Joint design and joint performance of Plain Concrete Pavements (JPCP)
- Investigations and experiences in Germany -

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Abstract

Unreinforced concrete pavements have to be equipped with longitudinal and transversal kerbs to guarantee controlled cracking (JPCP). The designs of such joints depending on the technical requirements are given in respective specifications. Main features for the design are aiming first for the controlled cracking at the foreseen position during young age of the concrete as well as avoidance of wild cracking during service life, second for sufficient load transfer at the joint to reduce edge load effects and third for a good long time performance, which requires joint sealing. This paper focus on research works performed in the field of joint efficiency (dowelling) of transversal joints, which is especially related to the design parameters and the positioning of dowels. New developments and alternative solutions concerning the today's usage of coated steel bars must be done within the area of conflicts of following headings: Load transfer efficiency, longitudinal resistance, long-time behaviour (corrosion). FEM models and laboratory tests offer evaluation criteria for modified parameters. Especially the coating-material foreseen to cover the steel bar must be evaluated within the area of conflicts shown above. Additionally the actual dowel position and alignment is of importance. Non-destructive inspection tools are under development. The outputs of these investigations are strengthening the background for the updating work concerning the respective specifications.

1. INTRODUCTION

Since the 1970´s the construction of concrete roads using short and unreinforced slabs (JPCP) has been established as a standard in Germany. Usually these pavements are built without expansion joints and controlled cracking must be guaranteed by accurately timed sawing of kerbs during young age of the concrete pavement. Expansion joints are given in case of discontinuities like bridges only.

Based on investigations concerning the warping stresses activated by the effective linear temperature gradient along the cross-section of the concrete slab it was recommended to limit the maximum slab length up to the 25-fold of the slab thickness. In practice a standard length of 5 m is used. Design thickness of today's road specification RStO-01 (FGSV 2001) is between 16cm (concrete pavement on asphalt base course for low volume roads) up to 30cm for high loaded pavements built on unbound granular material. But even for very thick concrete pavements (e.g. airport pavements) a slab length more than 7.50 m should be avoided to

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limit the loading on the joint-sealing materials. Sealing of the joints is required to avoid water penetration and therefore erosion effects underneath the slab edges. In addition to the temperature load causing elongation of the slabs and joint widths shrinkage effects must be taken into account, which are causing an additional increase of joint width up to 1 mm during the first 5 to 10 years.

Loading of the free edge of the concrete slab (single wheel load) will lead to an increase of the maximum bending stresses along the edge up to the 2-fold value compared to the situation in the middle of an infinite slab. Vertical deflection will be increased up to about 3.5 fold at the free slab edge. Due to interlocking effects along a crack given by small crack widths the deflection will be reduced by load-transfer between both slab edges along the crack. This effect can be determined by measurements using the Benkleman beam and the following equitation:

$$W = \frac{200 \cdot y_2}{y_1 + y_2} \text{ [\%]}$$

where:
W = Effectiveness of load transfer at a crack or joint, respectively
y_1 = Deflection of the loaded edge
y_2 = Deflection of the unloaded edge

The importance of the joint effectiveness on the bending stresses along the edge is shown by:

$$\sigma_{dowelled-joint} = \sigma_{Free-edge} \cdot (1 - \frac{W}{200})$$

where:
W: Effectiveness of load transfer at a crack or joint, respectively
σ: Bending tensile stress

The effectiveness of load transfer at the joint can be increased and will be assured for a long time in case of using doweling systems. Measurements performed at dowelled joints of concrete roads during the last years showed a joint effectiveness index of at least W=80% even after a service life of about 30 years. In this case the theoretical increase of the bending stress level compared to the situation at slab-mid is only about 20% (Eisenmann and Leykauf 2003). Loading conditions between slab edge and slab centre will be harmonised and pumping effects (erosion) between slab edges are controlled. The tool itself in order to achieve this requirement must be protected against corrosion to offer full functionality during the whole slab service life (usually at least 30 years).

2. TRANSVERSAL JOINTS FOR JPCP - DESIGN

The following investigations focus on the transversal joint type which is one of the most frequently needed joint types.

2.1 Cutting and sealing

The development of tensile stresses during the young age (phase of hydration) of the paved concrete pavement requires a sufficient weakening of the pavement cross section to reach a controlled cracking at the planned location. On the other hand a deep kerb will cause a strong redirection of the compressive stress trajectories during hot temperature conditions in summer time which will increase the risk of slab blow ups during service life. Therefore the German specification ZTV Beton-StB 01 (FGSV 2001) recommends a saw depth between 25% and 30% of the total thickness.

Requirements and design recommendations concerning any kind of joint sealing systems used for concrete pavements are given by the German specification ZTV Fug-StB 01 (FGSV 2001).

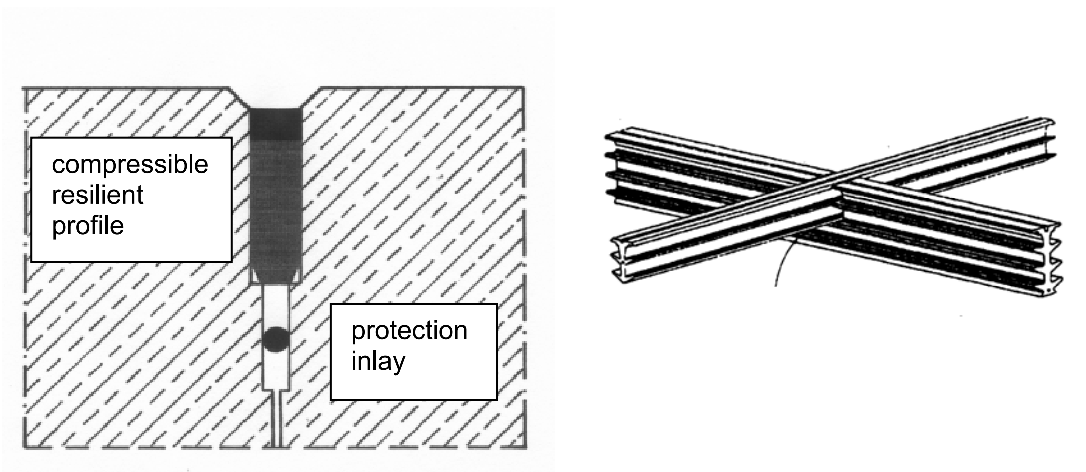

Figure 1. Joint design and joint sealing profile for transversal joints acc. to ZTV-Fug-StB 01 (FGSV 2001).

Hot and cold processible joint filling materials are appropriate for joint width-changes up to 25%; resilient joint-profiles up 30% of the total joint width. Standard mean values of joint width-changes are 2mm up to a slab length of 5 m and 3mm up to a slab length of 7.5m. These recommendations are based on long-time measurements performed on concrete pavements and on theoretical investigations using long time temperature measurements (Eisenmann and Lechner 1997). High standard deviations depending on the construction type of the pavement up to 1.5 mm (block cracking) must be taken into account.

Based on temperature changes measured within the concrete pavement during the cold season (surface temperature below +10°C) maximum daily changes of joint width (joint spacing 5.0 m) up to a range of 0.2 mm to 0.5 mm have to be expected (Eisenmann and Lechner 1997).

The vertical load cycles as well as the daily and yearly crack-width changes (crack opening) are widely reducing or eliminating the crack interlocking effect and therefore the respective joint effectiveness index.

2.2 Dowelling

According to the German specification ZTV Beton-StB 01 (FGSV 2001) concrete pavements designed for a life time loading of more than $0.8*10^6$ equivalent 10t single axle loads ("traffic class III") have to be equipped with anchors (longitudinal joints) and dowels (transversal joints). Dowelling is given by round steel dowels, diameter 25 mm, in a length of at least 500 mm. Regular dowel spacing is 25 cm. The distance to free edge or longitudinal joint respectively should be at least 25 cm.

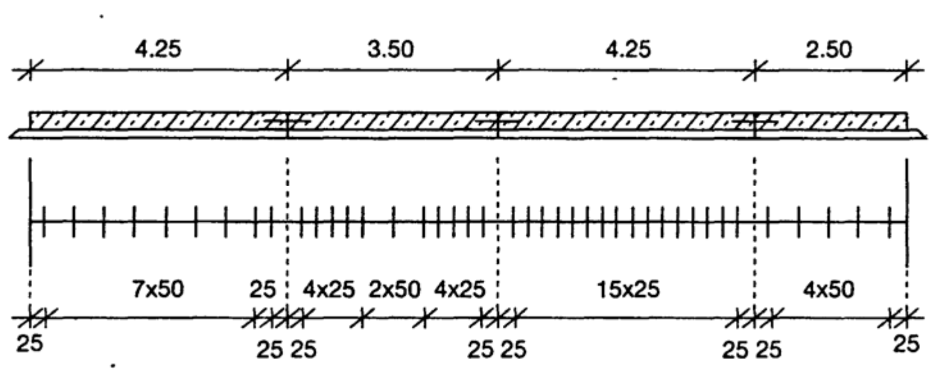

Figure 2. Cross section: Possible dowel arrangements for transversal joints acc. to ZTV-Beton-StB 01 (FGSV 2001)

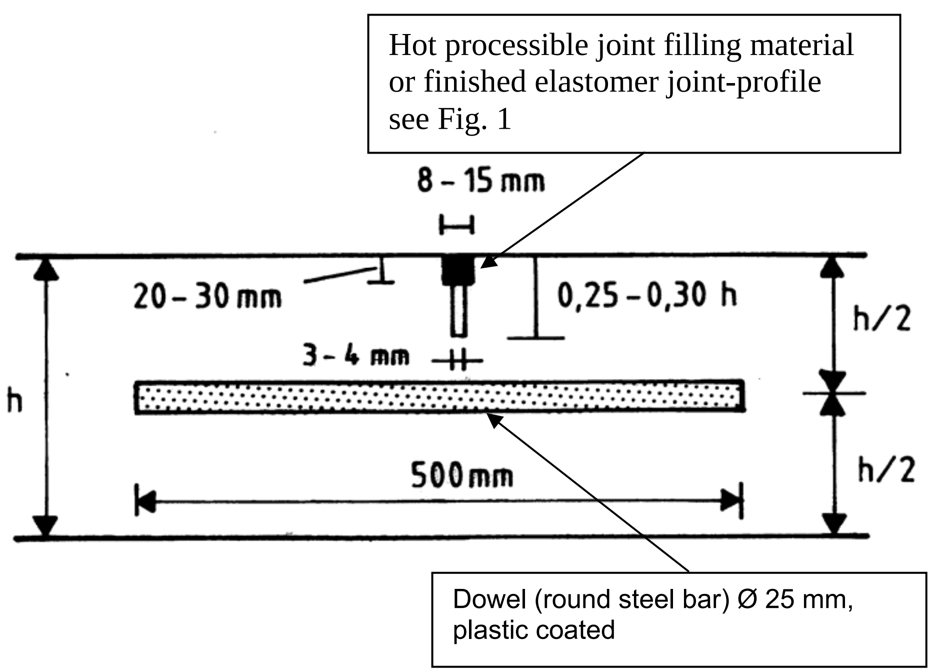

Figure 3. Cross section of a transversal joint.

Dowels should not activate significant anchoring effects during the phase of controlled crack appearance at the joint within the young age of the concrete pavement. Based on the gained experiences and lab test series the maximum pull-out force per dowel for the first loading (total movement 0.25 mm) under a loading speed of 13 kN/min should be limited to 18 kN; for repeated movements up to 12 kN (see chapter 4).

To reduce the transfer of longitudinal forces by the dowel between neighbouring slabs the dowels must be covered along the total length by plastic coating in a thickness of at least 0.3 mm. In addition this coating provides the dowel with a sufficient protection against corrosion (de-icing by salt water).

An increase of the diameter of the dowelling system will increase the risk of insufficient compaction above dowels in case they are inserted by vibration beams. Longitudinal cracks above dowel positions have been observed within few German highway sections.

3. DOWELLING SYSTEMS FOR TRANSVERSAL JOINTS – REQUIREMENTS

Purpose of the insertion of steel dowels is the transfer of vertical loading between the slabs at the joint to harmonise the load conditions for the concrete pavement between the load positions “joint” and “slab centre”. Even though the joints are equipped with sealing elements a sufficient protection against corrosion must be given to guarantee sufficient load transfer during the expected service life of the concrete pavement. But the parameters “efficiency of load transfer” and “durability” will be irrelevant for the pavement performance in case of wild cracking outside the joint-kerbs instead of controlled cracking. Controlled cracking will be ensured by sufficient depth of the kerb and limitation of the longitudinal friction between dowel bar and surrounding concrete. Therefore the design of the dowel itself must be done within the intersection zone or area of conflict, respectively of all the parameters as shown by fig. 4.

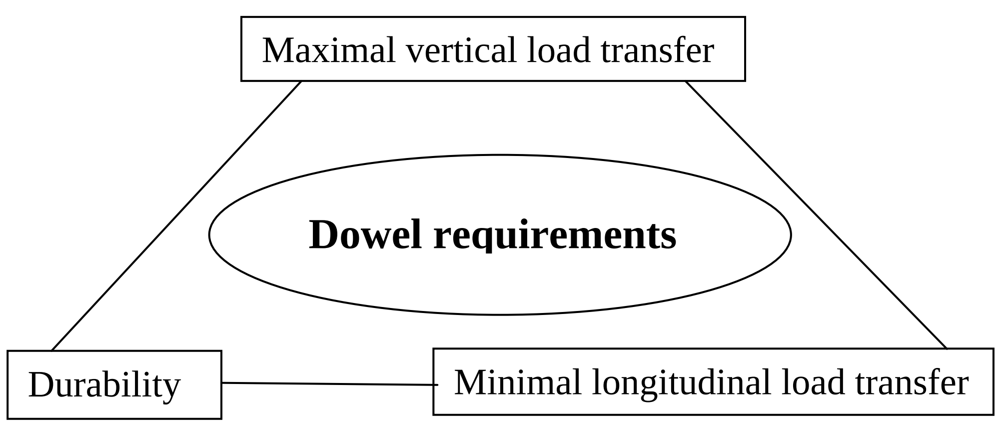

Figure 4. Area of conflict for new dowel designs.

In case of fixed dimensions and material properties of the steel bar itself this area of conflict (see fig. 4) must be completely transmitted into the design of the dowel coating. The ZTV Beton-StB 01 (FGSV 2001) requires an appropriate, adhesion able plastic coating in a thickness of at least 0.3 mm, which is covering the total length of the steel bar. The cross section of the steel bar including the coating must be uniform along the dowel to limit the transfer of longitudinal forces between the slabs.

Also the position of the dowel itself is affecting the performance according to longitudinal and transversal load transfer. Based on lab test series (Eisenmann and Leykauf 1980) a maximum allowable tilting position of 20mm based on a dowel length of 500 mm, a max. deviation of height position of 20mm and a max. deviation along the longitudinal axis (normal to the joint) of 50mm is given by the ZTV Beton-StB 01 (FGSV 2001).

4. DOWELLING SYSTEMS FOR TRANSVERSAL JOINTS - TESTING PROCEDURES

4.1 Corrosion protection

For initial testing and quality control the thickness of coating will be measured around top end (given for vertical coating process), middle and upper end of each dowel to control absolute values and uniformity of thickness.

4.2 Limitation of longitudinal load transfer

Transfer of longitudinal forces is controlled by pull-out tests performed on dowels which are concreted each within a concrete specimen in a centric position up to half length of the dowel. The pull-out tests should be performed up to a maximum age of the concrete of about 25h. The increase of longitudinal force or the respective concrete tensile stress outside the joint caused by the actual pull-out resistance of the dowel must be limited according to the ratio between joint-kerb depth and thickness of the concrete slab and according to the slab cross-section and number of dowels to control the risk of wild cracks between the planned locations. For the decisive load cases a maximum pull out force of < 18 kN per dowel can be derived.

Requirements for pull-out load tests performed under a loading speed of 13 kN/min for initial testing and quality control are as follows:
Maximum pull-out force for the 1st loading and measured at a displacement of 0,25mm must be limited to $P_{max} \leq 18$ kN. The maximum longitudinal force measured for repeated loading (here: 5th loading) at a displacement of 0,25mm must be limited to $P_{max} \leq 12$ kN. Finally the dowel must be pulled out of the concrete block completely. Thereby any damages at the coating (de-bonding, abrasion) must not occur.

4.3 Determination of the joint effectiveness index given by the dowel

The effectiveness of vertical load transfer given by the dowel itself can be determined using short concrete blocks in a length of about 1.0 m. The block consists of two slab sections connected by one dowel representing the situation at the joint. To guarantee comparability of the results interlocking effects activated in situ by fine crack-widths have been excluded by setting a defined gap (width 3.0 mm) with parallel boundaries. The loaded edge is free of support, while the unloaded edge is rigidly supported.

The vertical load is increased stepwise up to maximum load of 10 kN, which is the 2-fold of the assumed maximum in situ loading of one dowel of 5 kN (Freudenstein 2001). A repeated load test (minimum 10.000 load cycles) is followed to relieve adaptation effects which might be given by insufficient compaction of the concrete around the dowel or in general by gaps between steel bar, coating and concrete and to check the durability of the coating regarding the contact pressure between steel core and concrete (see chapter 5 “modelling). The results of the final step by step load test are used for evaluation work.

The change of the joint effective index during the repeated load test should be included into the evaluation.

Figure 5. “Model beam” for the evaluation of the dowel’s joint effectiveness (comparative testing procedures)

5. MODELLING THE VERTICAL LOAD TRANSFER

3D-FEM models have been created to evaluate the influence of the design parameters of the coating system and the dowel position, also to verify the used laboratory test (see chapter 4.3).

5.1 Influence of dowel coating properties

The resilient properties of the coating material itself have been described using spring elements between the steel bar and the surrounding concrete, while the real thickness of coating was given by the gap-width between the steel bar and the concrete (see Fig. 6). The springs are defined to act only for compression forces in radial direction. They represent the thickness and the modulus of elasticity determined for the respective coating system. So the model defines de-bonding between the dowel and the concrete in case of local tension and allows frictionless longitudinal movements.

The values of the spring coefficients or respective modules of elasticity used were based on compressive tests performed on coating materials and theoretical assumptions focusing on the effect of softer coating materials.

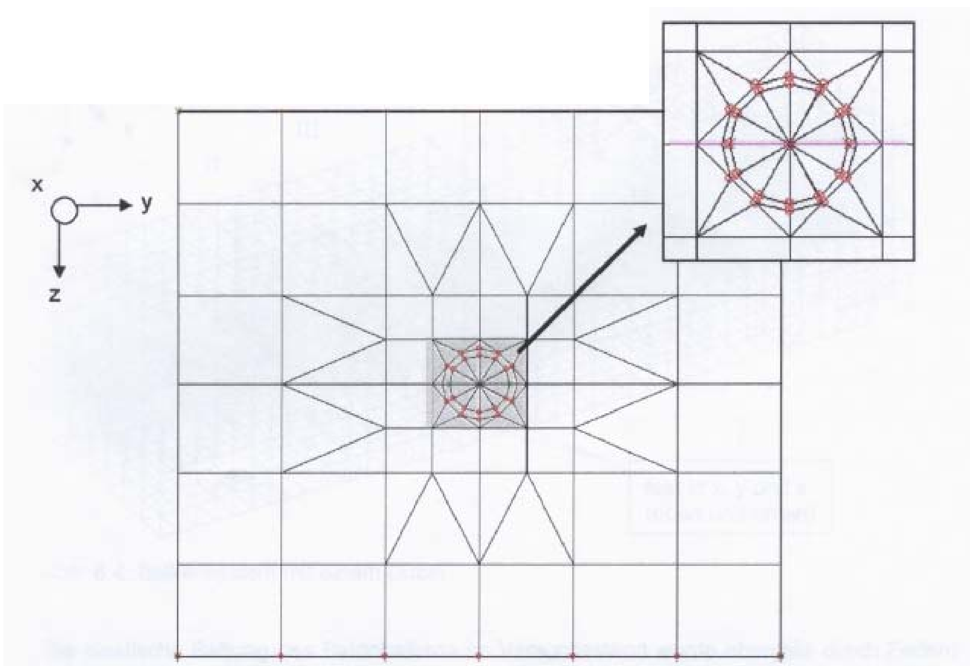

Figure 6. Cross-section of the "model beam" (see fig. 5) including the resilient properties of the steel bar coating material (Steidl 2003).

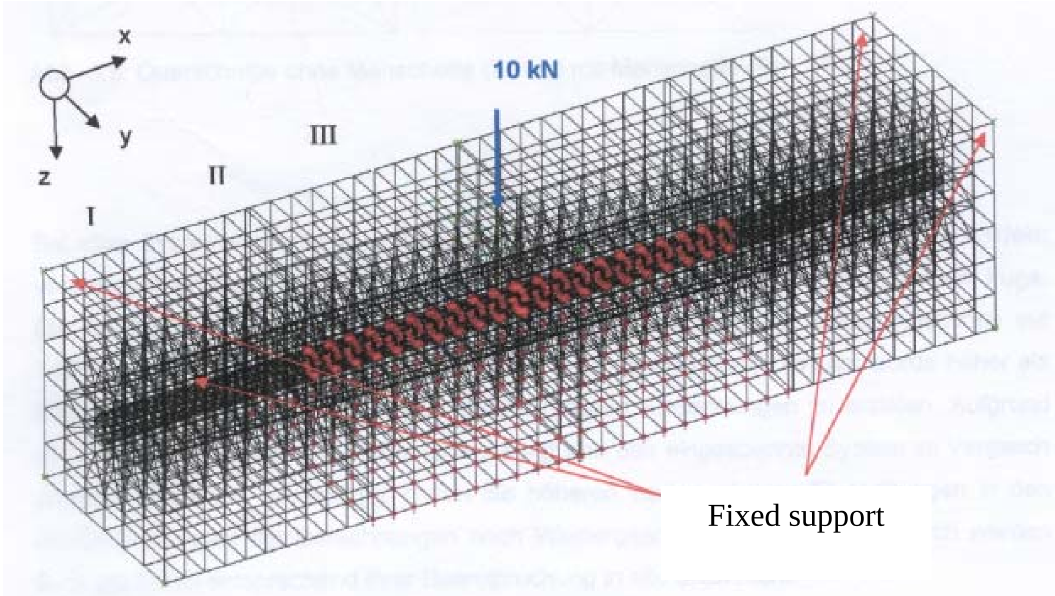

Figure 7. Implementing the coated dowel into the concrete slab section – "model beam" (see fig. 5) (Steidl 2003).

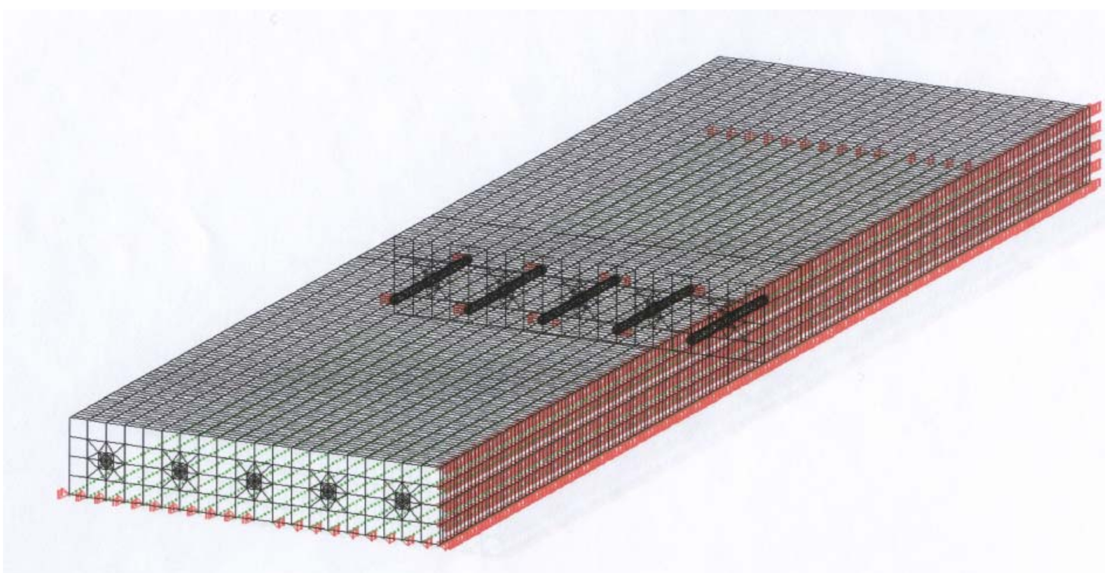

Figure 8. Implementing model beams into concrete slab sections; here: 10 dowels along a 2.5m wide transversal joint (symmetric model). Slab length 2.0m each (Steidl 2003).

Results of the FEM calculations using the model beam and the slab section model are shown in table 1.

Table 1. Relative vertical displacements between both edges at the joint and joint effectiveness indices dependent on the modulus of elasticity and thickness of the dowel coating. Load stage: 5 kN; cross-section of the "model beam": 0.24m x 0.25m; cross section of the slab 0.24m x 2.25 m (10 dowels).

No. Coating material	Modulus of elasticity [N/mm²]	Thickness of coating [mm]	Relative vertical displacement at the joint [mm]	Joint effectiveness index "FE-Model beam" [%]	Joint effectiveness index "Slab" [%]
1	225	0.30	0.016	92 (90*)	93
2	200	0.40	0.020	90	92
3	150	0.40	0.024	88	
4	200	0.60	0.025	88	
5	200	1.60	0.046	78	
6	50	0.40	0.046	78	
7	40	1.60	0.092	49	

*) Respective result born by "Model beam"-test (see figure 5)

The laboratory tests using the model beam showed the same tendency as given by the FEM-investigations: Increase of thickness or reduction of the modulus of elasticity of the coating material will cause a reduction of the joint effectiveness index. Using a coating material according to No. 6 (50 N/mm² and 0.40 mm) a joint effectiveness index of about 80% has been determined while a dowel coating according to No.1 (225N/mm² and 0.30mm) showed an index of about 90%. It must be taken into account that the respective values in situ will be increased by additional interlocking effects along the joint crack. This interlocking effect has not been taken into account for evaluating the dowel performance itself and is not included into the total joint effectiveness index.

The bending line of the dowel itself or the respective distribution of the contact stresses between the dowel and the surrounding concrete indicate that the effective length of load transfer is about 100mm at both sides of the joint in case of using dowelling systems as described in chapter 2.2 (length 500mm, diameter 25mm). Therefore the resilient properties of the coating system and/or gaps between the dowel and the concrete are playing an important role nearby the joint (Freudenstein 2001).

5.2 Influence of dowel position

5.2.1 Dowel alignment

The allowable tolerances concerning the dowel alignment are fixed by the German specification ZTV Beton-StB 2001 (FGSV 2001). The given values concerning the maximum allowable horizontal and vertical skews of 20mm for dowels equipped with a plastic coating in a thickness of 0.3mm (dowel length 500mm) are based on theoretical and experimental investigations ordered by the Federal Ministry of Traffic (BMVBW). Extraction test series using test specimens with two dowels (diameter 26mm), which were tilt towards each other symmetrically by exactly given values of mis-alignment between 0mm up to 40mm related to the dowel length of 500mm.

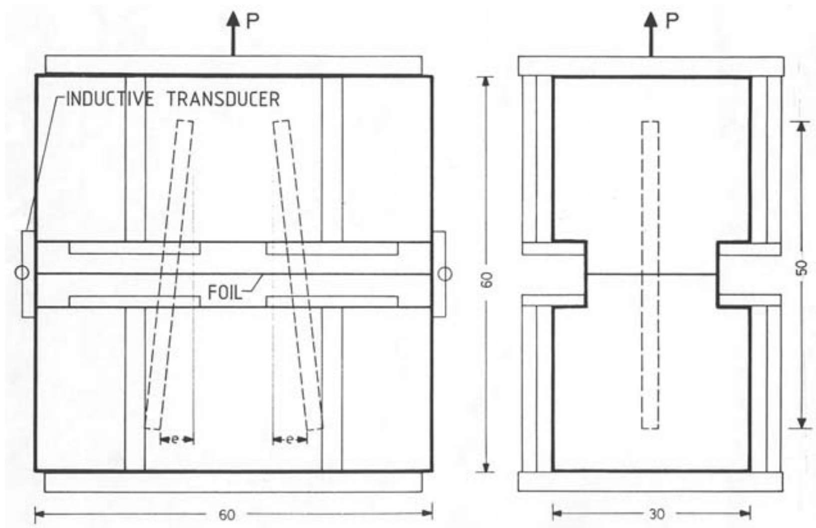

Figure 9: Pull-out test using two skewed dowels
(Leykauf and Freudenstein 2004)

The force-displacement histories have been analysed using the comparison stress

$$\sigma_v = \sqrt{\sigma^2 + 3 \cdot \tau^2} ,$$

which is generated by the concrete stress (caused by the moment due to the skew position) and the shear stress between dowel and concrete. The comparison stress has been set in relation to the cube compressive strength of the test specimen. The comparison stress criteria indicated that the allowable skew values must be reduced in case thinner (not recommended) or stiffer coating materials are used! A limit of 10mm based on a dowel length of 500mm has been recommended for dowels with a thin (mean value 0,06mm) bituminous coating, which however does not guarantee sufficient corrosion protection (Eisenmann and Leykauf 1980).

5.2.2 Length of embedment

Theoretical investigations have been done using the small 3-D FEM model beam or the slab model, respectively. Concerning the maximum contact stresses between dowel and surrounding concrete there was not any significant difference given by lengths of embedment greater than 100 mm. For embedment lengths below 50mm a strong increase of the contact pressure as well as a strong decrease of the joint efficiency index have been determined (Freudenstein 2001). These values are calculated assuming stiff coating materials in a thickness of about 0.3 mm according to ZTV Beton-StB (FGSV 2001).

These conclusions have been verified by a full scale repeated load test performed on a transversal joint between two 3,25m x 3,25m concrete slabs (thickness 0.25 m). The dowel positions had been fixed to check one-sided dowel embedment lengths of 68 mm and 30mm (both values were measured after finalisation of the test). The repeated load test has been done within several load stages simulating the load transition between the slabs up to a maximum single wheel load of 125 kN. During $8{,}3\times10^6$ load cycles an increased vertical relative deflection between the slabs as well as between dowel and surrounding concrete has been observed only in case of a very short length of embedment of about 30mm. It has been detected that the increase of relative movements was caused by plastic deformations of the coating (unloaded thickness 0.3 mm) and not by damages of the surrounding concrete (Freudenstein 2001). One should consider however that no stresses due to unfavourable climatic conditions were acting during the tests.

5.2.3 Position control

Test series had been performed to check the performance of non-destructive procedures to control the exact positions of steel bar dowels within concrete pavements. The devices and methods investigated were based on georadar and electro magnetic induction. The latter method can be used not only for hardened concrete, but already at the freshly paved concrete. It must be taken into account, that accuracy of these control methods is partly influenced by ferritic aggregates and moisture content. Therefore up to now no penalties for the contractor concerning dowel misalignments are given by the German specifications ZTV Beton-StB (FGSV 2001) based on these methods (Birmann and Noske 2003).

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