Unbound or hydraulically bound base layers supporting concrete pavements for road and rail infrastructure

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ABSTRACT: Most of the ballastless track systems built on earthwork sections for the German high speed rail network are characterised by a pavement design using two bound layers. The upper part of the pavement is designed as a continuously reinforced concrete layer (CRCP) or as a prefabricated concrete slab system with coupled joints. They are supported by cement treated base layers (CTB) or alternatively by asphalt base layers. There is also a steady tendency observed in ballastless track construction to use cement treated base layers with increasing requirements concerning strength or even using concrete base layers with respect to bearing capacity and durability. But the interaction between the treated base layer and the concrete pavement (CRCP or others) may lead to negative effects like reflective cracking, which must be taken into account for the base layer and CRCP design to really improve the entire two-layer system. For concrete road design Jointed Plain Concrete Pavements (JPCP) on unbound base layers had been established during the last decades as a technical and economic alternative. Technical and economic benefits for road construction were born by the usage of unbound base layers instead of CTBs especially due to the shortage of construction time and the usage of potential alkali-reactive material for unbound layers. Unbound base layers offer a uniform and more flexible support especially for concrete slabs. But special requirements to guarantee sufficient stability (resistance against erosion) due to repeated loading, permeability etc. shall be applied on those unbound base course materials used to support concrete pavements. Using synergetic effects between road and rail design unbound base layers offer also alternative solutions for ballastless tracks. Designs and constructive features of such multi-layer systems based on CRCP technology are shown achieving comparable bearing capacity and durability.

KEY WORDS: Unbound base layer, Hydraulically bound base layer, CRCP, Ballastless track

1 INTRODUCTION

Ballasted railway tracks require periodical tamping during operation due to uneven settlements of the sleepers within ballast and/or plastic deformation of subgrade or soil. The sleeper panel must be adjusted to guarantee a smooth run of the wheel sets. This will be significantly increased for high-speed lines due to vibrations. Resonance effects must be taken into account (Pahnke et al. 2010).

Properly designed ballastless tracks eliminate all potential settlements within the rail supporting layer (ballast) by implementation of a slab or beam shaped structure which offers sufficient load distribution into substructure during service life of the track (typically 50 to 60 years). Track conditions and performance shall be constant throughout the whole service life.

Track closures for maintenance needs are then cut to principle works like rail grinding which can be done by fast moving machinery. Furthermore the application of higher cant and cant deficiency allow horizontal alignment with higher curvature, respectively smaller radius. Vice versa speed can be increase if ballastless track technology is used. The initial investment costs for ballastless track superstructures are still significantly higher compared with the conventional ballasted superstructures. With respect to rail infrastructure performance the total project costs utilizing the specific advantages of ballastless tracks should be compared with superstructure costs. Consequently an improved ballasted track superstructure, which meets the requirements for high speed vehicles, must be used as basis.

Since 1972 (Rheda test section) main characteristic of ballastless track superstructures is the multilayered design of the rail supporting structure based on long term experiences on road and airfield pavements. Multi-layer structures are helpful to achieve high bearing capacity in combination with accurate surface level. The moment of inertia of the rail profile, the spacing and the elasticity of the fastening systems and/or rail supports activate longitudinal distribution of the vertical and horizontal loads applied on the rail. Therefore the maximum load applied on the slab is only a proportion of the axle load.

2 CONCRETE ROAD DESIGN

Up to 50´th concrete pavements for highways had been built using a slab length up to 20m placed on an unbound layer. An intermediate layer by sand offered a well levelled smooth support and low friction for relatively thin concrete slabs (220mm). Consequently all joints were designed as expansion joints.

Since 70´th short slabs without expansion joints and supported by cement treated base layer (CTB) had been established. CTB is helpful for material transport and concrete installation by slip-form paver.

According to the latest standard pavement catalogue RStO 12 (FGSV, 2012) following (see figure 1) pavement structures (excerpt) can be used for high loaded motorways with more than $32x10^6$ but less than $100x10^6$ Equivalent 10t Single Axle Load (ESAL). Maximum thickness of the concrete layer for heavy loaded motorways is up to 27 cm in case no bond with the 15cm thick Cement Treated Base (CTB) is activated by using an additional interlayer (non-woven fabric).

If bond towards the CTB is guaranteed the slab thickness can be reduced by 1cm but kerbs of the CTB must be in strict correlation to the joint layout of the concrete slab (FGSV, 2007) to avoid potential reflective cracking within the slab. If bond is used one must take into account that this interface has to handle shear loading by differential temperature changes as well as by traffic loading. De-bonding starting at the joints of concrete pavements had been widely observed (see figure 2). If joint sealing is not well maintained water has access to this horizontal interface via the joint. Even very small differential deflections of slabs at the joints activate erosive pumping actions. Efficiency of vertical load transfer at the joints is very important. Dowel bars shall be coated to increase resistance against attack of salty water but coating shall not soften the vertical interlocking between slab edges (Lechner, 2005).
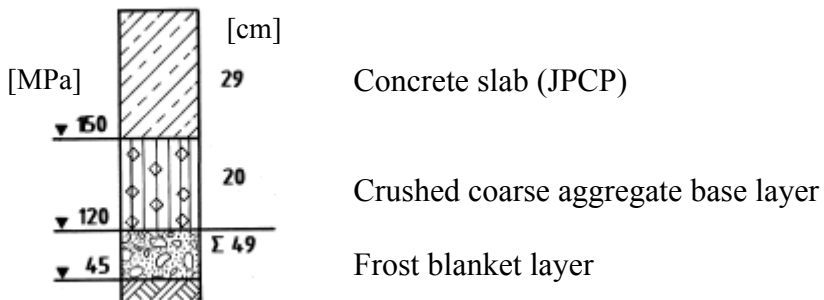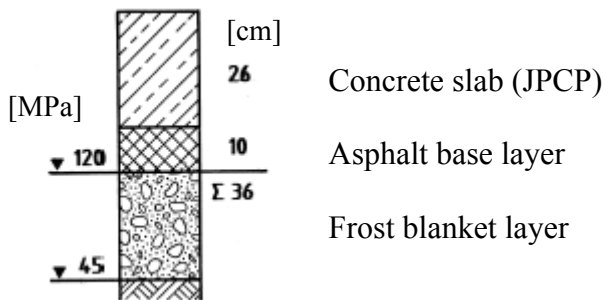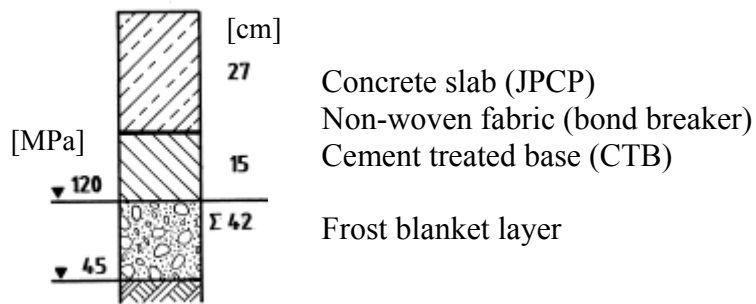
Concrete slab (JPCP)
Non-woven fabric (bond breaker)
Cement treated base (CTB)

Frost blanket layer

[cm] 27, 15, Σ 42
[MPa] 120, 45

Concrete slab (JPCP)

Asphalt base layer

Frost blanket layer

[cm] 26, 10, Σ 36
[MPa] 120, 45

Concrete slab (JPCP)

Crushed coarse aggregate base layer

Frost blanket layer

[cm] 29, 20, Σ 49
[MPa] 150, 120, 45

Figure 1: Excerpt of German RStO 12 (FGSV, 2012). Deformation modulus E_{v2} [MPa] and thickness [cm].

Figure 2: Eroded surface of CTB beside joint of the concrete pavement (longitudinal section)

2.1 General requirements for base layers supporting concrete roads

Warping stresses are caused by the linear part of the actual temperature distribution between the button and the surface of the pavement which is not equivalent to the stress-free conditions within the cross-section. Bending of the concrete slab due to heating of concrete surface will effect increased vertical contact pressures at the edges and corner sections and will activate a respective bending moment by the dead load of the slab. This bending moment can be significantly reduced in case the supporting layer offers respective adaptation and therefore reduces the effective span between slab supports.

Better adaptation between concrete slab and supporting structure may be achieved by respective intermediate layers (e.g. asphalt intermediate layer on CTB) or unbound base layers. The impact on reduction of slab dead load depends strongly on material properties. Recycled concrete or rubblized concrete layers could be also quite stiff and dense due to late hardening effects after crushing the old concrete structure.

Sufficient Drainage, permeability etc. are very important topics esp. for unbound layers. But in general stiffer structures made by unbound materials as wells as CTBs show lower permeability. Therefore bearing capacity requirements of base layers should be on a moderate level. E.g. the discussed increase of deformation modulus Ev_2 up to 180 MPa (instead of 150MPa) was rejected to avoid permeability problems (see figure 3).

Figure 3: Unbound base layer with high bearing capacity but low permeability.

2.2 Cement treated base layers (CTB)

German standards deal the cement treated base layers first as unbound layers which are improved in terms of durable bearing capacity by using cement. Meanwhile this general approach is lost by re-arranging the content of the standards to fit with the EN structure. All

kind of layers with cement binder, concrete pavements and concrete base layers as well as CTBs, are now covered by one standard.

Like unbound layers the proctor density must be checked, min. 98% must be met. But min. binder content is 3% and a min. compressive strength of 15N/mm^2 determined using proctor test samples (Height/Diameter = 120mm/100mm) must be achieved is the CTB should support a concrete pavement (FGSV, 2007). Cement treated base layers shall have a minimum thickness of 12cm or 15cm, respectively dependent on construction procedure and aggregate size. Kerbs and other measures to control cracking behaviour of CTB are not required if this layer is not directly supporting the concrete slab or a non woven fabric acting as intermediate layer and bond-breaker is used. Otherwise crack control by kerbs exactly following the joint layout of the JPCP must be applied. Alternatively continuous stress release using a heavy roller or a cracker blade must be done if the CTB is thicker than 20cm (FGSV, 2007). Additionally risk of reflective cracking in the concrete slab may also be increased if the CTB comes with high strength and kerbs are not properly installed.

Alternatively concrete base layers can be applied using concrete class C12/15 up to C20/25. Quality control follows standard concrete material procedures. Measures concerning crack control dependent on the interfaces condition to the concrete slab are the same as mentioned for CTB.

Roos et. al. observed that Young´s modulus of CTB samples taken from different section showed were higher than expected. It has been concluded that CTBs are relatively stiff layers in terms of bearing capacity acting as supporting layers for concrete slabs. But resistance against erosion can be progressively increased by increasing the strength of the cement treated base layer. Water content of CTB mixture as well as treatment of CTB after installation is important for resistance against erosive effects (Weller, 2008). One must balance with risk of reflective cracking.

2.3 Unbound base layers used for road construction

Based on economic and technical demands concrete pavements (JPCP) on unbound base layers had been tested successfully, therefore implemented in the German standard in 1981. Advantages were already assessed during construction. Unbound base layers require no treatment after placing and due to absence of hardening effects the next layer can be installed immediately, no check of cracking behaviour in terms of reflective cracking needed. Recycled material, which may be sensitive to alkali-silica reactions, can be used. Smooth adaptation between concrete slab and base layer reduces bending stress in the slab if it´s deformed by changing temperature and moisture gradients.

Based on construction work experience the width of the unbound base layer should be sufficient to support the heavy slip form paver for concrete pavement installation (min. 65cm at both edges are recommended). Top layer of the unbound base layer (minimum thickness 12cm) should be laid using a paver to meet the surface level requirements. Unevenness and loosened aggregates should be removed by a roller compactor. Surface of the unbound base layer must be sprayed with water before paving the concrete.

Package cracking of the concrete pavement dependent on seasonal changes of ambient temperature must be expected. Joint opening of dummy joints could be partially wider and non-uniform which must be taken into account for joint sealing works.

Only crushed stone base layers with minimum thickness 30cm (FGSV, 2004) are accepted as support for concrete pavements to achieve sufficient deformation resistance and water permeability. Surface deformation modulus of must be at least E_{v2} = 150 N/mm² (plate bearing test - second loading). In addition the California Bearing Ratio test must show more than

80% determined on material 0/22 (after removal of aggregates > 22mm) (FGSV, 2004). The test had been established as a tool to demonstrate durable water permeability.

The lower bearing capacity of unbound layers vs. CTB is balanced by a slight increase of concrete pavement thickness which is +2cm for pavements with an intermediate layer (bond breaker) or +3cm for full-bond conditions.

Unbound base layers should be able to drain off penetrated water and capillary effects by substructure properties must be disrupted. The unbound layer must be resistant against erosion (Weller, 2008)

3 BALLASTLESS TRACKS USING CONCRETE PAVEMENTS

3.1 Design principles

Bearing behaviour of ballastless tracks is characterised by a defined elastic support of the rails and a slab system with a sufficient bearing capacity. Decisive load scheme for the design is the theoretical load model 71, which is determined by four 250 kN wheel set loads with 1,6m spacing. Alternatively real train loads can be used e.g. for high speed dedicated lines. Design loads have to cover additional dynamic effects by application of respective factors. (DB-Systemtechnik, 2002)

Due to the load distribution activated by the bearing capacity in combination with the elastic support (fastening systems) of the rails the loads on the pavement are significantly lower than axle loads. All rail seat loads contributing to the maximum overall bending moment in the slab shall be captured for slab design. Rail seat loads reducing the overall bending moment shall be excluded. An iterative approach is needed in case a FE-model is used. Additionally the thickness-design has to consider thermal impacts during service life.

To reflect the behaviour of continuously welded rail (CWR) also continuously reinforced concrete pavements (CRCP) with free or controlled transversal cracking (JRCP) were used. Typical longitudinal reinforcement (diameter 20mm) placed at the neutral axis of the slab is 0,8% to 0,9% of the total cross section (0,4% to 0,5% for jointed JRCP). This amount of reinforcement is sufficient for vertical load transfer at the crack or dummy joint and limits crack width. The design of slab thickness is based on the tensile bending stress capacity of the concrete as applied for road and airfield pavement design.

Figure 4: Track adjustment preparing for continuously reinforced concrete pavement (CRCP) on a cement treated base layer (CTB).

Figure 5: Ballastless track with discrete rail seats on a continuously reinforced concrete pavement (CRCP) with dummy joints to control transversal cracking.

For ballastless track design/modelling following parameters are typical (mixed traffic, axle load up to 250kN):
- Rail 60E2 according to TSI with resilient rail fastening systems.
  For the design a dynamic spring coefficient of c_{dyn} = 40 kN/mm with regard to low temperatures and high frequency loading is recommended.
- Rail supporting structure, like prestressed mono-block sleepers acting as load distributors
- Concrete slab with minimum bending tensile strength $\beta_{BZ} \geq 5,5$ N/mm²,
- Crushed stone base layer with modulus of deformation E_{v2} = 150 MPa
- Frost blanket layer: E_{v2} = 120 MPa and high water permeability
- Subbase: E_{v2} = 45 MPa

3.2   Cement treated base or unbound base layers

Most of the concrete slabs for ballastless tracks had been built with a cement treated base layer (CTB), usually in a thickness of 30 cm. During the decades there is a clear tendency visible that the strength of the CTB-material has been increased, obviously contractors had in mind that ballastless tracks should survive 60 years of service life. Higher strength of the CTB similar to conventional concrete leads to higher bearing capacity, better resistance against erosion but reflective cracking effects in reinforced slabs (CRCP and precast slabs) became an issue. The CTB and its cracking behaviour start dominating the entire track system. Adjustments toward moderate bearing capacity and strength of CTB are needed. Alternatively the capabilities of unbound base layers instead of CTB should be utilized.

In a first stage theoretical investigations had been done to show comparable ballastless track designs using CRCP, JRCP or JPCP on CTB or unbound base layers. Ballastless track systems are relatively narrow compared to road pavements. Consequently the limitations concerning load distribution in transversal direction must be taken into account dependent on the individual, detailed track design (Sleeper panel on slab or direct support of rail). Lack in width requires compensation by respective bearing capacity of the slab (thickness) itself to control the vertical stresses acting on unbound layers. It is recommended that vertical stress on subgrade or subsoil by traffic load should not exceed 0,05 N/mm².

Economic thickness design first leads to sleeper panel on a continuously reinforced concrete pavement with controlled transversal cracking (JRCP) on an unbound base layer. Release of longitudinal forces by kerbs gives lower thickness compared with conventional CRCP.

Table 1: General types of ballastless track systems with sleeper panel supported by a continuously reinforced jointed concrete pavement (JRCP) on unbound base layers

System	1	2
Concrete slab JRCP	$h = 30$ cm; $b = 3{,}20$ m Controlled cracking $a = 1{,}95$ m Reinforcement 13 Ø 20mm according to 0,43 %	
Crushed stone base course	$E_{v2} = 150$ N/mm² 70 cm	$E_{v2} = 150$ N/mm² 30 cm
Frost blanket layer		40 cm

The determination of the required thickness of the concrete slab supported by an unbound base layer shows that controlled cracking (see figure 5) will reduce stresses within longitudinal direction significantly. Regular crack spacing should be 3-fold (1,95m) up to 4-fold (2,6 m) of rail seat spacing. The joints should be sawed exactly between rail seats. (Lechner, 2008)

The vertical contact stresses between concrete slab and unbound base layer are quite uniform. One passage of the load scheme 71 is equivalent to one load cycle. The joints are displayed only by small discontinuities within vertical stress distribution. The maximum vertical pressure on unbound layer by dynamic loading is $\sigma = 0{,}07$ N/mm², but contact pressures of truck tyres during construction time could be $\sigma \geq 0{,}7$ N/mm², which is at least the 10-fold value. This again emphasises the requirement to limit weight and number of axle load on the unbound base layer during construction time. Compared with concrete pavements on cement treated base course (CTB) the vertical stresses are increased based on the lower width of the concrete slab.

The allowable bending stresses within longitudinal direction of the slab are limited by the amount of warping stresses due to non-linear heating of the concrete slab. Unbound base layers show respective advantages due to the ability of surface deformation, which leads to harmonisation of contact stresses between the warped slab and the base layer. It is advantageous to choose quadratic slab dimensions, Furthermore bending of the slabs itself must be taken into account if slab length is increased. Warped or curled slabs interfere with rail seat loading (pre-loading due to deformation), therefore with vehicle track interaction and ride quality.

For the design of single layered continuously reinforced concrete slabs with direct fixation of the rail seats measures to control cracking are essential to avoid cracking at rail seats and to avoid potential loosening of bolts (see table 2).

Table 2: General types of ballastless track systems with discrete rail seats on a continuously reinforced jointed concrete pavement (JRCP) on unbound base layers

System	1	2
Concrete slab	*Thickness* = 36 cm; *Width* = 3,20 m Controlled cracking *a* = 2,60 m Longitudinal reinforcement 16 Ø 20mm according to 0,44 %	
Crashed stone base course	E_{v2} = 150 N/mm² 64 cm	E_{v2} = 150 N/mm² 30 cm
Frost blanket layer		34 cm
Layer with frost-unsusceptible material		
Subbase	E_{v2} = 60 N/mm²	

Shorter transversal crack spacing has no impact on the required slab thickness due to the fact, that the allowable bending stress within transversal direction is limited by the given stress level caused by the non-linear temperature gradient during summertime heating.

Instead of continuously reinforced jointed concrete pavements (JRCP) also concrete slabs with dummy joints (JPCP) but without longitudinal coupling can be investigated using the long term experiences of concrete pavements for road construction.

4   CONCLUSIONS

Road experiences show advantages but also potential problems by using cement treated base layers (CTB) or alternatively unbound base layers supporting Jointed Plain Concrete Pavements (JPCP) which is standard pavement design in Germany. The lower bearing capacity of an unbound layer compared with the one treated with cement will be compensated by just a slight increase of concrete slab thickness. The smooth adaptable support offered by an unbound layer reduces loading of the concrete slab. But unbound granular material (UGM) must be resistant against erosive effects starting below the joints of the concrete pavement. Permeability of UGM and overall drainage are very important. Base layers shouldn't be too stiff to avoid a dense structure by high compaction energy applied. Moderate bearing capacity should be achieved.

Transfer of CTB technique into rail application supported the development in ballastless track technology for decades. Today problems were observed because in rail application CTB is used for continuous pavements (CRCP or coupled slabs) in a thickness of usually 30cm. In combination with increased requirements by contractors concerning compressive strength of CTB reflective cracking effects had been observed. CTBs start dominating the entire track system behaviour. Consequently moderate bearing capacity of CTB or jointed reinforced concrete pavements (JRCP) instead of CRCP are recommended. Kerbs of CTB must match with joint layout of the JRCP. Alternatively unbound layers should be taken into account utilising road experiences. Due to load transfer by the rails erosive effects at the joints (kerbs) are less severe compared with road pavements. Continuous reinforcement or coupled joints are essential to offer constant support conditions for the continuous rail.

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