Concrete pavements for railway tracks

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Abstract

During the last three decades major steps ahead were done in the field of high-speed railway tracks based on the implementation of proven road pavement technologies. Some modifications and adaptations were needed with respect to the requirements of railway tracks especially on high speed lines. Different ballastless track systems were developed and tested and are in use for high speed links worldwide as well as for urban transportation networks. Main feature of ballastless track structures is an elastic connection between rails and treated layers. Following designs had been used:

- Sleeper panels connected to a concrete or asphalt pavement or sleeper panels monolithically embedded within a concrete slab;
- Prefabricated, prestressed slabs or frames connected to a treated base by an intermediate layer;
- Discrete rail seats on Jointed Reinforced Concrete Pavement (JRCP) or embedded rails on Continuously Reinforced Concrete Pavements (CRCP).

High quality railway tracks based on concrete pavement technology will show increasing applications worldwide. The research activities on concrete pavements have to strengthen synergetic effects between road and railway looking for new applications and steady improvements.

Introduction

The main advantages of a conventional ballasted track are its low investment costs and its ability to bear very high axle loads at moderate speed. Ballasted railway tracks require periodical tamping due to uneven settlements of the ballast during operation. The sleeper panel, which is embedded within the ballast bed without any rigid fixation, must be adjusted in certain intervals to guarantee a smooth run of the wheel sets. Long term experiences and highly developed effective working machinery are available for all the maintenance work, which must be performed on those tracks.

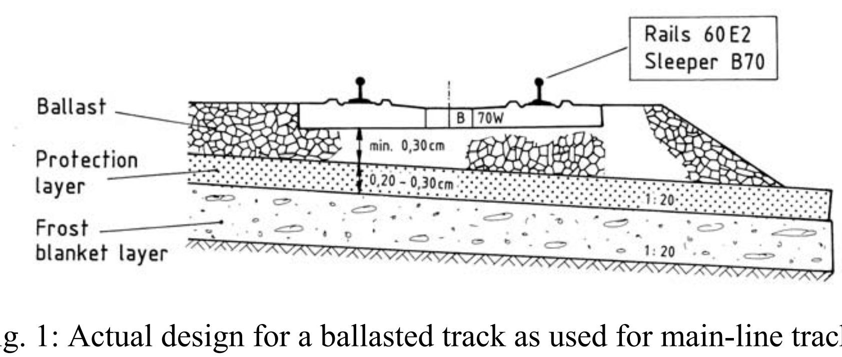

Fig. 1: Actual design for a ballasted track as used for main-line tracks in Germany (Figure shows one track of a double track line)

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First considerations to implement ballastless track technology were fostered by the observation that ballast on a stiff substructure, like bridge decks or tunnel floors, suffered much more rapid degradation than when laid directly on a soil surface. It must be taken into account that any kind of maintenance work in tunnels is difficult with respect to the safety aspects. Such experiences, like poor long-term durability of ballasted track on concrete structures, were confirmed on the 515 km Tokaido Line (between Tokyo and Osaka), which was opened in 1964. About 50% of the route had been built on civil structures and after 30 years of service within 75% of the whole line the ballast had been exchanged twice. Similar experiences were born on the French TGV route Paris – Lyon (opened 1981) and the German High Speed Line put into operation in 1990/1991, where highly compacted (high modulus of elasticity) formation protection layers and frost blanket layers were installed. The behaviour of the ballast bed demonstrated, that the durability was approximately halved and ballast renewal was needed after about 15 years. A stiff substructure limits the load distribution by the rails, which results in higher vertical contact stresses on the ballast under the sleepers even by a quasi-static load. Consequently respective elasticity by elastic elements must be implemented additionally within the track superstructure (see fig. 2). Furthermore by usage of sleepers with a wider base the contact area towards the ballast can be significantly increased, while the contact stresses are decreased (Leykauf et al, 2006). Evaluating the life cycle costs (LCC) of ballastless track structures this kind of improved ballasted track must be taken as comparable basis. Additionally the availability of ballasted tracks is limited due to required maintenance works like tamping or ballast renewal. Track closings and interruptions are generally in conflict with the demands of the operator. E.g. for the “HSL Zuid” in the Netherlands, which was built based on a DBFM contract basis (Design, Build, Finance and Maintain), an availability has to be guaranteed at a specified high level of 99 % for 25 years (Leykauf et al., 2006). Therefore the awarded consortium INFRASPEED decided to construct a ballastless track in spite of the existing poor subgrade conditions.

Secondly at increased speeds greater vibration velocities of the ballast stones within the ballast layer had been measured. E.g. the velocity of vertical movement of the ballast stones under the sleeper is doubled as the train speed increases from V = 160 km/h to 250 km/h. This effect is reduced by installation of higher elasticity in the track structure.

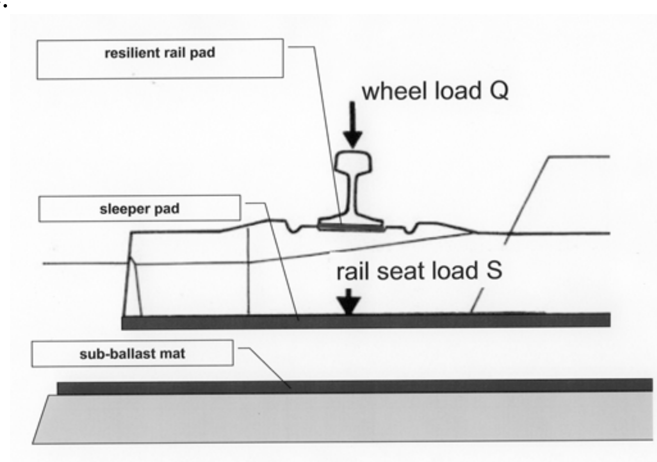

Fig. 2: Possible measures (but not in combination) to improve conventional ballasted tracks by implementation of elastic elements to achieve required overall track elasticity (Leykauf and Stahl, 2004)

It is important to take into account that the non-contact eddy current braking system used by high speed trains like the ICE 3 causes an additional heating of the rails affecting the safety margin of track stability, which is decisive for ballasted tracks (no rigid fixation of the sleeper panel within ballast bed). Another aspect is the problem of "flying" ballast stones (aggregates whirled out of the ballast) already observed on high speed networks (Leykauf et al., 2006).

Furthermore the use of conventional ballasted track structure is limited concerning the lay-out parameters of new lines. The 155 km long ballastless track section of the high speed line Cologne-Frankfurt (V_{max} = 300 km/h) with a regular track radius of 3350 m, a superelevation (railway: cant) of 170 mm and a gradient of 40 ‰ could hardly have been realised with a conventional ballasted track structure according to the design standards of DB-AG.

Fig. 3: Bundling of road and railway line between Cologne and Frankfurt.

Development and design of ballastless track superstructures

In 1972 an innovative railway superstructure was installed at the station of "Rheda", Germany, which consists of a continuously reinforced concrete pavement (CRCP) on a cement treated base (CTB) instead of a ballast bed. The exactly aligned concrete sleepers (prestressed monoblocksleepers) were monolithically fixed to the CRCP by a filling concrete (see fig. 4). Despite the poor subgrade conditions at this area, which would not satisfy present-day technical requirements, the track is still in service after having passed more than $500 \cdot 10^6$ gross tonnes. Except rail grinding, no any other maintenance work has been done during 35 years! This Rheda test-section is therefore seen as the prototype for present-day ballastless track constructions.

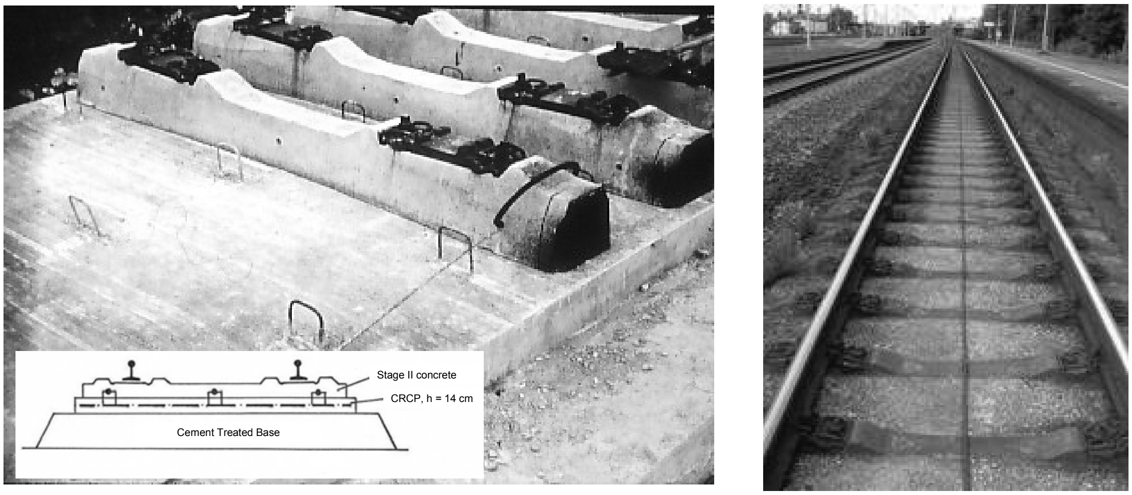

Fig. 4: Test track at "Rheda" station during construction in 1972 (left) and today (right).

The idea to use prestressed monoblock sleepers, which are directly supported by a treated base layer is first of all a self explaining combination of components which are proven elements in the field of conventional, ballasted tracks and technologies derived from road construction. The experiences and quality level obtained form both techniques can be utilised and synergetic effects are activated. The usage of prefabricated sleepers helps to meet the very strict requirements concerning the exact gauge and the correct rail-cant! The interface between sleeper and concrete pavement surface requires high level of accuracy within the complete cross section, which must be met even if the superelevations are much higher compared to concrete roads (up to 12,5% equivalent to a cant of 180mm, respectively).

Since the beginning of the 70´s numerous ballastless track systems had been developed in Germany. For ballastless tracks planned to be installed within the network of the German railway company "DB-AG" design standards with respective requirements had been fixed (DB-Systemtechnik, 2002) to guarantee a sufficient life time of ballastless track structures up to 60 years, which is doubled compared with the design life of concrete pavements for road infrastructure. This design standard covers only the special requirements needed for railway tracks, while it refers to numerous specifications and standards established for road construction – like design and construction of concrete pavements.

Bearing behaviour of ballastless tracks is characterised by a defined elastic support of the rails and a relatively stiff slab system with a sufficient bearing capacity. Up to now continuously reinforced concrete pavements (CRCP) with free or controlled transversal cracking (jointed reinforced concrete pavements – JRCP) in combination with a cement or bituminous treated base layer or asphalt pavements had been chosen for the multi-layered ballastless track design. CRCP are determined by longitudinal reinforcement (diameter 20mm) placed at the neutral axis of the slab by an amount of 0,8 to 0,9% of the total cross section. This reinforcement provides a sufficient vertical load transfer at the crack or dummy joint and a limitation of crack widening as well. Crack width limit of the specification is in general 0,5mm (DB-Systemtechnik, 2002). The design of slab thickness is based on the tensile bending stress capacity of the concrete, which is based on the experiences of road and airfield pavement design. Ballastless tracks in Germany require a frost blanket layer with a high water permeability (Deformation modulus E_{v2} = 120 N/mm²). All applications of ballastless tracks up to now can be grouped as follows:

Sleeper Panels with monolithic connection to a pavement (CRCP). Those systems were derived from the original Rheda system as described above. For good long term behaviour it is evident to achieve full bond between sleepers, filled concrete and CRCP. Therefore the longitudinal reinforcement of the filled concrete was connected to the monoblock sleepers (equipped with holes see fig. 4 and fig. 5) and also to the CRCP by steel bars. The first design was followed by modifications in terms of installation procedures and other economic aspects.

The first modification was the usage of a trough instead of a plane surface of the CRCP to avoid the necessity of formworks for the filled concrete and of the vertical steel bars to the CRCP (see fig. 5). Furthermore the side-walls were used to fix the spindels and to adjust the sleeper panel horizontally. The sidewalls were not taken into account for the thickness design of the CRCP!

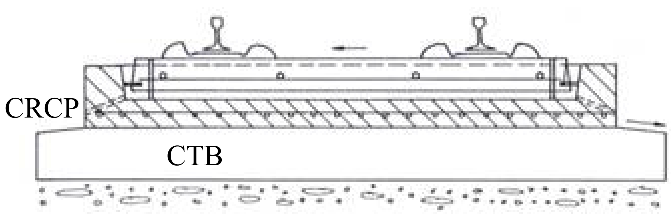

Fig. 5: Hannover – Berlin opened 1998; System "Rheda" with trough.

Transverse cracking of the filling concrete usually occurs at the edges of the embedded sleepers. In case those cracks showed a wider opening due to unfavourable temperature regimes during placing and hardening of the filling concrete water penetrates and de-bonding between filling concrete and sleepers had been observed. De-bonded sleepers start to move vertically due to the elastic connection with the rails which - together with the presence of water - activates severe erosion effects. To improve the bond between the filled concrete and the prefabricated sleepers two-block sleepers or lattice girder sleepers (modified two-block sleepers) have been used (see fig. 6).

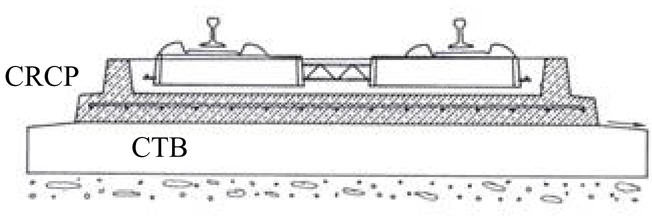

Fig. 6: High speed line Cologne – Rhine/Main; CRCP with sidewalls and two-block sleepers aligned before concreting the filling concrete.

Latest step of development is shown by the actual "Rheda 2000" design, which integrates the lattice girder sleepers directly within the CRCP. The CRCP gives together with the CTB (bond at the interface) the required bearing capacity and rigid fixation of the sleepers. A first section had been constructed within the line Erfurt - Leipzig/Halle in year 2000 followed by a about 38 km long double track section within the Nuremberg-Ingolstadt high speed line (see fig. 7 and 8).

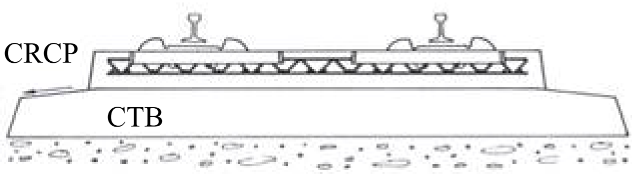

Fig. 7: The “Rheda 2000” system, which is using lattice girder sleepers integrated in the CRCP.

Fig. 8: Final adjustment of the sleeper panel before concreting the CRCP-layer (Highspeed line Nuremberg – Ingolstadt)

Concrete pavements used as support layers for sleeper panels. Paving of cement or bituminous treated base layers with a plain surface is a proven technology in the field of road construction. Requirements for ballastless track construction are much tighter. Design factors such as superelevation are more extreme than roadway. For example, the maximum cant for German tracks up to 180 mm (equivalent to 12,5 % superelevation) in comparison with a maximum superelevation of 8 % for roads and other requirements connected to the railway design speeds up to 300 km/h must be converted into a continuously high quality level at the construction site.

To guarantee sufficient adaptation and uniform contact pressure between sleeper-bottom and pavement-surface and to avoid damages by dynamic loading an interlayer which allows small elastic/plastic deformations must be used. For example, geo-textiles with a thickness of 5 mm fixed to the sleeper contact area in sleeper plant. Like in ballasted tracks the sleeper centre must be free of vertical contact not to activate negative bending moments in the sleeper. Using sleepers with a large contact area (minimum length 2,4m) towards the pavement the pressure between sleeper and pavement by rail seat loading will be reduced to about 0,3 N/mm², which is much lower than the contact pressure of conventional truck-wheels of about 0,7 N/mm². Asphalt pavements are also a possible solution and are competitors for concrete pavements for this type of ballastless tracks. More than 80km of asphalt tracks are in operation within the German railway network. In addition to the thickness design according to bearing capacity the deformations of asphalt caused by time and temperature dependent visco-elastic behaviour must be taken into consideration.

Centrifugal forces are activated by guiding the train along curves. Those forces must be transferred to the substructure as well as longitudinal forces activated by braking or accelerating the train. Also, horizontal forces caused by temperature changes (climate conditions or usage of eddy current brakes) within the continuously welded rails must be controlled to avoid track buckling with a sufficient margin of safety. Suitable connectors to handle these horizontal forces have to be inserted between sleeper and pavement (see fig. 9).

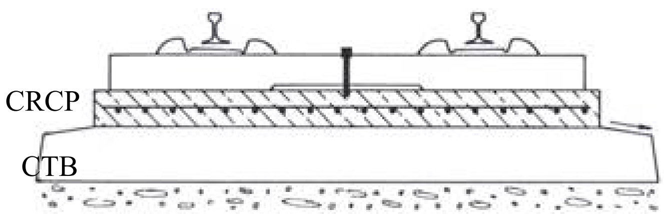

Fig. 9: Line Hannover – Berlin opened 1998; Track systems “BTD - V 2” using steel anchor bars for longitudinal and transversal fixation of the sleeper panel.

Currently under study is the use of jointed concrete pavements - without longitudinal coupling but dowelled – based on the long term experiences of JPCP applied in road construction. Therefore it would be also possible to exchange the cement treated or the asphalt base layer by a special crushed stone base layer (Lechner, 2008). Design and construction of the transversal dummy joints should be done according to (Forschungsgesellschaft, 2001). The dispense with longitudinal and transversal reinforcement to control crack width in case of unplanned but potential wild cracking between dummy joints should be discussed based on the design features of the chosen ballastless track system. A safe and durable fixation of the sleeper panel towards the concrete pavement concerning horizontal load transfer must be given!

The allowable bending stresses within longitudinal direction of the jointed slabs are limited by the amount of warping stresses activated due to non-linear heating of the concrete slab. Furthermore changes within vertical curvature of the slabs themselves must be taken into account if slab length is increased.

Prefabricated slabs or frames connected to a treated base using sealant mortars. 30 years of experiences concerning prefabricated slabs (equipped with up to 10 fastening systems per rail) connected to a rigid base using sealant mortars have been collected on the Shinkansen lines in Japan. In this case the rigid base was usually given by bridge decks. A first test-section in Germany has been built 1977 near Munich showed good long term performance thus far. Prefabricated slabs were not fit in the past for the competition in the railway track market because of high production and installation costs. Using the experience in fully-automatic, computer aided production of prefabricated concrete parts the Max Bögl company, Germany, renewed this slab track technology and had now successful installations (35km double track) of prefabricated, prestressed (in transversal direction only) slabs on a cement treated base (CTB) within the new high-speed line Nuremberg-Ingolstadt (see fig. 10).

The track alignment is implemented into the prefabricated 6,45m long slabs (ten rail seats) by exact grinding of the pre-formed rail seats itself. At the construction site the slabs are exactly positioned by special lift quoins (see fig. 10) and coupled in longitudinal direction to activate the benefits of a CRCP. After filling the horizontal gap between the slab and the treated base, which can be 30 cm asphalt or cement treated base layer, with a special, bitumen modified mortar the coupled joints between the slabs are working as prestressed joints.

Fig. 10: Nuremberg-Ingolstadt opened 2006; System "Bögl".

Discrete rail seats or embedded rails on CRCP. Main characteristic of the following systems is not to use sleepers as an element to reach the exact gauge and rail inclination. The elastic rail-fastening-systems are directly connected to the CRCP or implemented, respectively. It is essential to avoid transversal cracks at the positions of the dowels of the fasteners, which requires controlled cracking of the concrete pavement by saw cuts after every e.g. third or fourth rail seat (see fig. 11 and fig. 12). This technology has been applied only within test sections (about 400m each), which were installed in 1996 showing a good long term behaviour up to now.

By using slip form paving technology it is very challenging to meet the very tight requirements concerning the exact position of the fastening systems. The most ambitious approach was to pave the CRCP surface according to the shape of the sleeper for direct fixation of the fastening system (see fig. 12). Of course many small adjustments and corrections within the fastening system or the concrete surface were needed to get the correct alignment of the rails. Therefore measures for those vertical and horizontal adjustments must be implemented into the track design. One measure is to grind the pavement surface at the position of the fastening systems and to use fastening systems, which enable respective horizontal adjustments (see fig. 13).

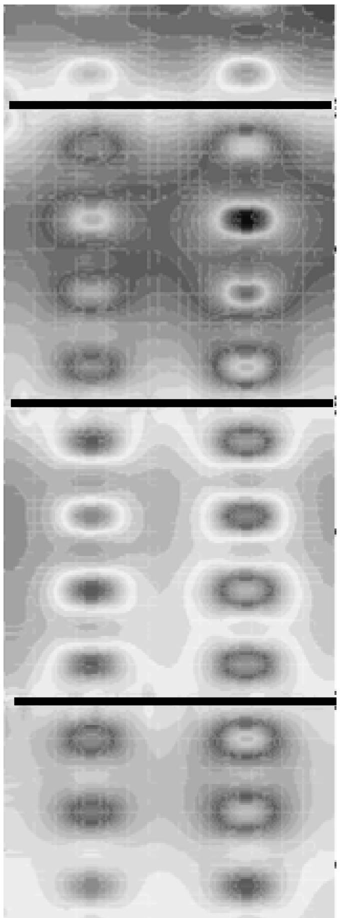

Fig. 11: Ballastless track with discrete rail seats on a continuously reinforced concrete pavement with dummy joints (controlled transversal cracking). Test section near Waghäusel.

Fig. 12: Distribution of bending tensile stresses within longitudinal direction of a 36 cm thick concrete pavement (controlled cracking in a distance of a = 2,60m) with discrete rail seats. Loading by load scheme 71.

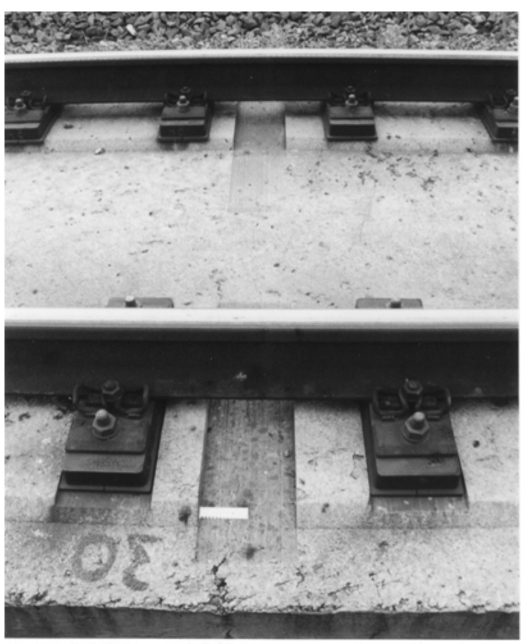

Fig. 13: Ballastless track with discrete rail seats on a JRCP. Exact support of the fastening systems had been provided by grinding of the concrete pavement.
Test section near Waghäusel.

To reduce sealing and coverage of natural areas by ballastless tracks for railway infrastructure the CRCP-slab itself can be minimized just up to two continuously reinforced concrete beams for support and fixation of the fastening systems (see fig. 14). To reach sufficient water permeability the cement treated base layer is replaced by a special slab made of drainable concrete. The drainable concrete layer is additionally equipped with transversal reinforcement to avoid changes within track gauge in case of occurrence of longitudinal cracks, which should first of all be avoided by sufficient thickness design of the drainage concrete layer. The cross-section areas between and beside the beams are filled with gravel and a substratum which gives the nutrient medium for the special grass seeds. Reduction of noise emission compared to tracks with a plain concrete or asphalt surface gives an additional positive effect. That kind of green tracks became very popular for urban transportation systems like tramways. Numerous designs using discrete rail seats or continuously embedded rails were developed in the last years.

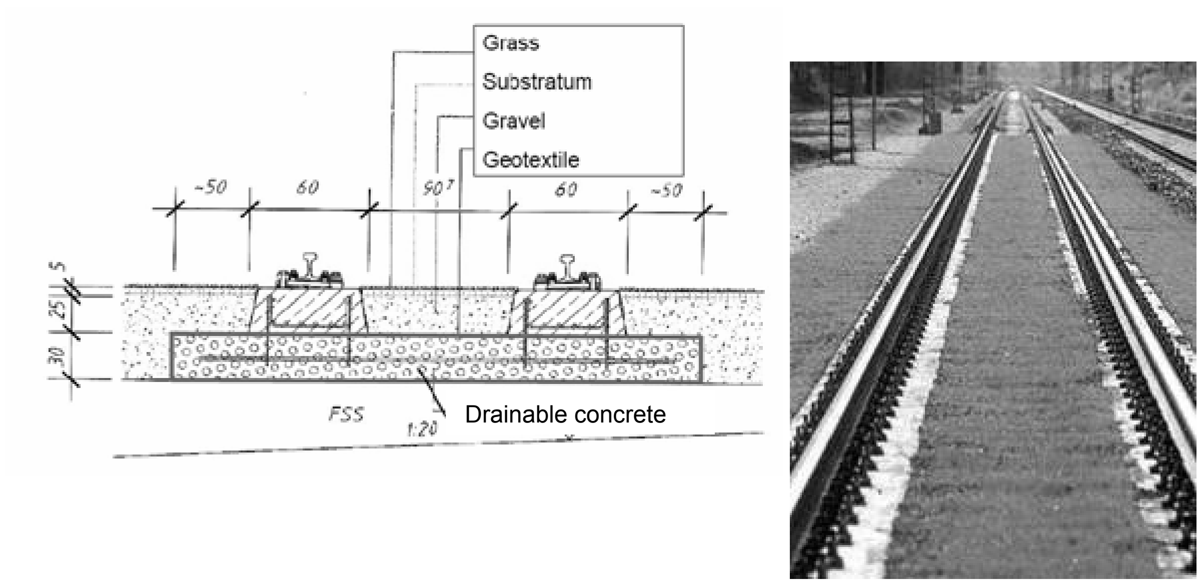

Fig. 14: Green track for main lines and urban transport; Main-line test section in Waghäusel opened 1996

Embedded rail technology is aimed at a continuous elastic rail support without any rail fastening systems. The CRCP built by slip form paver is equipped with two u-shaped pockets in rail axis. Minimum thickness of the CRCP beneath those rail pockets is 20 cm. Continuous elastic rail pads and rails are inserted into the pockets, fixed in the exact height, position and rail inclination and than filled with a elastic Polyurethane-material. It must be guaranteed, that horizontal and vertical loading to the rail will be transferred to the CRCP by the elastic rail embedment and respective bond conditions among all components. A main-line test-section had been installed and is in service near Waghäusel since 2001 (see fig. 14).

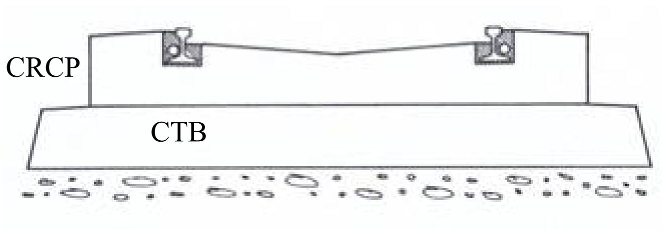

Fig. 14: Embedded rail main line test-section in Waghäusel opened 2001

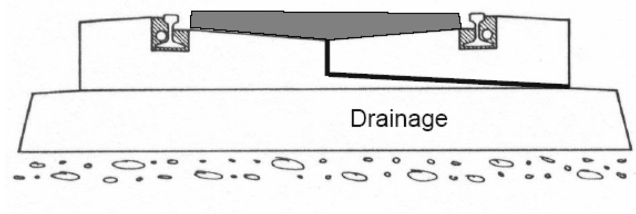

Fig.15: Greening of the surface by embedded rail systems (here tramway application)

Conclusion

Proven concrete pavement technology is an important platform for many ballastless track designs. Research on concrete pavement applications for ballastlass tracks has to foster ongoing improvements concerning quality and cost effectiveness to open new markets not only for new high speed or urban transportation networks. The rebuilding of conventional tracks into ballastless tracks is one field of activity in the near future.

Synergetic effects of road and railway superstructures can be utilized taking into account additional but tightened requirements of railway tracks. Based on more than three decades of experience on ballastless tracks it is recommended to handle the interface between prefabricated track-parts (usually railway components) and layers paved in situ (road paving technology) with special care.

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