application, had a bond-separating effect. Curing with a bituminous emulsion of ≥ 0.5 mm thickness (5 D, V) led to a ductile fracture in the bitumen if the deformation rate was about $0.05 \text{ N/mm}^2/\text{s}$.

For hydraulically bound base courses underneath concrete pavements a curing procedure using vapoured water for mini-

mum 3 days will be required. Underneath asphalt pavements a bituminous curing may be useful. To what extent hydraulically bound base courses underneath concrete pavements could also be cured by using viscous bituminous emulsions and whether such a treatment could produce an elastoplastic bond with a favourable effect on the behaviour of the total system will be investigated. This type of bond could help to eliminate the slowly rising restraining stresses between concrete and base by plastic deformation, whereas under short-time traffic loads a predominantly elastic bond would be maintained. This elastic bond will assure that, as desired, the traffic-induced stresses in the concrete will be reduced.

3.2.2 Moreover, for a better surface strength of the HBB a minimum binder content was introduced which - as research in the Research Institute of German Cement Works showed - depends on the type of mineral material used, its gradation and its maximum grain size. It amounts to about 3 % for well-graded gravel-sand 0/32 mm and about 10 wt.% for open graded sand, see fig. 8. The detailed studies had shown previously that the minimum compressive strength values as a measure for the sufficient binder content listed in table 1 could in some cases be reached with very low quantities of binder of only about 2 to 2.5 wt.%. However, such small quantities of only about 60 kg/m^3 could not be mixed evenly into the mineral material and were not sufficient to bind all inert components durably /10/. In such cases the strength, frost and erosion resistance of the HBB surface (and sometimes of the whole of the hydraulically bound base) were inadequate. Today there is a steady trend to still use higher binder quantities. This might even lead to the use of lean concrete, e.g.

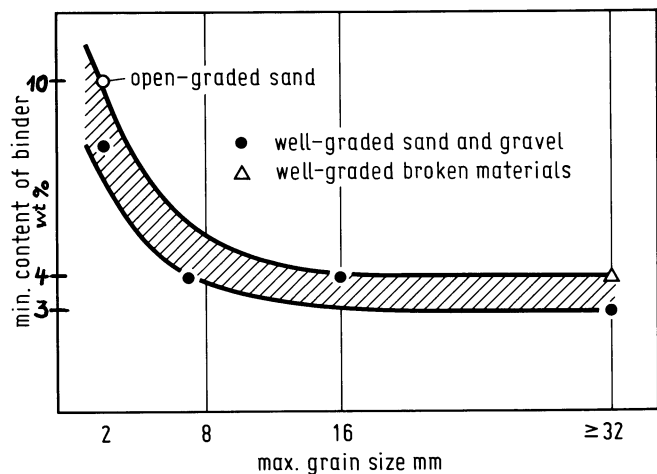


fig. 8: Minimum content of binder for sufficient durability of the HBB

roller compacted concrete, for base courses underneath concrete pavements in the future.

3.2.3 Erosion of the base course will not occur if the surface water is kept from infiltrating to the interface between the concrete pavement and the HBB, e.g. by installing a waterpermeable base course or by drainage measures. As a rule drain pipes will be placed on the outside and, if necessary, in the center line of roads. In order to prevent the water from penetrating from the higher level of the cross-section into the structure the hydraulically bound base is built with a counter balancing slope of 4 % in this area, see fig. 9. In this way, the water is always led to the nearest drain pipe. By way of experiment so-called flat drains, i.e. special plastic profiles with about 0.5 to 1 cm naps and wrapped in geotextile, were placed underneath the transverse joints in order to drain the water that has penetrated into the joint directly to the outside. So far these tests have not been very successful, because many of the drains were compressed by the construction traffic or by the concrete paver. They were also often found to be obstructed by fine particles and therefore ineffective. The tests are continued with new profiles.

3.2.4 The most effective measure against water penetration into the structure still is a dense sealing of the joints. Tests on several highways [11] have shown that, although the effectiveness of a bituminous joint sealing begins to decrease after about three years, the quantity of water penetrating into the joints even then amounts to not more than about 1/10 of the quantity measured in an unsealed joint even if its width is only 3 mm. At present new more durable and therefore more economical joint sealing methods are being tested, such as placing prestressed

elastomere joint profiles or using highly adhesive and extensible plastic materials. Nevertheless, careful maintenance of the joints is required. According to our experience, the joint filling should be replaced every 5 to 6 years in view of the prevailing weather and traffic conditions. This relatively modest expenditure can contribute to substantially extending the life of the concrete pavement and to save expensive repair measures due to water penetration into the road structure.

4. Alternative Designs

In unnotched hydraulically bound base-courses gaping cracks occurred at intervals of about 10 m in some cases. In order to avoid reflection cracks in the young concrete placed on the HBB a thin (about 3 to 5 cm) intermediate asphalt layer was installed. In the past bituminous-bound sands were often used for this purpose. However, their stability and erosion resistance were so poor that these highway sections must now be completely renewed after a period of only about 15 years. The bitumen-sand was virtually washed out. Greater durability is expected from stable intermediate layers made of asphalt with polymere-modified bitumen. Such intermediate layers, however, are extremely expensive and should therefore be used in special cases only.

By way of experiment, a water permeable geotextile with a thickness of about 5 mm was incorporated between the hydraulically bound base course and the concrete pavement. This was done with the following objectives in mind:

- Improving the drainage of the interface between HBB and concrete slabs in order to prevent erosion.
- Producing an evenly "soft" underlay for the concrete slabs even if they are vaulted due to temperature and moisture gradients and avoiding unfavourable knife-edge bearing of the slabs.
- Avoiding reflection cracks in structures with unnotched basecourses by separating the bond.

After some five years of experience with such designs no damage has as yet been observed. However, as a result of the "softer" underlay and due to the lower k -value the concrete pavement must be about 1 to 2 cm thicker than without the geotextile to keep the stress level constant. Moreover, it was found that considerable quantities of water remain in the geotextile. This means a permanent water supply over the whole of the area between the concrete slabs and the HBB. As laboratory measurements have shown [12], the concrete pavement may, as a result, suffer additional stresses and deformations due to greater moisture gradients, especially if concrete aggregates susceptible to swelling are used. How

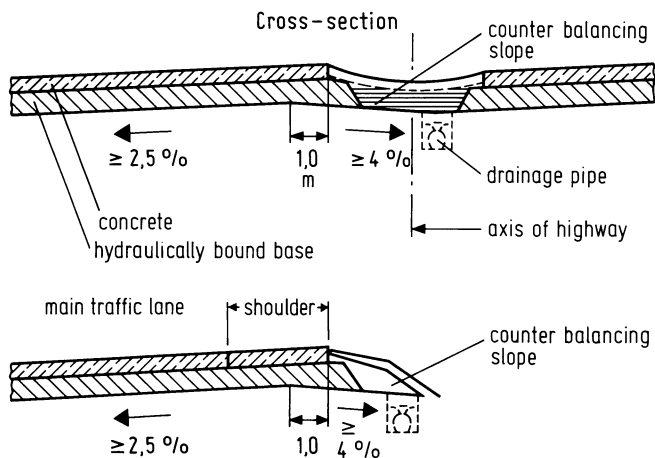


fig. 9: Cross-section of a highway structure

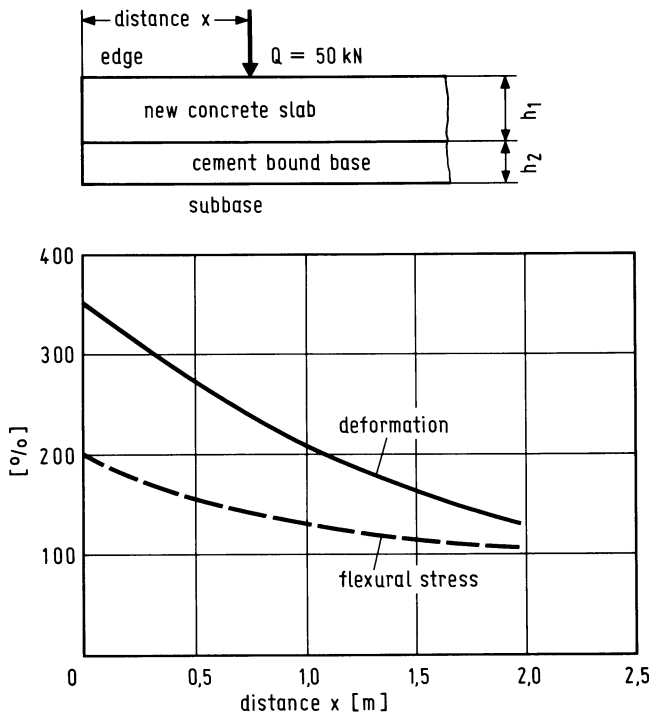


fig. 10: Deformation and bending tensile stresses of a concrete slab added to an existing pavement /13/

much this - as all other fatigue-inducing factors - may shorten the life of the concrete pavement can only be determined by long-term tests.

5. Addition of traffic lanes

Due to the increasing traffic volume, additional lanes are added to existing concrete or asphalt roads. Usually these are a main traffic lane predominantly used by heavy trucks and a new shoulder, see fig. 10. A durable system requires that the load assumption for the thickness design be based on the load conditions at the free edge of the slabs because the left wheel track of the trucks comes closer to the edge than it does on usual driving lanes and because the longitudinal connecting joint cannot be anchored or dowelled when new lanes are added to old

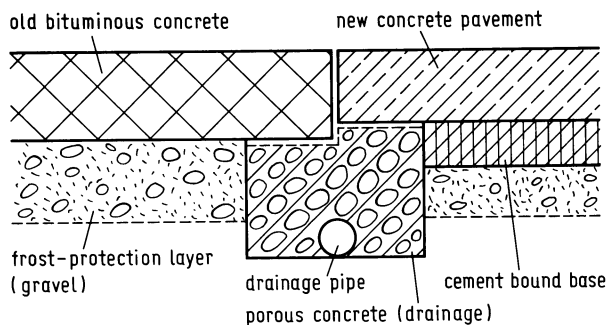


fig. 11: Drainage installations between old and new pavement

asphalt roads, see fig. 10 /13/. This means that the concrete pavement must be built about 2 cm thicker over the full width of the lane than in new pavements, e.g. 28 cm in the heavy traffic class SV, see section 2. Furthermore between the old and the new lanes longitudinal drains, as depicted in fig. 11, be installed at least in cases in which the joint cannot be tied with tie bars. Moreover, when tie bars are used they may easily be shorn off if the added pavement structure rests on an embankment which has not yet settled.

6. Surface characteristics

So far the surface of the fresh concrete pavement has been textured in transverse direction by means of a broom with wire bristles. This texture with a roughness depth of up to 1.5 mm provided an extremely good skid resistance for many years as long as the fine mortar remained on the surface. In addition, crushed stone sand has a favourable effect on the micro-roughness. However, on a rough surface the tires generate more noise than they do on a smooth surface at identical speed. Moreover, a regular and especially a transverse surface profile leads to an unpleasantly high frequency of sound. This was the reason why concrete pavements were increasingly rejected by the population in the densely populated Federal Republic of Germany. The noise reduction efforts led to a new approach to optimizing the concrete pavement surface: It must offer adequate friction and, at the same time, be as quiet as possible. A surface with a roughness depth of less than approx. 1 mm and an irregular structure of the texture meets this requirement. Fig. 12 shows the results of friction and noise measurements on experimental road sections of different textures /14/. A coarse burlap dragged behind the paver provides a still adequate friction and - compared with the steel broom - the least noisy surface with an acceptable deep frequency of sound. The use of a paver with a smoother also has a favourable effect. If these results are confirmed in further tests it can be expected that the wire broom will not be used anymore in the future.

A further reduction in the noise level by partial absorption of the sound generated be obtained by using a porous concrete with more than 15 vol.% of open pores. It is important that the surface texture of this type of concrete pavement must not be rougher initially than an optimized "traditional" surface - e.g. textured with a burlap - because otherwise more noise would be generated and thus the porous structure would not be effective enough to reduce the total noise. Tests leading to the development of a so-called

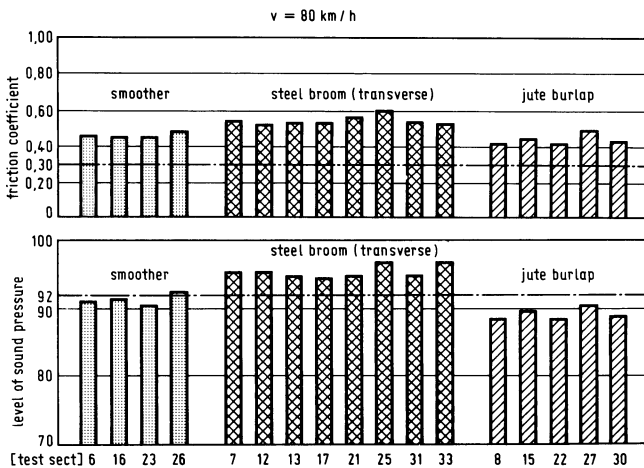


fig. 12: Noise and friction properties of differently textured surfaces (sound pressure in dB(A)) /14/

"whispering concrete" even for highly trafficked roads will be continued on a larger scale and at a European level.

7. Future developments

Due to the higher axle loads rutting in asphalt pavements has increased and thus repair and maintenance costs have risen. In order to avoid both, tests are made with new road constructions consisting of an approx. 25 cm thick base course made of high-quality roller compacted concrete (RCC) and a quite thin asphalt overlay. The asphalt overlay is necessary as the surface of RCC normally is not even enough for high speed traffic and because laboratory tests have shown, that the RCC may not be sufficiently resistant against the large quantities of anti-freeze salt used in most parts of Germany. In this context the following questions still have to be answered:

- How do cracks form in the roller compacted concrete, can the crack formation be adequately controlled by notching the fresh RCC and how do cracks affect the durability of the total structure?
- How can an adequate adhesion be achieved between the asphalt overlay and the roller compacted concrete?
- How can the construction process be optimized so that the placing of the RCC in one single layer up to a thickness of about 25 to 30 cm would be possible, e.g. by using asphalt pavers with high-energy compaction beams and special rollers?

These questions are being studied at present on test road sections. First results are expected for the beginning of 1989.

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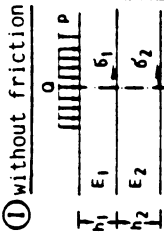
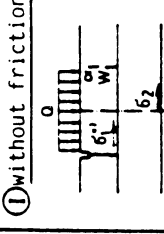
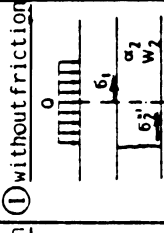
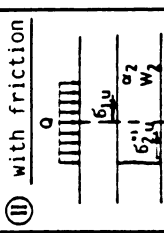
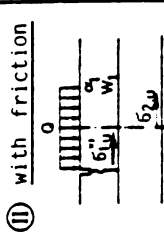
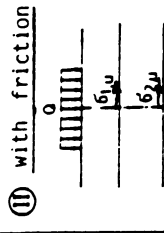
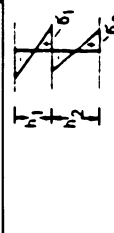
type of base	mineral materials		hydraulic binder		28 days ²⁾ compression strength N/mm ² specimen mm	mixing and placing
	type grain size	content of fines wt %	type	amount wt %		
hydraulically bound base (HBB)	well-graded gravel or broken stone 0/32 mm	≤ 15 ¹⁾	cement, hydraulic lime, road base binder	3 - 5	9 - 12 cylinder 150/125	mixer, asphalt, paver
soil-cement	sand-gravel < 63 mm	≤ 15 ¹⁾		3 - 10	6 ³⁾ cylinder 100/120 or 150/125	mixed-in place

1) ≥ 5 wt %: frost-heave test

2) measure for the adequate binder content

3) 9-12 N/mm² in future

Table 1: Roadbases with hydraulic binders for concrete pavements

column number	1	2	3	4	5	6
range of application $\alpha_1 E_1 \gg E_2 \gg E_3$ resp. $E_1 \approx \alpha_2 E_2 \gg E_3$ resp. $h_2 \approx 1.5 \cdot h_1$	① without friction 	① without friction 	① without friction 	① with friction 	① with friction 	① with friction 
load position for calculation of moment	- interior edge in case of a wide crack	- interior 1st layer *) parallel to the crack	- interior 2nd layer *) parallel to the crack	- interior 2nd layer crack	- interior 1st layer *) parallel to the crack	- interior edge in case of a wide crack
modulus of subgrade reaction $k = E_3/h^*$	$h^* = 0.83 h_1 \sqrt{\frac{E_1}{E_3} \cdot c \cdot h_2} \sqrt{\frac{E_2}{E_3}}$	$h^* = 0.83 h_1 \sqrt{\frac{E_1}{E_3} \cdot c \cdot h_2} \sqrt{\frac{E_2}{E_3}}$	$h^* = 0.83 h_1 \sqrt{\frac{E_1}{E_3} \cdot c \cdot h_2} \sqrt{\frac{E_2}{E_3}}$	$h^* = 0.83 h_1 \sqrt{\frac{E_1}{E_3} \cdot c \cdot h_2} \sqrt{\frac{E_2}{E_3}}$	$h^* = 0.83 h_1 \sqrt{\frac{E_1}{E_3} \cdot c \cdot h_2} \sqrt{\frac{E_2}{E_3}}$	$h^* = 0.83 h_1 \sqrt{\frac{E_1}{E_3} \cdot c \cdot h_2} \sqrt{\frac{E_2}{E_3}}$
E-modulus of the equivalent system	E_1	$\alpha \cdot E_1$	E_1	E_1	$\alpha \cdot E_1$	E_1
thickness of the equivalent system	$h_1 = \sqrt[3]{\frac{E_1 \cdot h_1^3 \cdot E_2 \cdot h_2^3}{E_1}}$ relevant load for load position edge = $Q \cdot [1 - W/200]$	$h_1 = \sqrt[3]{\frac{\alpha \cdot E_1 \cdot h_1^3 \cdot E_2 \cdot h_2^3}{\alpha \cdot E_1}}$	$h_1 = \sqrt[3]{\frac{E_1 \cdot h_1^3 \cdot \alpha \cdot E_2 \cdot h_2^3}{E_1}}$ $\alpha = 0.29 \cdot \frac{100 + W}{100}$ relevant load = Q	$h_{II} = h_1 + 0.9 \cdot h_2 \sqrt[3]{\frac{\alpha E_2}{E_1}}$	$h_{II} = h_1 + 0.9 \cdot h_2 \sqrt[3]{\frac{E_2}{\alpha \cdot E_1}}$	$h_{II} = h_1 + 0.9 \cdot h_2 \sqrt[3]{\frac{E_2}{E_1}}$ relevant load for load position edge = $Q \cdot [1 - W/200]$
bending stresses	$M_1 \cdot M_1 \cdot \frac{E_1 \cdot h_1^3}{E_1 \cdot h_1^3 \cdot E_2 \cdot h_2^3}$ $M_2 \cdot M_1 \cdot \frac{E_2 \cdot h_2^3}{E_1 \cdot h_1^3 \cdot E_2 \cdot h_2^3}$ 	$M_1 \cdot M_1 \cdot \frac{\alpha \cdot E_1 \cdot h_1^3}{\alpha \cdot E_1 \cdot h_1^3 \cdot E_2 \cdot h_2^3}$ $M_2 \cdot M_1 \cdot \frac{E_2 \cdot h_2^3}{\alpha \cdot E_1 \cdot h_1^3 \cdot E_2 \cdot h_2^3}$ $\delta_1 = \frac{6 \cdot M_1}{h_1^2}$	$M_1 \cdot M_1 \cdot \frac{E_1 \cdot h_1^3}{E_1 \cdot h_1^3 \cdot \alpha \cdot E_2 \cdot h_2^3}$ $M_2 \cdot M_1 \cdot \frac{\alpha \cdot E_2 \cdot h_2^3}{E_1 \cdot h_1^3 \cdot \alpha \cdot E_2 \cdot h_2^3}$ $\delta_2 = \frac{6 \cdot M_2}{h_2^2}$	$\alpha = \frac{\alpha \cdot E_2}{E_1}$	$\alpha = \frac{E_2}{\alpha \cdot E_1}$	$\alpha = \frac{E_2}{E_1}$

Annotation: W = joint effectiveness of the crack in %
 $c = \begin{cases} 0.83 & \text{for cement treated basecourse} \\ 0.90 & \text{for bituminous or untreated basecourse} \end{cases}$
 $W = \frac{2 \cdot y' \cdot 100}{y + y'} [\%]$ y' = deflection of the unloaded edge
 y = deflection of the loaded edge

Table 2 Eisenmann's method for calculation of the bending stresses in a three layer system consisting of concrete slab and treated basecourse for a system with and without a friction /4/

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