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SCIENTIFIC REPORT

Ballastless Track

Minimizing the Climate Impact

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Report ACE-2021:2
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Institutionen för arkitektur och samhällsbyggnadsteknik
Chalmers tekniska högskola, 2021

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Cover:
The track shown on the cover page is located in Edinburgh, UK, and links the airport with the city center. It covers a distance of 14 kilometers and has 15 stops. It was opened in 2014. The use of the picture on the cover page of this report is permitted by RAIL.ONE.
Department of Architecture and Civil Engineering
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ABSTRACT

Railway transportation is becoming increasingly important for transport of passengers and goods in Sweden, Europe and many parts of the world. Ballastless (slab) railway systems are increasingly in use; however, their construction is known to cause a substantial climate impact.

The objective of this study was to investigate possible methods to reduce greenhouse gas (GHG) emissions of slab tracks and to provide required knowledge to identify the methods with high potential for further development. The approach adopted in this study consists of two steps. First, a comprehensive literature study was carried out, including a survey of existing methods for reducing GHG emissions for slab tracks, and of those which require further research. These methods are presented and assessed with respect to criteria related to potential benefit, possibility to use in large volumes, quality assurance and cost.

In the second step, recommendations are made on which of the different methods of reducing GHG emissions are suitable to further develop in future projects. Two uncertainties identified for all methods are related to quantification of potential benefits and the associated costs. Nonetheless, *structural optimization* of slab tracks is found to have potential to reduce the climate impact quite substantially, with the smallest risks associated. The most promising methods for structural optimization includes: geometry optimization to focus on the use of material where it is structurally most effective; stiffness optimization to reduce the energy consumption of trains; prestressing of concrete to minimize crack width; and employing steel fiber reinforced concrete to control cracks and reduce the use of traditional reinforcement. Three solutions combining these methods in different ways are suggested for future studies. Furthermore, methods related to the use of *alternative binders & materials* are also recommended to reduce the climate impact; however, it is noted that such methods in general exhibit larger uncertainties than structural optimization. Of the alternatives focusing on *alternative binders & materials*, the following were evaluated to be most promising: textile reinforcement, other cement types (e.g. CSA, BCSA & BYF cements) as well as optimized mix design of concrete. It is to be noted that the three suggested solutions based on *structural optimization* can also benefit from the use of *alternative binders & materials*. To sum up, combination of several methods is required to minimize the environmental impact, as in the suggested solutions. The needs for future investigation for each solution are also identified in the report.

The project contributes to the overall goal of *increasing consideration for the environment and climate* by providing knowledge and road map on how GHG emissions can be reduced for slab tracks.

Key words: Ballastless (slab) tracks, concrete, GHG emission, climate impact, railway

Ballastfria spår - minimerad klimatbelastning

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SAMMANFATTNING

Järnvägstransporter av passagerare och gods blir allt viktigare i Sverige, Europa och många delar av världen. Ballastfria spårsystem används alltmer, men de är kända för att orsaka en betydande klimatpåverkan vid produktion.

Syftet med denna studie var att undersöka möjliga metoder för att minska utsläppen av växthusgaser från ballastfria spårsystem och att samla nödvändig kunskap för att identifiera metoder med stor potential för vidareutveckling. Arbetet i studien har utförts i två steg. Först genomfördes en omfattande litteraturstudie där metoder för att minska växthusgasutsläppen för ballastfria spårsystem kartlades - både befintliga metoder och sådana som kräver ytterligare forskning. Dessa metoder presenteras och bedöms med hänsyn till kriterier relaterade till potentiell nytta, möjlighet att använda i stora volymer, kvalitetssäkring och kostnad.

I det andra steget rekommenderas vilka av de olika metoderna för att minska utsläppen av växthusgaser som är lämpliga att vidareutveckla i framtida projekt. Potentiella fördelar och tillhörande kostnader gick inte att kvantifiera, då det för alla metoder fanns för stora osäkerheter. Det var dock möjligt att bedöma vilka av metoderna som är mest lovande. *Konstruktiv optimering* av ballastfria spår var den övergripande metod som bedömdes ha potential att minska klimatpåverkan väsentligt, med de minsta riskerna. De mest lovande metoderna för konstruktiv optimering inkluderade: geometrisk optimering, som innebär att material används där det konstruktivt är mest effektivt; optimering av styvheten, som tar hänsyn till tågens energiförbrukning; förspänd armering för att minimera sprickbredden; och användning av stålfiberarmerad betong för att kontrollera sprickor och minska nödvändig traditionell armering. Tre lösningar som kombinerar dessa fyra metoder på olika sätt föreslås för framtida studier. Dessutom rekommenderas metoder relaterade till användning av *alternativa bindemedel och material* för att minska klimatpåverkan - det är dock värt att notera att dessa i allmänhet uppvisar större osäkerheter än konstruktiv optimering. Av alternativen som fokuserar på alternativa bindemedel och material bedömdes följande vara mest lovande: textilarmering, andra cementtyper (t.ex. CSA-, BCSA- och BYF-cement) samt optimering av betongrecept. Det bör noteras att de tre föreslagna lösningarna baserade på konstruktiv optimering också kan dra nytta av användning av alternativa bindemedel och material, och optimerade betongrecept. Sammanfattningsvis krävs en kombination av flera metoder för att minimera miljöpåverkan, som i de föreslagna lösningarna. Behovet av framtida forskning och utveckling för varje förslag har identifierats och beskrivits.

Projektet bidrar till det övergripande målet att öka miljö- och klimathänsyn genom att tillhandahålla kunskap och en färdplan för hur klimatpåverkan från ballastfria spår kan minskas.

Nyckelord: Ballastfria spår, betong, utsläpp av växthusgaser, klimatpåverkan, järnväg

Contents

Preface

This study was initiated by the Swedish Transport Administration. It was carried out from January 2020 to June 2021. Kamyab Zandi (Chalmers) authored Chapters 1-3 as well as Chapters 5 and 6; and Karin Lundgren (Chalmers) and Ingemar Löfgren (Chalmers & Thomas Concrete Group) authored Chapter 4. We gratefully acknowledge valuable contribution from Ignasi Fernandez (Chalmers) for subchapter *4.1.5 Recycled concrete as aggregates*. Furthermore, the contribution of Tang Luping (Chalmers) in form of discussions, comments and inputs are much appreciated. Last but not least, the fruitful discussions and guiding advise from the members of the reference group of the project are greatly acknowledged: Martin Schilke (Trafikverket), Veronika Sarik (Trafikverket), Emil Aggestam (Chalmers), and Jens Nielsen (Chalmers).

1 Introduction

Mobility through railway network is a major mode of transportation in Sweden and it is becoming more attractive all across the world. The railway system requires a complex infrastructure which consists of several elements. The operational and logistic challenges also augment the complexity of the system. The design service-life of railway infrastructure may be beyond hundred years, and it is a function of several factors such as construction type, construction material, traffic load and speed, climate conditions, operational variables and maintenance program, just to name a few. During the service life, maintenance and rehabilitation of deteriorated or damaged elements are vital to ensure proper functionality and safety of the railway network (Remennikov and Kaewunruen, 2008).

Among the existing railway infrastructure types, there are two popular construction systems: ballasted and ballastless (slab) tracks. Ballasted tracks consist of a *substructure* laid on crushed aggregates and capping/structural layers, and a *superstructure* supporting a combination of sleepers, rails, and fixings (Manalo *et al.*, 2010). Slab tracks however employ a concrete slab system and special fixings to support the steel rails which transfer the loads from passing trains to the concrete slab (Krezo *et al.*, 2016).

Slab tracks are often assumed to be superior to ballasted tracks due to their improved stability, less frequent maintenance, reduced thickness and longer service life (Michas, 2012). However, slab tracks exhibit higher construction costs, and are known to have larger greenhouse gas (GHG) emission, both primarily caused by the increased use of concrete and steel materials. Ballasted tracks have been employed in railway networks since the early 1800s and are still very common; however, the popularity of slab tracks have grown over the last few decades primarily due to improved performance and lower maintenance costs over the entire life cycle of the railway system (Michas, 2012).

Ballasted tracks have been subjected to major improvements and advancements in twentieth century (Indraratna *et al.*, 2017). Nonetheless, for railway networks to remain a competitive mode of transportation in the coming years, the slab track technology needs to be further evaluated and improved (UIC - International Union of Railways). Today, there is no consensus on whether slab track or ballasted track is a more beneficial construction type over the full lifecycle of the railway network. This is influenced by several different considerations, for instance operational conditions, maintenance requirements, technical features as well as environmental impact of the railway system (Aggestam, 2018).

Global warming and climate change have led to increasing concerns regarding GHG emissions in railway systems (Baron *et al.*, 2011), and life cycle analysis has become an essential part of the design procedures for the development of railway systems (Chester and Horvath, 2009). As a direct result of such concerns, the choice of railway construction types is much influenced by the anticipated GHG emissions. In recent years, the environmental impact of railway systems has gained much attention among research scholars as well as policy makers, and our knowledge and understanding of methods to reduce GHG emissions of railway constructions have substantially improved (Kiani, Parry and Ceney, 2008) and (Milford and Allwood, 2010).

The current study was carried out with the main objective to identify the most effective and practically viable methods of reducing GHG emissions caused by slab track systems. This was done by a comprehensive survey of the relevant body of literature, followed by a systematic evaluation of the state-of-the-art methods, and finally by providing further recommendations on future research directions. The provided recommendations can then be used for research and development projects targeting development of certain methods, tools and procedures.

The objective of this study was to investigate possible methods to reduce GHG emissions of slab tracks and provide needed knowledge to identify the methods with large potential for further development. To this aim, *Chapter 2* of the present report gives an overview of the two most important railway construction types, ballasted and slab tracks, and discusses major parameters contributing to GHG emission for slab tracks. *Chapter 3 and 4* present methods by which the environmental impact of slab tracks can be minimized, namely through structural optimization and the use of alternative binders and materials, respectively. In *Chapter 5*, different methods of reducing GHG emissions of slab tracks are assessed with respect to certain criteria providing the needed knowledge to identify solutions with significant potential for further development which are presented in *Chapter 6*.

2 Railway construction type and GHG emission

2.1 Railway construction type

Among the existing railway infrastructure types, there are two popular construction systems: ballasted and ballastless (slab) tracks. When comparing the two construction types several technical, economical, and environmental factors need to be taken into account. A major advantage with slab track systems is the need for less maintenance work; therefore, they are more accessible and more effectively utilized during the life cycle of the railway network (Michas, 2012). Furthermore, slab tracks provide an overall stiffer track structure which is more suitable for high speed trains. On the other hand, ballasted tracks are known to have a higher deterioration rate, primarily because the track structure exhibits less stiffness in both lateral and longitudinal directions due to the discrete supports by sleepers (Aggestam, 2018). Further, the ballast in certain areas may be dislocated due to sustain loading resulting in an uneven sleepers' support (Esveld, 2001). The uneven support by the ballast, combined with dynamic loads from vehicles, cause movements of the sleepers which induce ballast degradation and differential track settlement (Aggestam, 2018). Last, drainage problems may be caused by wearing and fracturing of ballast (Esveld, 2001).

For high speed trains, the requirements on the track design become even tougher to meet. In order to fulfil such requirements for certain geographical settings, more tunnels and bridges are needed for which slab track systems are better suited given their smaller overall thickness (Esveld, 2001). From full life-cycle cost standpoint, a common understanding is that slab track systems require a larger initial investment during construction, but much less maintenance costs during the service life (Michas, 2012).

Above all, a well-functioning and sustainable rail transport infrastructure is crucial for our mobility network, and slab tracks are among very few railway construction systems that are promising. Nonetheless, construction cost and climate impact of slab track systems remain major concerns. The latter is the primary focal point in this report.

2.2 Ballasted tracks

A ballasted track is made up of the rail, the fastening system, sleepers, ballast and capping/structural layer; see Figure 1. The system needs to carry the traffic and to resist the climate so that the subgrade is adequately protected and that the performance of the track is effectively supported during the design life. A primary function of the layers that make up the track sub-structure is the distribution of wheel/rail contact forces in order to ensure that the stresses in the subgrade are at a satisfactory level. The use of geosynthetics within this structure can significantly reduce track substructure renewal costs as well as enhancing its performance, reducing maintenance costs and increasing the lifetime of the design. The track sub-structure is the foundation that supports the track and facilitates drainage.

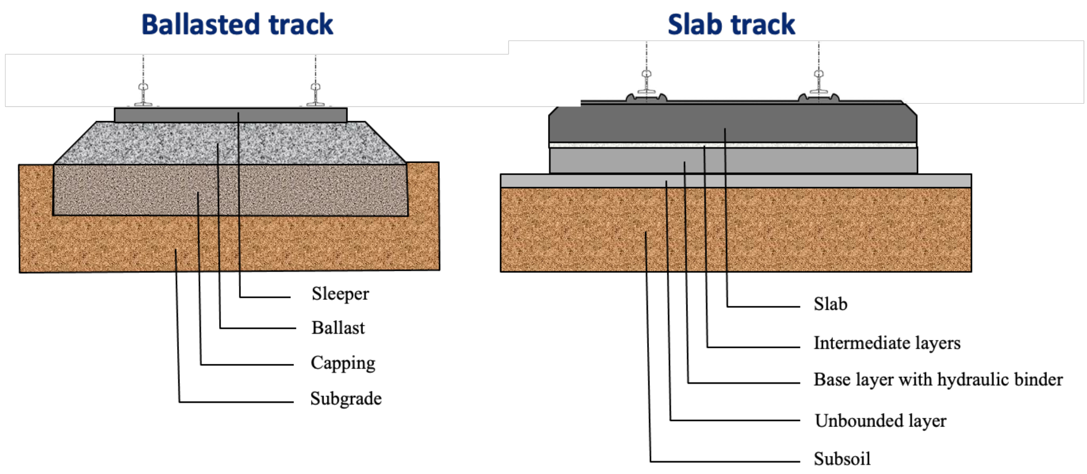


Figure 1. Schematic illustration of Ballasted track and slab track foundation

A ballasted track foundation comprises of the following layers:

- Ballast: is the free draining granular material placed at the top of the substructure layer in which the sleepers are embedded. It is typically a uniform particle size of approximately 60 mm.
- Capping/structural Layer: Capping layers and structural layers are well-graded natural or artificially blended gravels/soils which have sufficient fine aggregates to permit compaction to high densities. Their function is to improve load spreading and increase track stiffness, as well as providing a free draining formation.
- Subgrade (Natural ground): The subgrade is the upper part of the earthworks or natural ground upon which the capping layers and ballast layers are placed. The subgrade is the most inconsistent and potentially weakest component of the track, yet it is the foundation on which all other components are supported.

There are various mechanisms that can result in a failure of the track, and although there may be links between each, they must be viewed independently in order to establish the most effective way to treat them. There are four common types of ballasted track failure: Ballast Deterioration; Mud pumping Failure; Capping Layer Failure; and Subgrade Failure.

Ballast Deterioration – Rail ballast is subjected to repeated loading under traffic and mechanical maintenance. As it ages, it breaks down gradually until the voids become filled with fine aggregates. This reduces the effectiveness of tamping and the ballasts ability to drain, however the track geometry is not significantly impacted until the fine aggregates reduce the permeability to the point at which the pore water pressure is unable to dissipate under vehicle loading. This is a particular problem when ballast is saturated under heavy rainfall. This type of failure is often characterized by wet spots and the deterioration of track geometry. Fine aggregates deposited from other environmental factors such as wind, freight and coal dust can add to the problem.

Mud Pumping Failure – Mud pumping occurs as a result of cyclic loading on ballast in contact with a fine-grained subgrade, such as silts or clays, which when mixed with water is pumped upwards. This is due to the repeated loading and unloading of the sleepers. The outcome of mud pumping is similar to ballast deterioration, i.e. loss of track geometry, formation of “slurry” and the appearance of wet spots. When the “slurry” migrates towards the base of the sleepers the load-bearing functionality of the ballast can be significantly compromised. At this point, the failure in the ballast performance, reduction in track modulus and consequential reduction in bearing capacity cannot be rectified by tamping. The rate at which mud pumping develops will vary with drainage being a determining factor. If ballast is placed upon a susceptible subgrade, with poor drainage, mud pumping can develop quickly under trafficking. Even with good drainage, mud pumping cannot be rectified without a modification to the track substructure to inhibit the upwards migration of "slurry".

Capping Layer Failure – The capping layer is a well compacted layer of road base material between the formation and the ballast. The capping layer is designed to prevent water entering the formation from above and to stop small particles of silts and clays from migrating upwards into the ballast. Instability of the track's capping layer can be attributed to a weak subgrade, inadequate capping layer, inadequate thickness of the ballast layer, presence of expansive soils and poor drainage. All these issues could result in subgrade shear failure, ballast pocket formation, mud pumping or ballast heaving.

Subgrade Failure – Subgrade strength failure results in heaving of the ballast shoulders due to a rotational failure which occurs between the base of the ballasted tack layers and the ground surface. This heaving can occur on both sides of the track foundation although the final movement usually occurs only on a single side accompanied by loss of level on one rail.

2.3 Slab tracks

2.3.1 Major parameters contributing to GHG emission

In discrete rail support systems, which are the systems that dominate high-speed slab track lines, the rail is supported at discrete, equidistant locations. Discrete rail support systems can be further divided into systems with or without sleepers (Esveld, 2001).

When sleepers are used, they are either embedded in the slab or placed on top of the slab. One of the most popular designs with sleepers embedded in the slab is the so-called Rheda system (Esveld, 2001), which consists of a concrete filigree twin-block design ensuring a precise location of the rails. The sleepers are embedded in a concrete slab, which is supported by a hydraulically bound layer (HBL). Today, the system has successfully been installed in Germany, the Netherlands, Taiwan and Korea (Gautier, 2015). This system and prefabricated slab track systems are commonly called compact systems, since the height from slab track base to rail head is less than 0.5 m.

When sleepers are not used, prefabricated concrete slabs or monolithic slabs are used. Continuous monolithic slab track structures, which are particularly well suited on civil structures such as bridges, are not built in any larger scale for high-speed railway lines. When comparing prefabricated slab track systems to other slab track designs, the main advantages are that prefabricated systems are maintenance friendly, have a high quality due to a high level of automation and a short construction time. A brief summary of the most wide-spread prefabricated slab track systems is presented in (Aggestam, 2018).

Both concrete and steel are known to have high contribution to GHG emissions. Therefore, using less steel and concrete and using more recycled steel and recycled concrete, as well as improving recycling techniques are among major methods for reducing environmental impact of slab tracks (Pons *et al.*, 2020). If, upon improved design and the use of alternative binders and materials, the service life of slab tracks are prolonged beyond 75 years, the environmental impacts are reduced significantly, even less than that of ballasted tracks (Pons *et al.*, 2020)

2.3.2 Material usage

Most material parameters can be derived from the regulations and from experience gained through roadbuilding. Generally, the principle of a modulus of elasticity that decreases from top to bottom is assumed when designing slab track. Layer thicknesses and widths result from the respective design steps. It should be mentioned that when dimensioning the layers, owing to the load distribution (assumption of 45°) and the maximum vertical stresses in the non-bonded layers, the layer widths increase from top to bottom. Figure 2 shows a generalized system arrangement for a slab track on terrain.

The subsoil, or substructure, consists of the in-situ soil or fill material. Calculations according to (Heukelom and Klomp, 1962) are suitable for analyzing the allowable vertical compressive stresses base on the top surface of the subsoil. In addition, (Heukelom and Klomp, 1962) refers to the importance of drainage, both in the base layers and in the substructure. This means considering not only surface water, primarily due to precipitation, but also water that can move through the subsoil and reach the slab track structure. According to the earthworks regulations of *Deutsche Bahn*, the slab track structure should be designed so that water cannot normally rise higher than 1.50 m below the top-of-rail level.

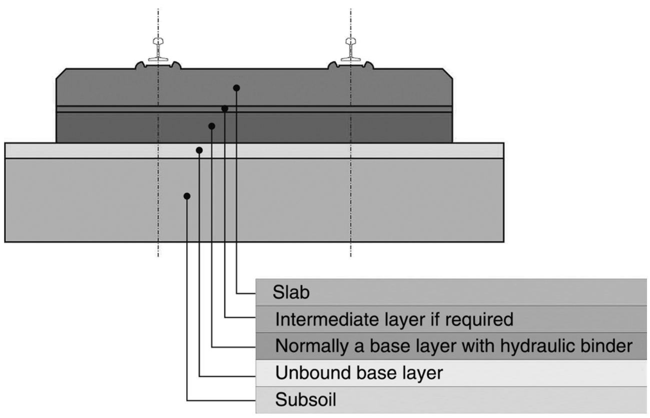


Figure 2. Typical section through slab track supported on terrain (source: Institute of Road, Railway and Airfield Construction, Technical University of Munich, Fiedler)

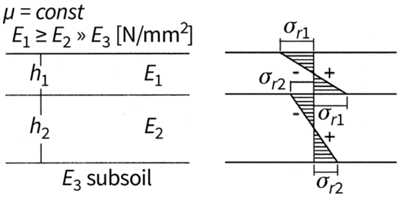
In order to guarantee that the slab track remains protected against the effects of frost, an unbound base layer is laid over subsoil that can be affected by freezing temperatures. This unbound base layer can be provided in the form of ballast, gravel or a frost protection layer, and can be made up of several layers if necessary.

2.3.3 Design principles

The Theory of Winkler's beam on resilient support can be applied to a continuously supported track panel situation, with the requirement that owing to the adequate load distribution for high-speed rail traffic, the concrete sleepers must be at least 2.6 m long. When designing a system with individual rail seats, considering the slab on resilient foundation (or 'slab on springs') is recommended. As biaxial stresses must be considered here, it is therefore necessary to examine tensile bending stresses in the longitudinal and transverse directions (or radial and tangential directions). The principle of design is outlined below for two popular systems.

System I without bond between layer 1 and layer 2

$\mu = const$



1) Fictitious bedding modulus

$$k = \frac{E_3}{h^x} \text{ [N/mm}^3\text{]}$$

$$h^x = 0{,}83 \cdot h_1 \cdot \sqrt[3]{\frac{E_1}{E_3}} + c \cdot h_2 \cdot \sqrt[3]{\frac{E_2}{E_3}} \text{ [mm]}$$

$c = 0.83$ for hydraulic binder
$c = 0.90$ for bituminous binder

2) Thickness of the equivalent system with equal stiffness for $E = E_1$

$$h_I = \sqrt[3]{\frac{E_1 \cdot h_1^3 + E_2 \cdot h_2^3}{E_1}} \text{ [mm]}$$

3) Determination of M_I for the equivalent system (k, h_{II}, E_1) after *Westergaard*, or *Pikett & Ray*

4) Bending stress in layer 1 and layer 2

$$M_1 = M_1 \cdot \frac{E_1 \cdot h_1^3}{E_1 \cdot h_1^3 + E_2 \cdot h_2^3} \text{ [N} \cdot \text{mm]}$$

$$M_2 = M_I \cdot \frac{E_2 \cdot h_2^3}{E_1 \cdot h_1^3 + E_2 \cdot h_2^3} \text{ [N} \cdot \text{mm]}$$

$$\sigma_{r1} = 6 \cdot \frac{M_1}{h_1^2};\ \sigma_{r2} = 6 \cdot \frac{M_2}{h_2^2} \text{ [N/mm}^2\text{]}$$

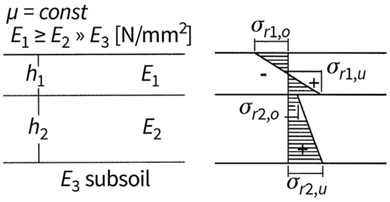
5) Elastic length (slab)

$$l_1 = \sqrt[4]{\frac{E_1 \cdot h_1^3}{12 \cdot (1 - \mu^2) \cdot k}} \text{ [mm]}$$

where Poisson`s ratio μ is
$\mu_{concrete} = 0.15$
$\mu_{(asphalt)} = 0.50$

System II with bond between layer 1 and layer 2

$\mu = const$



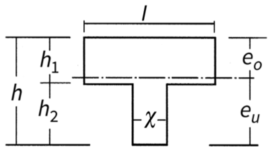
1) Fictitious bedding modulus equally to system I

2) Thickness of the equivalent system with equal stiffness for $E = E_1$

$$h_{II} = h_1 + 0{,}9 \cdot h_2 \cdot \sqrt[3]{\frac{E_2}{E_1}} \text{ [mm]}$$

3) Determination of M_I for the equivalent system (k, h_{II}, E_1) after *Westergaard*, or *Pikett & Ray*

4) Bending stress in layer 1 and layer 2 determined for a T-beam of equal stiffness



$$\chi = \frac{E_2}{E_1};\ E = E_1$$

$$I = \Sigma\,(I_i + F_i \cdot x_S^2);\quad e_o = \frac{\Sigma F_i \cdot x_i}{\Sigma F_i}$$

I = Moment of inertia of T-beam [mm⁴ per mm]

$$e_o = \frac{h}{2} \cdot \frac{E_2 \cdot h_2}{E_1 \cdot h_1 + E_2 \cdot h_2} + \frac{h_1}{2} \text{ [mm]}$$

$e_u = h - e_o$ [mm]

$$\sigma_{r1,o} = \frac{M_{II}}{I} \cdot e_o;\ \sigma_{r1,u} = \frac{M_{II}}{I} \cdot (h_1 - e_o) \text{ [N/mm}^2\text{]}$$

$$\sigma_{r2,o} = \chi \cdot \frac{M_{II}}{I} \cdot (h_1 - e_o);$$

$$\sigma_{r2,u} = \chi \cdot \frac{M_{II}}{I} \cdot e_u \text{ [N/mm}^2\text{]}$$

5) Elastic length (slab)

$$l_{II} = \sqrt[4]{\frac{E_1 \cdot h_{II}^3}{12 \cdot (1 - \mu^2) \cdot k}} \text{ [mm]}$$

Figure 3. Method for calculating the bending stresses in a three-layer system consisting of slab and a base layer with a hydraulic binder with and without bond on an resilient support (Freudenstein *et al.*, 2017).

3 Reduction of GHG emission by improved design

3.1 The effect of track stiffness

Track-vehicle interaction (TVI) describes the effect of track structural and surface properties on energy consumption of the vehicle. While the mechanics of TVI are not well understood, previous research has shown that it is a potentially important part of the track life cycle, especially for high-speed tracks (Santero and Horvath, 2009). Various empirical studies have looked into the impact of track deflection on energy consumption of the vehicle; however, their main focus has been on a binary view of construction type, with no consideration of the relationship between track deflection and its structure and material; see (Grossoni *et al.*, 2021) and (Milne *et al.*, 2021).

Even though the effect of TVI on vehicle fuel consumption is small, its impact within a full track life cycle can be significant due to the large number of vehicles that travel over time. The change in vehicle fuel consumption between pavement structures due to TVI becomes increasingly important for high volume traffic and can surpass energy consumption and emissions due to construction and maintenance of the rail systems in its lifetime. In general, deflection of a track is considered as the main contributors to track-vehicle interaction (Santero and Horvath, 2009). This section focuses on latter phenomenon, i.e. the impact of deflection on TVI and its relation to fuel consumption.

There are several methods for modelling the dynamic response of a track to moving loads. The track can be modelled as a beam, a plate, or the top layer of a multilayer soil system. The substructure can also be modelled as a system of elastic springs with dashpots, or a homogeneous or layered half-space. There are also various methods of modelling the track material behavior: elastic, viscoelastic or even inelastic. The loads are either presented as concentrated loads, or distributed loads with a finite width. These conditions define the model and the predicted response, under certain material and structural conditions. The tracks deflection response can be calculated through analytical or numerical methods such as the Finite Element Method (FEM), or the Boundary Element Method (BEM). (Beskou and Theodorakopoulos, 2010) reviewed various models and solution strategies in more detail.

In (Santero, Masanet and Horvath, 2011), the deflection response of a beam to a moving load on an elastic, damped, and a viscoelastic subgrade has been extensively studied. This model is coming into attention recently in railway and highway industries, as it is one of the simplest models and it provides a basic understanding of various factors within the structural system (Sun, 2001). Figure 4 displays a schematic representation of this system.

The beam on an elastic foundation represents various properties of a slab. It draws a relationship between elastic modulus of the top layer E_t, mass per unit length m, and subgrade modulus E_s (referred to as k in the literature), along with the structural property of moment of inertia I, with deflection y under an external load of $q(x,t)$. By assuming a moving coordinate system on the load (vehicle axel), a relationship between deflection under (and at distances away from) the load can be calculated. The governing equations of a beam on an elastic foundation are presented in (Akbarian, 2012) in more detail.

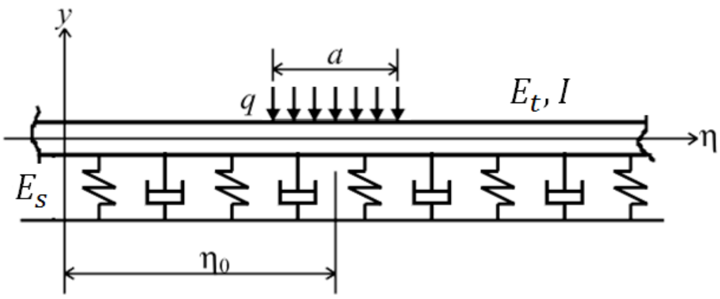


Figure 4. Schematic representation of a beam on damped elastic foundation under line load (Akbarian, 2012).

Relation between track stiffness and energy consumption – As stated, the beam on damped elastic foundation is an idealized model and allows first-order understanding of the importance of different input parameters and their impact on pavement deflection. The main input parameters that correspond to the slab structure and material, along with its response to an external load are:

- M: Loading weight
- E_t: Top layer elastic modulus
- E_s: Subgrade modulus
- h: Top layer thickness

It can be observed from the equations of a beam on damped foundation and from the model, that deflection, w, have the following relations with the above parameters:

$$w \sim M^1 \, E_t^{-1/4} \, E_s^{-3/4} \, h^{-3/4} \qquad \text{(Eq. 1)}$$

The energy consumption of a vehicle is in a direct relationship with the resisting forces that it has to overcome while travelling on a track. By defining the gradient force, a link can be established between the instantaneous fuel/energy consumption (IFC) and the tracks properties as shown below (Santero, Masanet and Horvath, 2011):

$$IFC \sim M^2 \times E_t^{-1/2} \, E_s^{-1/2} \, h^{-3/2} \qquad \text{(Eq. 2)}$$

To illustrate the importance of such a relationship, various examples can be represented. For instance, if two tracks are assumed with the same subgrade modulus, and under the same load with modulus of elasticity of E_{t1} = 5,000 MPa and E_{t2} = 20,000 MPa , and the same energy consumption (IFC) is pursued, the equation above can be used to determine thickness ratios of the two pavements (Santero, Masanet and Horvath, 2011):

$$\frac{IFC_1}{IFC_2} = \frac{M^2 \times E_{t1}^{-1/2} \, E_s^{-1/2} \, h_1^{-3/2}}{M^2 \times E_{t2}^{-1/2} \, E_s^{-1/2} \, h_2^{-3/2}} = 1 \qquad \text{(Eq. 3)}$$

$$\frac{h_1}{h_2} = \sqrt[3]{\frac{E_{t2}}{E_{t1}}} = \sqrt[3]{\frac{20{,}000}{5{,}000}} = 1.6 \qquad \text{(Eq. 4)}$$

Therefore, there is a clear relation between the increased modulus of elasticity of concrete and the reduction in energy consumption. Geometry optimization and use of high strength concrete, among other methods, is then considered as a way to increase the modulus of elasticity of concrete.

3.2 The thickness of slab track system

Reducing the thickness of the slab tracks system will directly save on the use of materials, primarily concrete, and thus reduce the environmental impact. While minimizing the thickness, the functional properties of the slab track must be maintained. An important functional property is the railway vehicle and slab track dynamic interaction which needs to be studies and optimized.

Coupled vehicle–track dynamic interaction of slab tracks has been studied using models and numerical simulations. In such models, a large system of coupled equations of motion needs to be solved. (Nielsen and Igeland, 1995) introduced a procedure for computing the dynamic interaction using a complex-valued modal analysis for ballasted tracks. Later, the complex-valued modal superposition technique is applied to the slab track (Aggestam and Nielsen, 2020). The performance of the simulation procedure was illustrated by two demonstration examples, including a parametric study of the influence of two track design parameters when the slab track is supported by a gradient in soil stiffness; see details in (Aggestam, 2018) and (Aggestam and Nielsen, 2020).

The work of (Aggestam, 2018) concluded that with decreased thickness of a roadbed, the load on the foundation is distributed over a smaller area with an increased peak value for the load. Furthermore, it has been found that the influence of a foundation stiffness gradient on the load distribution on the foundation varies significantly depending on the considered roadbed thickness. Last, a lower rail pad stiffness reduces the bending moment in the panels.

Furthermore, (Aggestam *et al.*, 2021) presented a methodology to optimize slab tracks' cross-section and concrete class with the objective to minimize GHG emissions while fulfilling the requirements in the European Standard (EN 16432-2, 2017). The optimized track was analyzed using a 3D dynamic vehicle-track interaction model and a structural model of the reinforced concrete slab track. It was concluded that the thickness of slab track can be significantly reduced without the risk of cracking. The study best demonstrates the potential gains when targeted structural optimization are performed.

4 Reduction of environmental impact through use of material

In this chapter, the focus is put on how the environmental impact of slab tracks can be reduced by using alternative materials. Furthermore, possible alternatives to traditional concrete and reinforcement steel are discussed.

4.1 Concrete

4.1.1 Reducing CO_2 emissions from the cement industry

Cement production is responsible for large CO_2 emissions, globally 6% of total CO_2 emissions due to the large volumes used. Hence, this gives concrete a large environmental footprint in total, even though the emissions per kg is rather low compared to other materials. For concrete, roughly 85 to 90% of the emissions comes from the Portland cement clinker. The cement industry is well aware of the challenge and addresses that; e.g. Cementa has formulated a zero vision for CO_2 emissions over the product's life cycle by addressing these five areas (Cementa, 2020):

1. Improving energy efficiency e.g. by optimizing production
2. Replacing coal with alternative fuel sources, such as biomass
3. Using new cement types; i.e. replacing clinker with e.g. fly ash and slag.
4. Developing and implementing Carbon capture and storage (CCS)
5. Including carbonation in life cycle analyses, and increase carbonation speed by crushing used concrete.

The third area, new cement types and replacing clinker with fly ash and slag, will be treated more in the following of this report. The other four areas are considered to be outside the scope of this work, but can of course still be of major importance to reduce the environmental impact of concrete in general. Furthermore, others measures discussed in this chapter include: reducing cement using advanced nanotechnology, e.g. Functionalized Graphene Oxide (FGO), as well as recycled concrete as aggregates.

4.1.2 Replacing cement with slag

Ground granulated blast-furnace slag (GGBS) is a waste product in iron production. Replacing cement with slag reduces the environmental footprint, at least as long as the environmental cost for iron production is considered for the steel only. Current regulations (SS-EN 206 2013) and (SS 137003 2015) allow fairly high amounts of slag, while for infrastructures only lower amounts are allowed in Sweden (Ref: AMA Anläggning). A replacement level up to 65-80 % slag is possible with retained mechanical and resistance properties, except frost resistance which decreases at higher levels (about 40%); this is discussed more in detail further on. In general, the larger replacement level, the larger the environmental benefit; however, the greater the challenge to achieve a good and stable quality of the concrete. On the positive side though, high replacement levels reduce the porosity of the concrete and the risk of chloride-initiated corrosion of reinforcement, and improve the sulphate resistance. There is extensive experience on the use of slag in Europe. Even though the use is rather limited in Sweden today, historically slag cement has also been manufactured and used in Sweden.

Ongoing research aims at raising the quantities of slag to around 80% while maintaining mechanical and resistance properties. At such high levels, alkali or sulfate is added to start the reaction, so-called alkali-activated concrete. Note though that large shrinkage is a major remaining challenge for concrete with this high replacement level; this is therefore probably not suitable for ballastless tracks.

As mentioned, the frost resistance is decreased when high amount of slag is used, especially the resistance to salt frost scaling. This is linked to coupled deterioration mechanisms; carbonation or leaching alter the frost resistance. It is shown that the resistance to salt frost scaling decreases when concrete with high amount of slag is carbonated. Though, it has been found that the accelerated tests commonly used show a much more negative effect than what is experienced in field conditions. Hence, modifications to the test methods have been proposed. Test results show that exposing specimens to accelerated carbonation at a young age will result in an increased frost scaling. By increasing the age of test specimens to around 80 days before accelerated carbonation exposure, the frost scaling resistance is significantly improved. The salt frost scaling resistance measured in this way seems to correlate better with field observations. From experiments using this modified testing method (Löfgren, Esping and Lindvall, 2016) concluded that a GGBS content of about 30 to 40% is reasonable with respect to the salt-frost scaling resistance. For frost exposure with fresh water (XF3), results from field exposure indicate that higher slag dosages can have acceptable frost resistance (Boubitsas *et al.*, 2018).

4.1.3 Replacing cement with fly ash

Fly ash is a waste product from coal-fired power and heating plants, and consists of fine particles of burned fuel. The first modern use of concrete fly ash was in the 1930s. Fly ash and its effect on the characteristics of the fresh and hardened concrete are extensively treated in e.g. (ACI232.2, 2003). Fly ash shows a great variety, both due to different sources but also within the same source. Further, the reactivity also depends on the properties of the cement; pre-testing with the materials in question must therefore be carried out for each case. Similar as for slag, the larger replacement level with fly ash, the larger the environmental benefit; however, the greater the challenge to achieve a good and stable quality of the concrete.

Replacing cement with fly ash most often leads to a decreased risk of temperature cracks (Bjøntegaard, 2011). Frost resistance of concrete with moderate amounts of fly ash (up to about 25 %) is usually good and equivalent to concrete without fly ash.

4.1.4 Reducing cement using advanced nanotechnology, e.g. FGO

Functionalized Graphene Oxide (FGO) can be added to increase the strength. It forms covalent bonds with cement hydration products. (Wang *et al.*, 2020) showed that the bonding strength between cement and aggregates was improved more than 21 times, and that the early and ultimate strength of cement mortar samples increased up to 40 % by the addition of FGO.

4.1.5 Recycled concrete as aggregates

Waste concrete can be crushed and recycled as aggregates and applied either in new concrete or as filler material; this is denoted Recycled Concrete Aggregates (RCA). It can be noted that in contrast to the other alternatives discussed in this report, the reduction of greenhouse by the use of RCA depends on many factors, (e.g.

transportation distances, scenario for production, efficiency of recycling etc.), which makes its use very application dependent; however, it clearly contributes in the reduction of the use of raw material and at the same time in the reduction of the amount of Construction and Demolition Waste (CDW) generated. In this regard Sweden is very behind to the limits stablished by the community regulations of EU for 2020 (European Union Regulation, 2008), (European Aggregates Association, 2018), (Tam, Soomro and Evangelista, 2018) and (Arm *et al.*, 2014). Further, it can be noted that aggregate is relatively inexpensive and readily available in Sweden. This is likely a major reason why the use of recycled aggregates in concrete production is very limited in Sweden, while it is larger in many other European countries, where the codes and regulations allow even 100% of coarse aggregate replacement for any kind of application, structural or non-structural.

The highest proportions of recycled aggregate which may be used in concrete in relation to a given exposure class is specified in Swedish Standard (SS-137003, 2015). For instance, the maximum proportion (in mass fraction) of the coarse aggregate (> 4 mm) that may consist of aggregate from recycled residual materials is 50 % for concrete in exposure class X0.

Crushed concrete waste is already used in the Swedish construction industry, mainly for use in roads and parking areas, i.e. non-structural applications. Research in Sweden on RCA is related to processing methods, quality and applicability, with a focus on the material level (Molin, Larsson and Dahl, 2003), (Molin, 2005) and (Rogers *et al.*, 2016). The structural behavior of RCA concrete, in terms of flexural, shear and seismic behavior, has been reported to be comparable to concrete with natural aggregate, being able to fulfil relevant structural code requirements (Maruyama *et al.*, 2004), (Li, 2009), (Etxeberría, Marí and Vázquez, 2007) and (Gonzalez-Corominas, Etxeberria and Fernandez, 2017) . A lot of research has been conducted studying the structural behavior of RCA concrete sleepers (Gonzalez-Corominas, Etxeberria and Fernandez, 2017), (Remennikov and Kaewunruen, 2014), (Koh *et al.*, 2012) and (Manalo *et al.*, 2010). The results of such studies have proven that the use of this material in this specific application can perfectly fulfil the demands in terms of structural performance and durability. Not so extensive research can be found related to the use of such material in track slabs. However, being the structural requirements for sleepers and track slabs similar it can be assumed that the material is equally suitable for such applications (European Committee for Standardization, 2009).

4.1.6 Other cement types

There exist several alternative cements which rely on different raw materials compared to Portland cement and which have a lower environmental impact. Some of these alternative cements are commercially available while others are still under development. The papers by (Gartner and Hirao, 2015) and (Gartner and Sui, 2018), offers a comprehensive discussion of the alternatives to Portland cement clinker as the basis for hydraulic cements and the following alternative cements are mentioned:

- Calcium sulfoaluminate (CSA) cement
- Belite calcium sulfoaluminate (BCSA) cement
- Belite ye'elimite ferrite (BYF) cement
- Limestone Calcined Clay Cement (LC3[1])

[1] https://lc3.ch/

Calcium sulfoaluminate (CSA) cements is composed of the following main phases: ye'elimite (Ca_4 $(AlO_2)_6$ SO_3); belite (C_2S); and gypsum. CSA show rapid setting properties and a high degree of early strength development (Gartner and Hirao, 2015). However, as Bauxite is used as a raw material it leads to high production costs but the CO_2 emissions from production are significantly lower compared to Portland cement clinker. At present the annual global CSA cement production is around 2 Mio. t, the majority of which is produced in China (ECRA, 2017). Recently research was started in Germany to investigate the potential of CSA cement for production of railway sleepers, see (Dienemann *et al.*, 2013).

Belite calcium sulfoaluminate (BCSA) cement is an extension of CSA cement technology. Combining the binding properties of ye'elemite with belite, the compound in Portland cement responsible for later strength development, BCSA was developed to improve the durability of CSA cements, while offering a lower environmental footprint than ordinary Portland cement. This leads to reduced CO_2 emissions from its production (Gartner and Hirao, 2015) compared to Portland cement. BCSA cements are increasingly being used in special applications where high early strength and shrinkage compensation are required.

Belite–ye'elimite–ferrite (BYF) cement is an alternative type that circumvent some of the disadvantages of CSA cement, while still having the potential for low-CO_2 emissions. Recent research, mainly in Europe (Dienemann *et al.*, 2013), have focused on systems that are intermediate between "classical" CSA cements and belite-rich Portland cements (Gartner and Hirao, 2015). The composition range of such binders is not yet formally defined by any standards, but they can be said to lie at or below the low-CSA end of the range of binders recognized in the Chinese CSA cement norms.

Another promising material is calcined clay which together with limestone can replace approximately 50% of the Portland cement in combination with limestone. Calcined clays (mainly metakaolin) can be used as Supplementary Cementing Materials (SCM) in concrete, but the replacement level is usually less than 10 %, higher replacement levels needs additional sulfate addition (gypsum) as the clays contain a high portion of alumina. Potential clays that can be used as a cement replacement material have been evaluated in a research project conducted at RISE (the Research Institute of Sweden) financed through the industry consortium (Plusquellec, Babaahmadi and Mueller, 2021). Clays are available in large quantities, however not all clays are suitable. Kaolinitic clays are those who have the best reactivity, but these are not found everywhere and is only found in south of Sweden. In the RISE project different clay minerals (Kaolinite, Illite, Smectite/Chlorite) was investigated to see which clays could be activated, how activation should be done and how reactive the different clays were. The glacial/post glacial clays were found to be a mix of Smectite, Illite and some Kaolinite and for this type of clays mechanical activation by grinding was more effective than calcination. All tested activated clays showed fairly good reaction when used in a ternary binder (cement, activated clay and limestone). Moreover, a satisfactory strength gain was achieved in mortar samples cast with activated calcined clay, but further investigation is needed. Furthermore, Limestone Calcined Clay Cement (LC3), where 40 to 50 % of the Portland clinker can be replaced and a CO2-reduction can be achieved with a performance similar to current available cements. However, research on durability and mechanical properties as well as structural behavior/applications is needed.

For CSA the CO_2 reduction can be 44% (Quillin, 2007), while BCSA and BYF can have a potential of 20 to 30% reduction (Miller and Myers, 2020). However, there are still many questions regarding the long-term durability of some of these new cements, e.g. regarding carbonation, reinforcement corrosion and frost; see e.g. (Gartner and Sui, 2018) and (Dachtar, 2004).

4.2 Reinforcement

4.2.1 Fibers

Fiber-reinforced concrete (FRC) is a concrete containing dispersed fibers. In comparison to conventional reinforcement, the characteristics of fiber reinforcement are that: (1) the fibers are generally distributed throughout a cross-section, whereas reinforcement bars are only placed where needed; (2) the fibers are relatively short and closely spaced, whereas the reinforcement bars are continuous and not as closely placed; and (3) it is generally not possible to achieve the same area of reinforcement with fibers as with reinforcing bars. This means that, unlike ordinary reinforced concrete with an appropriate minimum reinforcement, a softening response is observed after cracking. In contrast to plain concrete, the toughness is significantly increased as a result of fibers transmitting force across cracks.

There is a wide range of fibers used (Löfgren, 2005). Steel fibers are common, modern such are often made of high-strength steel and typically have high slenderness and complex geometries. Synthetic fibers are becoming more common; many types exist: polyethylene (PE), polypropylene (PP), acrylics (PAN), polyvinyl acetate (PVA), polyamides (PA), aramid, polyester (PES), and carbon.

Fracture characteristics and structural behavior are enhanced through the fibers' ability to bridge cracks. This mechanism influences both the serviceability and ultimate limit states. The effects on the service load behavior are controlled crack propagation, which primarily reduces the crack spacing and crack width, and increased flexural stiffness. The effect on the behavior in the ultimate limit state is increased load resistance and, for shear and punching failures, fibers also improve the ductility.

In some types of structures, such as slabs on grade, foundations, and walls, fibers can replace ordinary reinforcement completely. In other structures, such as beams and suspended slabs, fibers can be used in combination with ordinary or pre-stressed reinforcement. In both cases the potential benefits are due to economic factors as well as to rationalization and improvement of the working environment at the construction site.

For the application in mind, ballastless tracks, it may very well be doable for fibers to replace ordinary reinforcement, partially or even completely.

4.2.2 Textile reinforcement

One possibility to reduce the environmental impact of new concrete structures is to use textile reinforcement instead of traditional steel bars. Textile Reinforced Concrete (TRC) can offer the possibility to build corrosion resistant, slender, lightweight, modular, and freeform structures with relatively small environmental impact, (Williams Portal *et al.*, 2015). The textile reinforcement commonly consists of two-dimensional open textile meshes, with spacing 1-5 cm, combined with fine grain concrete; the maximum ballast size can be 2-4 mm, (Brameshuber, 2006). TRC resembles fiber reinforced concrete as both include fibers more distributed in the concrete matrix compared to traditionally reinforced concrete structures; however, in TRC, the fibers are bundled and can thus be positioned considering the principal loading direction, which gives more effective use of the fibers. This resembles the use of traditional reinforcement. Thus, TRC combines the benefits of both traditional reinforcement and fiber reinforced concrete, (Hegger *et al.*, 2006).

A textile two-dimensional mesh consists of perpendicular yarns: warp and weft. Each yarn consists of many continuous fibers (also known as filaments) that are assembled into a yarn during manufacture, (Fangueiro, 2011). Often, some form of "sizing" is used, i.e. the filaments are held together using some form of glue, (Brameshuber, 2006).

Textile reinforcement is made of fibers of several different materials: e.g. alkali-resistant glass, carbon, basalt, aramid, and polyvinyl alcohol (PVA) with a coating of polyvinyl chloride (PVC). For a comparison between the properties of different materials, both mechanical and seen from a sustainability perspective, (Williams Portal *et al.*, 2015).

It is important to note that it is usually not possible to use the full tensile strength of the material. This is mainly due to the fact that the filaments are not connected as a solid unit, instead they can slip versus each other. The surrounding fine grained concrete can penetrate the outer filaments of a yarn in the so-called fill-in zone, but the inner filaments, the so-called core, is not well-connected with the concrete, Figure 5a, (Hartig, J., 2008). Within the yarn, forces are transferred between the filaments. The tensile capacity of a textile yarn in concrete is thus smaller than the tensile strength of all filaments added together; this must be taken into account at design. The capacity that can be utilized depends on how well filaments are bonded together and to the concrete. These, in turn, are affected by "sizing", impregnation, different types of coating (for example with epoxy), and weaving techniques.

Normally, the connections to yarns in the transverse direction are relatively weak, and do not contribute much to yarn-to-concrete bond, but on the other hand, bond is affected when yarns run in waves above and below transverse yarns, see Figure 5b. This also causes the textile to become apparently stiffer at increased load, see Figure 5c, as the waves are straightened at increased load, (Schladitz *et al.*, 2012).

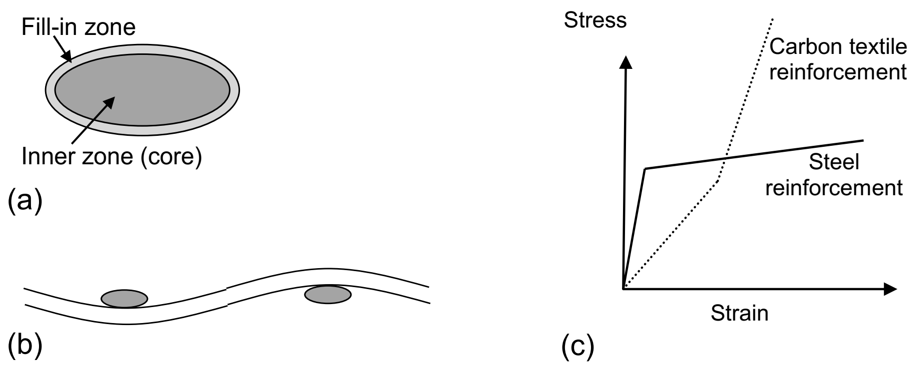


Figure 5. (a) Conceptual figure of a yarn, based on (Hartig, J., 2008)*. (b) Yarns running in waves above and below transverse yarns. Schematic, based on* (Brameshuber, 2006)*. (c) Idealized stress versus strain for a carbon textile reinforcement compared to traditional steel reinforcement. From* (Schladitz *et al.*, 2012)*.*

The materials commonly used for textile reinforcement are brittle; i.e. they have no capacity for plastic deformation. The maximum capacity of the filaments is limited by the tensile strength; however, possible initial defects give rise to failure at varying stress levels. Due to these varying stress levels, and due to the limited bond between filaments, a certain degree of ductility can still be achieved.

It can be noted that textile reinforcement in principle has no effect in compression; the woven structure gives a small stiffness in compression.

A strong argument for using textile reinforcement is that it does not corrode. Therefore, no requirements for concrete cover are needed for durability reasons. A certain cover layer is required to provide good adhesion, but it can be very small, down to few millimeters. Textile reinforcement is therefore very well suited in thin structures. However, there may be other durability issues, primarily linked to the alkaline environment of the concrete. Despite its name, alkali-resistant glass is not completely resistant in strongly alkaline environments, and also basalt has corresponding question marks (Williams Portal *et al.*, 2016). Efforts are being made to improve the long-term properties, both by using low-alkali concrete, and by using protective coatings on the textiles. Carbon fiber textiles are claimed to be very durable in concrete, but it can be noted that there is still no experience from long-term use of such.

The most studied applications for TRC is probably thin façade elements, thin shells and for strengthening. A recent suggested application is vaulted floors with textile reinforced concrete shells; for this application the embodied carbon is claimed to be reduced by 53–58% compared to an equivalent flat slab (Hawkins *et al.*, 2020). To the knowledge of the authors, this material has not been considered for ballastless slabs.

5 Methods for reduction of GHG emission

The objective of this chapter is to assess different methods of reducing greenhouse gas emissions of slab tracks, discussed in Chapters 3 and 4, with respect to certain criteria presented below. This will provide the needed knowledge to identify the solutions with significant potential for further developments which will be presented in Chapter 6. An overview of the assessment is shown in Table 1, followed by further details regarding each method in Table 2 to Table 12. The assessment of methods is carried out with respect to the following six criteria:

Criteria 1: How far away is the method from an implementable product?

This criterion relates to specific challenges that needs to be addressed before full implementation of the method can be realize. The challenges are outlined in the detailed tables for each method. Furthermore, Technology Readiness Level (TRL) according to the following interpretation made by BBT/ Trafikverket is used:

- Basic research: TRL 1-3
- Industrial research: TRL 4-5
- Experimental development: TRL 6-8

Criteria 2: How great is the potential benefit?

Given the limitation of the current study, the potential benefits are presented in light of the deployment of each method on other applications. For instance, due to limited experience/knowledge in the use of fibers in slab tacks, the potential benefits are discussed in light of the use of fibers in concrete edge beams in bridges where solid and reliable knowledge exists.

Criteria 3: Are there any potentially negative environmental impact?

This criterion relates to the risk of other negative environmental impacts such as local emissions or use of toxic substances. For instance, some curing agents for epoxy resins in use today have a certain toxicity that must be counted for; such effects will be outlined under this criterion.

Criteria 4: Is it possible to produce the concrete at the volumes needed?

This criterion takes into account the availability of raw material for large volumes, as well as challenges related to logistic and production.

Criteria 5: Is it possible to assure the quality of the product?

This criterion takes into account the ability to assure quality of the final product which is a function of the ability to assure the quality of the raw material as well as the production method for the final product. For instance, the quality of steel fiber reinforced concrete depends, among others, on the quality of steel fibers as well as the dispersion of steel fibers in concrete. Availability of standard methods of production and quality control play an critical role while determining whether the quality of the product can be assured.

Criteria 6: What is the cost of the product compared over the entire life cycle?

The cost of the product, in most cases, cannot be quantified as it is a function of the availability of and the market for the raw material (such as slag), or simply because several unknown parameters are involved for instance for CSA cements. In such cases, when possible the cost of the product for other applications are indicated.

Table 1. Evaluation of methods for reducing GHG emissions for slab tracks with respect to selected assessment criteria.

Evaluation criteria	**Structural Optimization**					**Alternative Binders**			**Alternative Materials**			**Others**
	Optimizing Stiffness	Minimizing Thickness	Geometry optimization	Prestressed concrete	Fiber-reinforced concrete	Replacing cement with slag	Replacing cement with fly ash	Other cement types	Functionalized graphene oxides (FGO)	Recycled Concrete Aggregate (RCA)	Textile-reinforced concrete (TRC)	Optimized mix design
How far away is the method from an implementable product?	OK	OK	OK	OK	OK	OK	OK	Unknown	Not OK	OK	OK	OK
How great is the potential benefit?	Unknown	Unknown	Unknown	Unknown	Unknown	OK	OK	Unknown	Unknown	Not OK	Unknown	Unknown
Are other potentially negative env. impact (e.g. toxic substance)?	OK	OK	OK	OK	OK	OK	OK	Unknown	Unknown	OK	OK	OK
Is it possible to produce the product at the volumes needed?	Not relevant	Not relevant	Not relevant	Not relevant	OK	Not OK	Not OK	Not OK	Not OK	Not OK	OK	Unknown
Is it possible to assure the quality of the product?	OK	OK	OK	OK	OK	OK	OK	Unknown	Unknown	OK	Unknown	Unknown
What is the cost of the product compared to existing products?	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown

OK	Not OK	Unknown	Not relevant

Table 2. Optimizing stiffness, minimizing thickness and geometry optimization.

Evaluation criteria	**Optimizing Stiffness** **(TRL: 4-5)**	**Minimizing thickness** **(TRL: 6-8)**	**Geometry optimization** **(TRL: 4-5)**
How far away is the method from an implementable product? OK	• No specific challenge is identified for implementation. • Increasing the stiffness of slab tracks can be done by e.g. increasing slab thickness, choosing a more efficient geometry, improving aggregate type, to name a few. • Thickness of slab track can be significantly reduced, while adhering to the requitements in standards . • Significant benefits are anticipated for a geometrically optimized slab track (Tayabji and Bilow, 2001).		
How great is the potential benefit? Unknown	• Optimizing Stiffness: Research is needed to quantify the potential benefits for slab track systems. In the case of road pavement, it has been shown that 5-15% reduction in GHG emission can be expected with increased stiffness (Akbarian, 2012). However, the potential benefits for slab tracks may be notably smaller since slab tracks are much stiffer structures than road pavements. • Minimizing thickness: minimizing the thickness while using lower concrete class can lead to 10 to 15% savings in GHG emission (Aggestam *et al.*, 2021). • Geometry optimization: a pilot test in the Netherlands estimates 12% saving in material using a slab track inspired by box girder bridge, (Bos, J. and Stuit, 1999)		
Are other potentially negative env. impact (e.g. toxic substance)? OK	• No potentially negative environmental impact is identified.		
Is it possible to produce the product at the volumes needed? Not relevant	• Not relevant		
Is it possible to assure the quality of the product? OK	• No specific challenge is identified to assure quality.		
What is the cost of the product compared to existing products? Unknown	• There are several unknown parameters before the stiffness/thickness/geometry optimization is carried out for a given slab track, and thus the cost cannot be quantified.		

Table 3. Prestressed concrete

Evaluation criteria	Prestressed Concrete (TRL: 6-8)
How far away is the method from an implementable product? OK	• The only challenge is related to production which must be investigated in future studies. Prestressing is possible for construction on site, but may be better suited for prefabrication elements. • The Bögl ballastless track system is an example of such systems, which consist of prefabricated slabs prestressed in transverse direction, and coupled in longitudinal direction on site.
How great is the potential benefit? Unknown	• Prestressing of concrete aims to control (minimize) crack width and thus enables a more optimized slab design. Quantification of potential benefits in terms of reduction in the use of material and thus in environmental impacts require further investigation.
Are other potentially negative env. impact (e.g. toxic substance)? OK	• No potentially negative environmental impact is identified.
Is it possible to produce the product at the volumes needed? Not relevant	• Not relevant
Is it possible to assure the quality of the product? OK	• No specific challenge is identified to assure quality.
What is the cost of the product compared to existing products? Unknown	• There are several unknown parameters, and thus the cost cannot be quantified.

Table 4. Fiber-reinforced concrete (FRC)

Evaluation criteria	**Fiber-reinforced concrete (FRC)** **(TRL: 6-8)**
How far away is the method from an implementable product? OK	• It may very well be doable for fibers to replace ordinary reinforcement, partially or even completely. • Fatigue of cracked fiber-reinforced concrete is a topic that requires further investigation
How great is the potential benefit? Unknown	• The potential benefits are due to economic factors as well as to rationalization and improvement of the working environment at the construction site. • Research is needed to quantify the potential benefits for slab track systems. In the case of edge beams in bridge infrastructures, it has been shown that the service life of edge beams made of hybrid reinforced concrete (steel fibers and traditional reinforcement) can be prolonged by over 58% (Chen *et al.*, 2021), thereby enabling a significant reduction in the total life-cycle costs and annual total greenhouse gas emissions.
Are other potentially negative env. impact (e.g. toxic substance)? OK	• No other potentially negative environmental impact is identified.
Is it possible to produce the product at the volumes needed? Not relevant	• As of today, there is no shortage of fiber. This however depend on future applications.
Is it possible to assure the quality of the product? OK	• Today, there exits European standard as well as national standard, for instance (SS 812310, 2014).
What is the cost of the product compared to existing products? Unknown	• There are several unknown parameters, and thus the cost cannot be quantified.

Table 5. Replacing cement with slag

Evaluation criteria	**Replacing cement with slag** **(TRL: > 6-8)**
How far away is the method from an implementable product? OK	• One major challenge has been the frost (scaling) resistance. Recent research however shows adequate frost resistance with a replacement content of about 30 to 40%. • Another challenge has been large shrinkage for high replacement content. Recent research results show that the shrinkage can be reduced by adding 3-5% gypsum. Another remedy is to use slag mixed with recycled concrete fine powders for production of well-graded aggregates. In this way the shrinkage problem can be eliminated. • Even though the use of slag is rather limited in Sweden today, there is extensive practical experience in Europe, and thus this is not considered as a limiting factor.
How great is the potential benefit? OK	• Replacement of cement by slag directly in concrete can reach up to 35% by mass of binder, implying a save of CO_2 release by about 30% in concrete production. • Using recycled concrete fine powder with alkali-activated slag for green aggregate in concrete can replace natural sand by 70-100%, implying savings in natural resources (sand) by 500-800 kg per m^3 concrete.
Are other potentially negative env. impact (e.g. toxic substance)? OK	• Minor/negligible other potentially negative environmental impact is identified.
Is it possible to produce the product at the volumes needed? Not OK	• The availability of slag depends on competing applications.
Is it possible to assure the quality of the product? OK	• No specific challenge is identified to assure quality. • The use of slag is certified according to standard.
What is the cost of the product compared to existing products? Unknown	• This cannot be quantified as the availability of and the market for slag will have a direct impact on the price. • Nonetheless, overall an increase of up to 20% in price is expected for concrete with 30% replacement content.

Table 6. Replacing cement with fly ash

Evaluation criteria	**Replacing cement with fly ash** **(TRL: > 6-8)**
How far away is the method from an implementable product? OK	• One challenge has been frost resistance for concrete with high amount of fly ash. However, the frost resistance of concrete with moderate amounts of fly ash (up to about 25 %) is usually good and equivalent to concrete without fly ash.
How great is the potential benefit? OK	• Replacing cement with fly ash with 25% have the potential to result in 120 CO_2 kg reduction in emission, out of approx. 870 CO_2 kg for one ton of concrete.
Are other potentially negative env. impact (e.g. toxic substance)? OK	• No other potentially negative environmental impact is identified.
Is it possible to produce the product at the volumes needed? Not OK	• Fly ash is not produced at all in Sweden nor in Europe.
Is it possible to assure the quality of the product? OK	• Fly ash shows a great variety, both due to different sources but also within the same source. Furthermore, the reactivity also depends on the properties of the cement. Pre-testing with the materials in question must therefore be carried out for each case, for which standard procedures exist.
What is the cost of the product compared to existing products? Unknown	• This cannot be quantified as the availability of and the market for fly ash will have a direct impact on the price. • Nonetheless, overall an increase of up to 20% in price is expected for concrete with 25% replacement content.

Table 7. Other cement types – CSA, BCSA and BYF cements

Evaluation criteria	**Alternative cements (CSA, BCSA & BYF cements)** **(TRL: 4-5)**
How far away is the method from an implementable product? Unknown	• CSA, BCSA & BYF cements are alternatives. However, they are not yet commercially available in Europe (on an industrial scale).
How great is the potential benefit? Unknown	• There are several unknown parameters, and thus the scale of potential benefits cannot be quantified. But producing CSA leads to a reduction of about 40% in production emissions while BCSA & BYF can lead to 20-30 % reduction.
Are other potentially negative env. impact (e.g. toxic substance)? Unknown	• No other potentially negative environmental impact is identified.
Is it possible to produce the product at the volumes needed? Not OK	• CSA, BCSA & BYF cement is not yet commercially available (on industrial scale) in Europe.
Is it possible to assure the quality of the product? Unknown	• There is no standard in Europe today.
What is the cost of the product compared to existing products? Unknown	• There are several unknown parameters, and thus the cost cannot be quantified. But the cost may be higher than OPC depending on the raw materials used.

Table 8. Functionalized graphene oxides (FGO)

Evaluation criteria	**Functionalized graphene oxides (FGO) (TRL: 1-3)**
How far away is the method from an implementable product? Not OK	• The use of FGO is at early research stage. • Several challenges exist.
How great is the potential benefit? Unknown	• This cannot be quantified.
Are other potentially negative env. impact (e.g. toxic substance)? Unknown	• This cannot be quantified.
Is it possible to produce the product at the volumes needed? Not OK	• Production at large scale does not exist.
Is it possible to assure the quality of the product? Unknown	• This cannot be quantified.
What is the cost of the product compared to existing products? Unknown	• This cannot be quantified.

Table 9. Recycled Concrete Aggregate (RCA)

Evaluation criteria	**Recycled Concrete Aggregate (RCA)** **(TRL: 6-8)**
How far away is the method from an implementable product? OK	• The use of recycled aggregates in concrete production is very limited in Sweden, but there is practical experience in other European countries.
How great is the potential benefit? Not OK	• The reduction of GHG emission by the use of RCA depends on many factors, e.g. transportation distances, scenario for production, efficiency of recycling etc., which makes its use very application dependent.
Are other potentially negative env. impact (e.g. toxic substance)? OK	• No other potentially negative environmental impact is identified.
Is it possible to produce the product at the volumes needed? Not OK	• This is application dependent, and cannot be quantified directly. • Transportation distance between the source of recycled aggregate and the construction site is a major issue, in particle in Sweden where natural aggregates are readily available.
Is it possible to assure the quality of the product? OK	• RCA can be used in layers where lower stiffness is required, e.g. unbounded layer in slab track systems.
What is the cost of the product compared to existing products? Unknown	• There are several unknown parameters, and thus the cost cannot be quantified.

Table 10. Textile- reinforced concrete (TRC)

Evaluation criteria	**Textile- reinforced concrete (TRC)** **(TRL: 4-5)**
How far away is the method from an implementable product? OK	• Traditional steel bars can be replaced by textile reinforcement. • A strong argument for using textile reinforcement is that it does not corrode; therefore, no requirements for concrete cover are needed for durability reasons. • For some materials, like basalt and AR-glass, there may be other durability issues, primarily linked to the alkaline environment of concrete. However, carbon textiles have so far not shown any such durability issue. • There is still little to no experience from long-term use of TRC and the associated durability challenges. • Fatigue is a topic that requires further investigation
How great is the potential benefit? Unknown	• The potential benefits are due to replacing traditional steel bars, as well as the possibility to reduce the thickness since requirement on concrete cover is not needed. • A recent suggested application is vaulted floors with textile reinforced concrete shells; for this application the embodied carbon is claimed to be reduced by 53–58% compared to an equivalent flat slab
Are other potentially negative env. impact (e.g. toxic substance)? OK	• No other potentially negative environmental impact is identified.
Is it possible to produce the product at the volumes needed? OK	• As of today, there is no shortage of fiber. This however depend on future applications.
Is it possible to assure the quality of the product? Unknown	• There is a lack of standard related to the use of textile reinforcement is structural members.
What is the cost of the product compared to existing products? Unknown	• There are several unknown parameters, and thus the cost cannot be quantified.

Table 11. Optimized mix design

Evaluation criteria	**Optimized mix design** **(TRL: 4-5)**
How far away is the method from an implementable product? OK	• Optimized mix design of concrete, in principal, enables reduced cement content while maintaining the same technical performance with a lower environmental impact. • The optimization of the mix design can be reached using different methods, e.g. by utilizing materials with low water demand, adding filler material, or by optimizing the particle size distribution. See for instance (Proske *et al.*, 2013). • One major challenge is production which requires more advanced production plants.
How great is the potential benefit? Unknown	• The potential benefits are estimated to be 10 to 30% in reducing GHG emission.
Are other potentially negative env. impact (e.g. toxic substance)? OK	• No other potentially negative environmental impact is identified.
Is it possible to produce the product at the volumes needed? Unknown	• There are production challenges and thus production at large volumes exhibits uncertainties.
Is it possible to assure the quality of the product? Unknown	• Due to lack of standards, possibilities to assure the quality is unknown.
What is the cost of the product compared to existing products? Unknown	• There are several unknown parameters, and thus the cost cannot be quantified.

6 Recommendation of future investigation

This chapter contributes to the overall goal of "increasing consideration for the environment and climate" by providing recommendations on potential solutions, and a roadmap for further investigations. While separate methods of reducing the environmental impacts of slab tracks were discussed and assessed in earlier chapters, it is the combination of several methods that can potentially lead to an effective and viable "solution". Recommendation regarding such solutions and identification of the needs for future investigations make up the primary focus of this chapter.

Based upon the information presented in this report, four solutions are presented in Figure 6. The present study indicates that there are relatively large environmental gains to be made through structural optimization of slab tracks, while facing least uncertainties; see Table 1. All methods listed under *structural optimization* fulfil four (out of six) criteria. The two uncertainties identified for all such methods are related to quantification of potential benefits and the associated costs. Therefore, the first three recommended solutions directly focus on structural optimization.

On the other hand, methods listed under *alternative binders and materials* exhibit larger uncertainties; see Table 1. The insecurity concerning the availability of materials in the needed volume is a major concern for most of such methods. For instance, the lack of production plant for Calcium Sulfoaluminate based cement in Europe or the lack of confidence in the availability of fly ash and slag in future, among others, give rise to serious uncertainties. Another uncertainty relates to a significant lack of knowledge for certain materials, such as functionalized graphene oxides (FGO), that give rise to fundamental questions regarding durability and performance. Nonetheless, this report acknowledges that optimized use of alternative binders and materials can potentially reduce the environmental impact of slab tracks, and thus the last recommended solution is devoted to this matter. More detailed information on each solution, as well as areas for future investigations are described in the following.

Figure 6. Recommended solutions for reducing the environmental impact of slab tracks.

(1) Structural optimization

- Optimized geometry
- Prestressing
- Optimize stiffness

(2) Structural optimization

- Optimized geometry
- Steel Fibre Reinforced Concrete (FRC)
- Optimize stiffness

(3) Structural optimization

- Optimized geometry
- Steel Fibre Reinforced Concrete (FRC)
- Prestressing

(4) alternative binders & materials

- Textile Reinforced concrete (TRC)
- Alternative binders
- Optimized mix design

(1) Structural optimization: Optimized geometry | Prestressing | Optimized stiffness

In this solution, three methods of structural optimizations are combined to enable a large reduction in environmental impacts of slab tracks by the efficient use of materials and reducing the energy consumption over the life cycle of a slab track system.

Geometry optimization aims to go beyond minimizing the thickness of the slab track, and to focus on the use of material where it is structurally most effective. A great example of such an optimized geometry is hollow core slabs, a precast prestressed concrete member with continuous voids provided to reduce the use of material, weight and cost. Another example is box girder bridge system in which the main beams comprise girders in the shape of a hollow box. The design and use of hollow core slabs and box girder bridge systems are enhanced and harmonized through guidelines and standard, e.g. (PCI Manual, 2015). Significant benefits are anticipated for a geometrically optimized slab track adopting a similar concept (Tayabji and Bilow, 2001). A pilot test carried out in the Netherlands estimate 12% saving on the use of material using a slab track inspired by box girder bridge systems, so called Deck Track System (Bos, J. and Stuit, 1999); see Figure 7. The specific objective for future investigation is to optimize the geometry of a “typical” slab track and to quantify the potential benefits in terms of reduction in the use of material and thus in environmental impacts, as well as possible improvement in structural performance. Furthermore, production challenges must be investigated taking into account issues related to production integration.

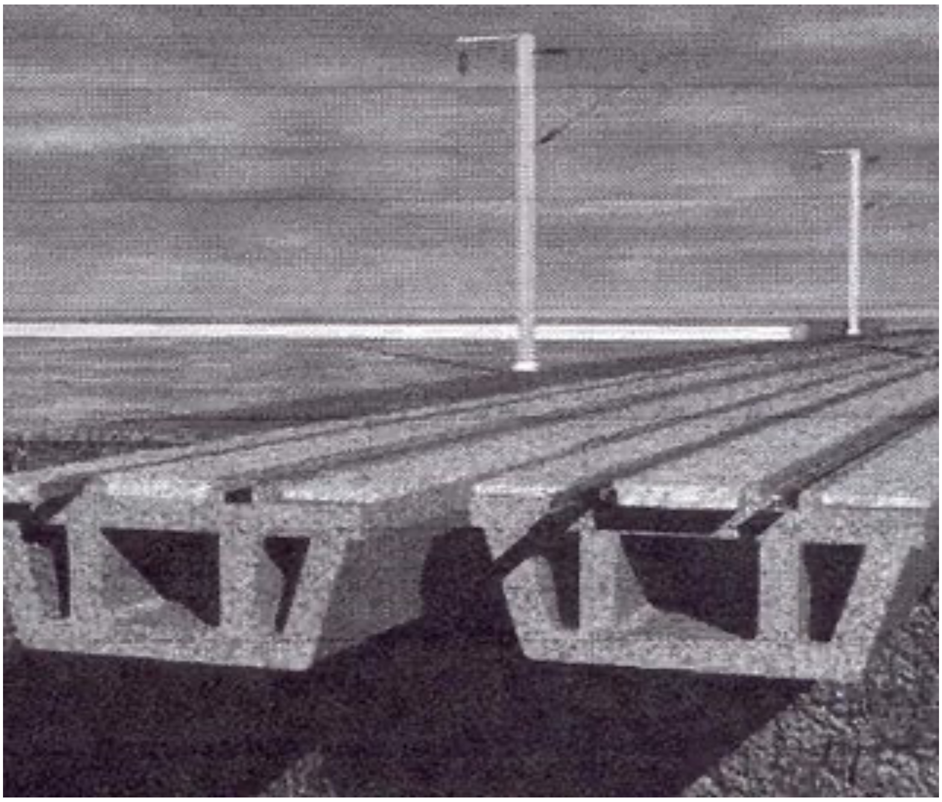


Figure 7. Deck Track System – A 200 m test section of the track constructed in 1999 near Rotterdam, the Netherlands (Bos, J. and Stuit, 1999).

Prestressing of concrete aims to control (minimize) crack width which is an important design criterion for slab track systems (EN 16432-2, 2017). Therefore, a more optimized slab design can be reached when crack widths are limited by prestressed concrete. In such a system, the concrete is prestressed in transverse direction where high bending moments are expected. The Bögl ballastless track system is an example of such systems, which consist of prefabricated slabs prestressed in transverse direction, and coupled in longitudinal direction on site; Figure 8. The specific objective for future investigation is to quantify the potential benefits in terms of reduction in the use of material and thus in environmental impacts, as well as possible improvement in structural performance. Furthermore, production challenges must be investigated. Prestressing is possible for construction on site, but may be better suited for prefabrication.

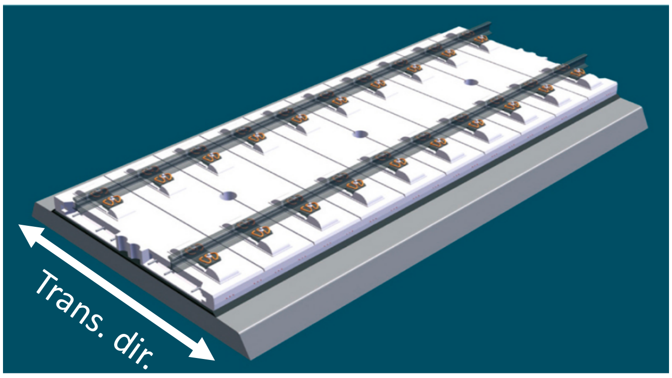


Figure 8. Prefabricated track system Bögl.

Optimized stiffness aims to minimize the energy consumption of trains by minimizing the slab's deflection while maintaining an optimal dynamic interaction between railway vehicle and slab track. The overall stiffness of a slab track system is primarily a function of the stiffness of concrete overlay, base layer with hydraulic binder and the unbounded layer, as well as the stiffness of railways. Thus, the specific objective for future investigation is to formulate and solve an optimization problem for the overall stiffness of a slab track, while counting for the dynamic interaction between railway vehicle and slab track, and finally to quantify the potential benefits in terms of saving in energy consumption over the life cycle of slab track systems.

(2) Structural optimization: Optimized geometry | Prestressing | FRC

In this solution, three methods of structural optimizations are combined to enable a reduction in environmental impacts of slab track by the efficient use of material. Similar to Solution (1), *Optimized geometry* results in the use of material where it is structurally most effective, and *prestressing* in the transversal direction reduces the crack width in the respective direction. The use of steel fiber reinforced concrete (FRC) is particular to this solution with the primary aim (a) to reduce steel reinforcement requirements, thus reducing the associated environmental impacts, and (b) to reduce crack spacing and crack widths in longitudinal direction of the slab track, and thus improving durability. Furthermore, the use of FRC can potentially reduce stress range in steel reinforcement and thus enhance the fatigue resistance, as well as improve impact resistance of the slab track, increase flexural stiffness (SLS) and improve ductility (ULS). The specific objective for future investigation is to study the fatigue performance of cracked steel fiber reinforced concrete, and to quantify the potential benefits in terms of reducing the environmental impact of slab track systems.

(3) Structural optimization: Optimized geometry | FRC | Optimized stiffness

In this solution, the main goal is to rely on steel *FRC* in order to reduce crack spacing and crack widths in both transverse and longitudinal directions. Furthermore, *optimized geometry* results in the use of material where it is structurally most effective, and *optimized stiffness* will reduce the energy consumption of trains by minimizing the slab's deflection while maintaining an optimal dynamic interaction between railway vehicle and slab track. The specific objective for future investigation is to study the fatigue performance of cracked steel fiber reinforced concrete, and to quantify the potential benefits in terms of reducing the environmental impact of slab track systems.

(4) Alternative binders & materials: TRC | Alternative binders | Optimized mix design

In this solution, the main goal is to reduce the environmental impact by optimizing the use of materials. This will be done by analyzing the impact of textile reinforcement as an alternative material to traditional reinforcing steel as well as alternative binders and optimized mix design. The use of textile reinforced concrete (TRC) will result in reducing environmental impact by replacing traditional steel bar, and allowing for smaller concrete cover by eliminating the risk of corrosion. *Alternative binders* will be investigated based on the availability and potential, and when used in combination with textile reinforcement which eliminates the risk of reinforcement corrosion. Furthermore, *optimized mix design* will be investigated for the final chosen design, where the use of filler materials and high quality aggregates and sand can further reduce the environmental impact by achieving low binder content while maintain mechanical properties and durability. The specific objective for future investigation is to study and quantify how alternative materials (reinforcement and binders) and mix optimization can reduce the environmental impact of slab track systems. It is to be noted that the first three suggested solutions also can benefit from the use of alternative binders & materials and optimized mix design.

Summary

To sum up, a single method will not allow to minimize the environmental impact. Instead, combination of several methods is required, as in the suggested solutions 1-4. The recommended future investigations (solutions 1 – 4) will enhance our understanding and knowledge regarding the most effective and practical methods to reduce the environmental impacts of slab track system, while maintaining all advantages of such a track system. Table 12 highlights the uncertainties that will be resolved by the recommended investigations.

Table 12. The uncertainties that will be addressed through the recommended investigations are highlighted.

Evaluation criteria	**Structural Optimization**					**Alternative Binders**			**Alternative Materials**			**Others**
	Optimizing Stiffness	Minimizing Thickness	Geometry optimization	Prestressed concrete	Fiber-reinforced concrete	Replacing cement with slag	Replacing cement with fly ash	Other cement types	Functionalized graphene oxides (FGO)	Recycled Concrete Aggregate (RCA)	Textile-reinforced concrete (TRC)	Optimized mix design
How far away is the method from an implementable product?	OK	OK	OK	OK	OK	OK	OK	OK	Not OK	OK	OK	OK
How great is the potential benefit?	OK	OK	OK	OK	OK	OK	OK	OK	Unknown	Not OK	OK	OK
Are other potentially negative env. impact (e.g. toxic substance)?	OK	OK	OK	OK	OK	OK	OK	OK	Unknown	OK	OK	OK
Is it possible to produce the product at the volumes needed?	Not relevant	Not relevant	Not relevant	Not relevant	OK	Not OK	Not OK	Not OK	Not OK	Not OK	OK	Unknown
Is it possible to assure the quality of the product?	OK	OK	OK	OK	OK	OK	OK	OK	Unknown	OK	OK	OK
What is the cost of the product compared to existing products?	OK	OK	OK	OK	OK	Unknown	Unknown	Unknown	Unknown	Unknown	OK	OK

OK	Not OK	Unknown	Not relevant

7 References

ACI232.2 (2003) 'Use of Fly Ash in Concrete. Reported by ACI Committee 232', *American Concrete Institute*.

Aggestam, E. (2018) 'Simulation of vertical dynamic interaction between railway vehicle and slab track', *Licentiate Thesis*, pp. 1–38.

Aggestam, E. *et al.* (2021) 'Optimisation of slab track design considering dynamic vehicle–track interaction and environmental impact', *to be submitted for international publication.*

Aggestam, E. and Nielsen, J. C. O. (2020) 'Simulation of vertical dynamic vehicle–track interaction using a three-dimensional slab track model', *Engineering Structures*, 222. doi: 10.1016/j.engstruct.2020.110972.

Akbarian, M. (2012) *Model based pavement-vehicle interaction simulation for life cycle assessment of pavements, Master Thesis*.

Arm, M. *et al.* (2014) 'Evaluation of the European recovery target for construction and demolition waste', *NORDEN. Nordiske Arbejdspapir*, p. 179. Available at: www.norden.org.

Baron, T. *et al.* (2011) 'High Speed Rail and Sustainability. Background Report: Methodology and results of carbon footprint analysis', *International Union of Railways.*, pp. 1–58.

Beskou, N. D. and Theodorakopoulos, D. (2010) 'Dynamic Effects of Moving Loads on Road Pavements: A Review', *Soil Dynamics and Earthquake Engineering*, pp. 547–567.

Bjøntegaard, Ø. (2011) 'Basis for and practical approaches to stress calculations and crack risk estimation in hardening concrete structures – State of the art. Trondheim, SINTEF Building and Infrastructure'.

Bos, J. and Stuit, H. (1999) 'Deck Track: Foundation for the Railways of the Future', in *Proceedings of the International Conference on Innovations in the Design & Assessment of Railway Track, Delft University of Technology, The Netherlands, December 2-3.*

Boubitsas, D. *et al.* (2018) 'Frost Resistance of Concrete – Experience from Long-Term Field Exposure: 153'.

Brameshuber, W. (2006) 'Report 36: Textile Reinforced Concrete-State-of-the-Art Report of RILEM TC 201-TRC, RILEM publications'.

Cementa (2020) 'Retrieved 2020-09-21, from www.cementa.se/en/carbon'.

Chen, E. *et al.* (2021) 'Comparison of the service life, life-cycle costs and assessment of hybrid and traditional reinforced concrete through a case study of bridge edge beams in Sweden', *Accepted for publication in Structure and Infrastructure Engineering*.

Chester, M. V. and Horvath, A. (2009) 'Environmental assessment of passenger transportation should include infrastructure and supply chains', *Environmental Research Letters*. Institute of Physics Publishing, 4(2). doi: 10.1088/1748-9326/4/2/024008.

Dachtar, J. (2004) 'Calcium Sulfoaluminate Cement as Binder for Structural Concrete', *University of Sheffield - Thessis*, (January).

Dienemann, W. *et al.* (2013) 'Belite-Calciumsulfoaluminate-Ternesite (BCT) - A new low-carbon clinker Technology', 11(4), pp. 100–109. Available at: https://www.mendeley.com/catalogue/708d031c-ff04-3c3d-bb3d-cb5e7b933c34/ (Accessed: 28 February 2021).

ECRA (2017) *(European Cement Research Academy) and Cement Sustainability Initiative (CSI) (eds.) (2017), Development of State of the Art Techniques in Cement Manufacturing: Trying to Look Ahead, ECRA, Düsseldorf and Geneva, www.wbcsdcement.org/technology.*

EN 16432-2 (2017) 'Standard, EN 16432-2:2017 CEN. Railway applications - Ballastless track systems - Part 2: System design, subsystems and components'.

Esveld, C. (2001) 'Modern railway track.', *MRT-productions, Zaltbommel.*

Etxeberría, M., Marí, A. R. and Vázquez, E. (2007) 'Recycled aggregate concrete as structural material', *Materials and Structures. pp. 529-541.*

European Aggregates Association (2018) 'Annual review 2017-2018'.

European Committee for Standardization (2009) 'EN 13230-2 Railway applications—Track-Concrete sleepers and bearers Part 2: Prestressed monoblock sleepers. 32'.

European Union Regulation (2008) 'Directive 2008/98/ EC of the European Parliament and of the Council of 19'.

Fangueiro, R. (2011) 'Fibrous and Composite Materials for Civil Engineering Applications', *Woodhead Publishing*.

Freudenstein, S. *et al.* (2017) *Ballastless Tracks*.

Gartner, E. and Hirao, H. (2015) 'A review of alternative approaches to the reduction of CO2 emissions associated with the manufacture of the binder phase in concrete', *Cement and Concrete Research*. Elsevier Ltd, pp. 126–142. doi: 10.1016/j.cemconres.2015.04.012.

Gartner, E. and Sui, T. (2018) 'Alternative cement clinkers', *Cement and Concrete Research*. Elsevier Ltd, pp. 27–39. doi: 10.1016/j.cemconres.2017.02.002.

Gautier, P.-E. (2015) 'Slab track: Review of existing systems and optimization potentials including very high speed', *Construction and Building Materials.*, 92, pp. 9–15.

Gonzalez-Corominas, A., Etxeberria, M. and Fernandez, I. (2017) 'Structural behaviour of prestressed concrete sleepers produced with high performance recycled aggregate concrete', *Materials and Structures 50.1 (2017): 94*.

Grossoni, I. *et al.* (2021) 'Modelling railway ballasted track settlement in vehicle-track interaction analysis', *Transportation Geotechnics*, 26. doi: 10.1016/j.trgeo.2020.100433.

Hartig, J., U. H.-C. and K. S. (2008) 'Influence of bond properties on the tensile behaviour of Textile Reinforced Concrete.', *Cement and Concrete Composites*.

Hawkins, W. *et al.* (2020) 'A design methodology to reduce the embodied carbon of concrete buildings using thin-shell floors', *Engineering Structures*.

Hegger, J. *et al.* (2006) 'Load-bearing behaviour and simulation of textile reinforced concrete', *Materials and Structures/Materiaux et Constructions*.

Heukelom, W. and Klomp, A. (1962) 'Dynamic testing as a means of controlling pavements during and after construction', in *International Conference on the Structural Design of Asphalt Pavements*, pp. 495–510.

Indraratna, B. *et al.* (2017) 'Current research into ballasted rail tracks: model tests and their practical implications', *Australian Journal of Structural Engineering*. Taylor & Francis, 18(3), pp. 204–220. doi: 10.1080/13287982.2017.1359398.

Kiani, M., Parry, T. and Ceney, H. (2008) 'Environmental life-cycle assessment of railway track beds', *Proceedings of the Institution of Civil Engineers: Engineering Sustainability*, 161(2), pp. 135–142. doi: 10.1680/ensu.2008.161.2.135.

Koh, T. H. *et al.* (2012) 'Dynamic performance of eco-friendly prestressed concrete sleeper', in *American Concrete Institute, ACI Special Publication*.

Krezo, S. *et al.* (2016) 'Field investigation and parametric study of greenhouse gas emissions from railway plain-line renewals', *Transportation Research Part D: Transport and Environment*. Elsevier Ltd, 42, pp. 77–90. doi: 10.1016/j.trd.2015.10.021.

Li, X. (2009) 'Recycling and reuse of waste concrete in China. Part II. Structural behaviour of recycled aggregate concrete and engineering applications', *Resources, Conservation and Recycling, Volume 53, Issue 3, pp.107-112*.

Löfgren, I. (2005) 'Fibre-reinforced Concrete for Industrial Construction - a fracture mechanics approach to material testing and structural analysis.', *PhD Thesis, Chalmers University of Technology*.

Löfgren, I., Esping, O. and Lindvall, A. (2016) 'The influence of carbonation and age on salt frost scaling of concrete with mineral additions.', *Technical University of Denmark, Lyngby, Denmark*.

Manalo, A. *et al.* (2010) 'A review of alternative materials for replacing existing timber sleepers', *Composite Structures*, pp. 603–611. doi: 10.1016/j.compstruct.2009.08.046.

Maruyama, I. *et al.* (2004) 'Flexural properties of reinforced recycled concrete beams', *International RILEM Conference on the Use of Recycled Materials in Buildings and Structures, 8-11 November 2004, Barcelona, Spain*.

Michas, G. (2012) 'Slab Track Systems for High-Speed Railways', *MSc Thesis*, p. 95.

Milford, R. L. and Allwood, J. M. (2010) 'Assessing the CO2 impact of current and future rail track in the UK', *Transportation Research Part D: Transport and Environment*. Elsevier Ltd, 15(2), pp. 61–72. doi: 10.1016/j.trd.2009.09.003.

Miller, S. A. and Myers, R. J. (2020) 'Environmental Impacts of Alternative Cement Binders', *Environmental Science and Technology*, 54(2), p. 677−686. doi: 10.1021/acs.est.9b05550.

Milne, D. *et al.* (2021) 'The influence of variation in track level and support system stiffness over longer lengths of track for track performance and vehicle track interaction', *Vehicle System Dynamics*, 59(2). doi: 10.1080/00423114.2019.1677920.

Molin, C. (2005) 'Återvunnen betongs kvalitet och möjligheter', *SBUF project number 11444*.

Molin, C., Larsson, K. and Dahl, L.-O. (2003) ‘Återvunnen betong – Krossningsmetodens inverkan på den krossade betongens kvalitet’, *SBUF project number 11128*.

Nielsen, J. C. O. and Igeland, A. (1995) ‘Vertical dynamic interaction between train and track—influence of wheel and track imperfections’, *Journal of Sound and Vibration*, 187(5), pp. 825–839. doi: 10.1006/jsvi.1995.0566.

PCI Manual for the Design of Hollow Core Slabs and Walls, 3rd Edition (2015) *PCI Manual for the Design of Hollow Core Slabs and Walls, 3rd Edition*. Precast/Prestressed Concrete Institute. doi: 10.15554/mnl-126-15.

Plusquellec, G., Babaahmadi, A. and Mueller, U. (2021) *Activated clays as supplementary cementitious material*. Available at: https://www.diva-portal.org/smash/get/diva2:1534080/FULLTEXT01.pdf.

Pons, J. J. *et al.* (2020) ‘Life cycle assessment of a railway tracks substructures: Comparison of ballast and ballastless rail tracks’, *Environmental Impact Assessment Review*. doi: 10.1016/j.eiar.2020.106444.

Proske, T. *et al.* (2013) ‘Eco-friendly concretes with reduced water and cement contents - Mix design principles and laboratory tests’, *Cement and Concrete Research*, 51. doi: 10.1016/j.cemconres.2013.04.011.

Quillin, K. (2007) *Calcium SulfoAluminate Cements: CO2 reduction, concrete properties and applications, Buildings Research Establishment, Watford, United Kingdom*, *Construction Research and Innovation*.

Remennikov, A. M. and Kaewunruen, S. (2008) ‘A review of loading conditions for railway track structures due to train and track vertical interaction’, *Structural Control and Health Monitoring*, pp. 207–234. doi: 10.1002/stc.227.

Remennikov, A. M. and Kaewunruen, S. (2014) ‘Experimental load rating of aged railway concrete sleepers’, *Engineering Structures*. doi: 10.1016/j.engstruct.2014.06.032.

Rogers, P. *et al.* (2016) ‘High Quality Reclaimed Concrete Aggregates for New Concrete’, *SBUF report ID 12771*.

Santero, N. and Horvath, A. (2009) ‘Global Warming Potential of Pavements’, *Environmental Research Letters*, 4(3).

Santero, N., Masanet, E. and Horvath, A. (2011) ‘Life-cycle assessment of pavements. Part I: Critical review.’, *Resources, Conservation, and Recycling*, 55(9–10), pp. 801–809.

Schladitz, F. *et al.* (2012) ‘Bending load capacity of reinforced concrete slabs strengthened with textile reinforced concrete’, *Engineering Structures*.

SS-137003 (2015) ‘Svensk Standard SS-137003:2015 Betong – Användning av EN 206 i Sverige.’

SS-EN206 (2013) ‘Betong – Fordringar, egenskaper, tillverkning och överensstämmelse. SIS förlag.’

SS 812310 (2014) ‘SVENSK STANDARD SS 812310:2014 - Fiberbetong - Dimensionering av Fiberbetongkonstruktioner’.

SS137003 (2015) ‘Betong – Användning av SS-EN 206 i Sverige, utgåva 5. SIS förlag.'

Sun, L. (2001) 'A Closed-Form Solution of a Bernoulli-Euler Beam on a Viscoelastic Foundation Under Harmonic Line Loads', *Sound and Vibration*, 242(4), pp. 619–627.

Tam, V. W. Y., Soomro, M. and Evangelista, A. C. J. (2018) 'A review of recycled aggregate in concrete applications (2000–2017)', *Construction and Building Materials*. doi: 10.1016/j.conbuildmat.2018.03.240.

Tayabji, S. D. and Bilow, D. (2001) 'Concrete slab track state of the practice', *Transportation Research Record*. National Research Council, (1742), pp. 87–96. doi: 10.3141/1742-11.

UIC - International Union of Railways (no date) 'High speed rail brochure. 2015'.

Wang, N. *et al.* (2020) 'Improved Interfacial Bonding Strength and Reliability of Functionalized Graphene Oxide for Cement Reinforcement Applications'.

Williams Portal, N. *et al.* (2015) 'Sustainable potential of textile-reinforced concrete', *Journal of Materials in Civil Engineering*.

Williams Portal, N. *et al.* (2016) 'Tensile behaviour of textile reinforcement under accelerated ageing conditions', *Journal of Building Engineering*.

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