Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0867

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Utilization of crushed concrete aggregate in light rail construction

Utilisation de granulats de béton concassé dans la construction de rails légers

T. Linden
Ramboll Finland Oy, Tampere, Finland

T. Dettenborn, A. Kalliainen, J. Forsman
Ramboll Finland Oy, Espoo and Tampere, Finland

P. Kolisoja
Tampere University of Technology, Tampere, Finland

ABSTRACT: As the popularity of light rail is growing, it has become apparent that there is a need to examine the possibilities of using recycled crushed concrete aggregate (CCA) in light rail construction as well. CCA has been used in Finland for road and street construction since the early nineties. Experiences have been good. In the follow-up studies of trial sections, higher values for bearing capacity were measured for the structures with CCA than for the reference structures constructed with crushed rock. The nature of the stresses in the sub-ballast layers of a light rail structure can be compared to the stresses in a road structure. Thus, it can be assumed that CCA is a suitable material to be used in the unbound layers under the ballast bed in a ballasted light rail track or under the concrete slab of a slab track -type light rail track. Experiences and research findings from Finland and other countries were collected as a literature review and light rail structure was studied on the basis of the experiences in road structure. In addition, stresses in a light rail track bed caused by train loads were estimated using a multi-layer linear elastic calculation approach. Using CCA in the ballast bed would require additional research, as the train loads in a ballasted track might cause different, more abrasive wear on the ballast material compared to the stresses in a road structure or the lower layers in a track structure.

RÉSUMÉ: Alors que la popularité du train léger sur rail augmente, il est devenu évident qu'il était nécessaire d'examiner la possibilité d'utiliser également du granulat de béton concassé recyclé (CCA) dans la construction de rail léger. Le CCA est utilisé en Finlande dans la construction de routes et de rues depuis le début des années quatre-vingt-dix. Les expériences ont été bonnes. Dans les études de suivi des sections d'essais, des valeurs plus élevées de la capacité portante ont été mesurées pour les structures avec CCA par rapport aux structures de référence construites avec de la pierre concassée. La nature des contraintes dans les couches de sous-ballastage d'une structure de rail léger peut être comparée aux contraintes d'une structure routière. Ainsi, on peut supposer que le CCA est un matériau approprié pour être utilisé dans les couches non liées sous le lit de ballast dans une voie de chemin de fer ballastée ou sous la dalle de béton d'une voie de type rail léger. Les expériences et les résultats de recherche en Finlande et dans d'autres pays ont été rassemblés dans une revue de littérature et la structure du train léger sur rail a été étudiée sur la base des expériences en matière de structure de route. De plus, les contraintes dans le lit des voies de chemin de fer léger causées par la charge des trains ont été estimées à l'aide d'une méthode de calcul élastique linéaire multicouche. L'utilisation de l'CCA dans le lit de ballast nécessiterait des recherches supplémentaires, car les charges de train dans une voie ballastée pourraient causer une usure différente, plus abrasive du matériau de ballast par rapport aux contraintes dans une structure de route ou les couches inférieures d'une structure de voie.

Keywords: crushed concrete aggregate; recycled concrete aggregate; circular economy; light railway; tramway

1 INTRODUCTION

In the last decades growing environmental concerns have made it more difficult to use virgin natural resources in infrastructure construction. At the same time the regulations concerning waste disposal have become stricter. Replacing virgin aggregates with recycled materials in construction projects offers benefits regarding both of these issues. By using recycled materials the amount of natural resouces needed, as well as the amount of construction waste transported to landfills are decreased.

Estimated amounts of rock aggregates used in Finland between 1970 and 2014 are presented in Figure 1. In 2014 the total volume of extration of gravel and crushed rock was approximately 79 million tonnes. About 45 % of this quantity is used in earth construction (Geological Survey of Finland 2017). Increase of construction waste recycling has been aimed at both in the national legislation and the European Union waste directive. A goal was set in the EU directive from 2008 to increase construction and demolition waste recycling to 70 % by weight by the year 2020 (European Union 2008).

Approximately 1,5 million tonnes of crushed concrete aggregate (CCA) is produced in Finland annually. Most of it comes from demolition sites but a significant amount also directly from the concrete industry. The main beneficial use for CCA in Finland is road and street construction, where it has been used for over 20 years (Linden 2018). Experiences have been good. A higher bearing capacity can be achieved by utilizing CCA instead of regular crushed stone in a road structure (Dettenborn 2013; Dettenborn et al. 2015).

More and more cities around the world are now building light rail as a part of their transit systems. It is considerably cheaper and more flexible than an underground metro or a heavy railway and it offers more capacity than a bus line. New light rail systems are also being built and planned in Finland. In the city of Tampere the construction of the first phase of a new light rail system began in 2017. The works should be finished in 2021. In Helsinki and its neighboring city of Espoo the construction planning phase of a new light rail line is underway. Final decision on the construction of the line will be made in early 2019. In case of a positive decision the construction will begin in 2019. The cities of Turku, Vantaa and Oulu are also conducting preliminary studies concerning the construction of light rail.

With the popularity of light rail growing, it has become apparent that there is a need to examine the possibilities of using recycled concrete aggregate in light rail construction as well. This paper is based on an MSc thesis by Linden (2018). The paper covers the key results of the thesis. In the thesis, experiences and research findings from Finland and other countries were collected as a literature review. Light rail structure was compared with road structure to find out if the research done on utilizing crushed concrete aggregate in road and street construction can be implemented in light rail construction.

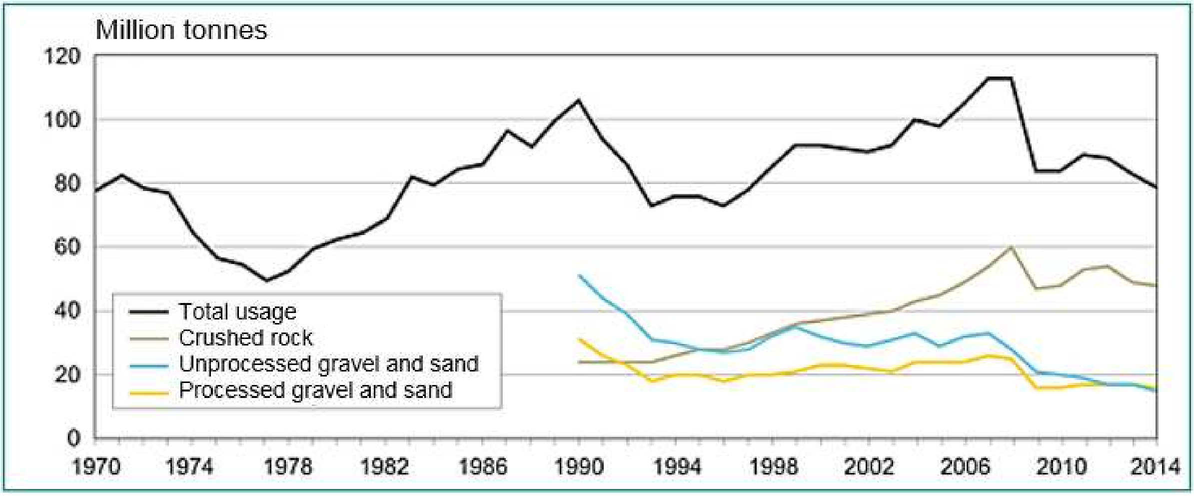

Figure 1. Estimated natural rock aggregate usage in Finland in 1970–2014 (adapted from Geological Survey of Finland 2017)

2 STRESSES IN A LIGHT RAIL TRACKBED

The stresses effecting a light rail trackbed are quite similar to the stresses in a road or street structure. There are some differences due to the different functioning principles of the permanent way on a track and the pavement on a road.

A light rail track can be built either as a ballasted track, similar to a traditional railway track, or as a non-ballasted track. On a non-ballasted track the rails are laid on a solid slab instead of a layer of rock aggregate. This slab is usually made of concrete. The basic principles of these different types of light rail track structures are presented in Figure 3.

The design of the ballasted track structure is based on the Finnish railway design manuals (Finnish Transport Agency 2018). Railway track design principles are the basis of ballasted light rail track design, even though the train loads are considerably smaller. Slab track design has more similarities to road or street design. The slab track structures shown in Figure 3 are based on the design principles used in light rail planning in Tampere and Helsinki (Raitiotieallianssi 2016; Raide-Jokeri 2015). The layers below the concrete slab have similar functions to the substructure of a ballasted track, but the terms used are equivalent to a road structure. In Finland the construction branch uses a collection of general requirements for infrastructure construction (InfraRYL 2017) in many applications. These standards are also used in light rail construction, for example when specifying suitable materials for structural layers.

The roads in northern countries, such as Finland, are usually constructed with a flexible pavement structure. Flexibility allows the road structure to withstand deformations caused by freeze-thaw and subrgrade settlement without major damages (Ehrola 1996). Compared to an asphalt-paved road, the topmost components on a light rail track form a more rigid structure. The rails and sleepers or a concrete slab of a track structure distribute train loads more evenly than the pavement and crushed aggregate layers beneath it do in a road structure.

In the study by Linden (2018), the vertical stresses in a ballasted light rail trackbed caused by a train load were estimated by a multi-layer linear elastic calculation approach. A computer program called BISAR was used for the calculations. Various configurations were modelled in the calculations by using different layer structures, subgrade properties and stiffness values for the CCA. The axle load used in the calculations was 120 kN. Differences in the resulting vertical stresses between the various combinations were very minor.

The results of the calculations by Linden (2018) were then compared to vertical stresses measured from a road structure in a previous field test by Haakana (2014). In the test an existing road embankment was instrumented to determine the stresses in it during a vehicle passing. Different axle weight and tyre combinations were used. The road used for the test was an asphalt paved road with a total structural thickness of about 0.5 m. The asphalt pavement layer of the test road was quite thin, only 40 mm.

The results of the field test and the calculations made in the thesis of Linden (2018) are presented in Figure 2. The dashed lines represent the lowest and highest stresses measured in the field test by Haakana (2014). The lowest stresses were measured with a wide NGWB-type wheel (New Generation Wide-Base) and the highest with an older type, narrower single wheel. The continuous lines represent the range of values calculated in the multi-layer calculations in the thesis of Linden. The straight blue line is the calculated stress caused by the weight of the trackbed itself.

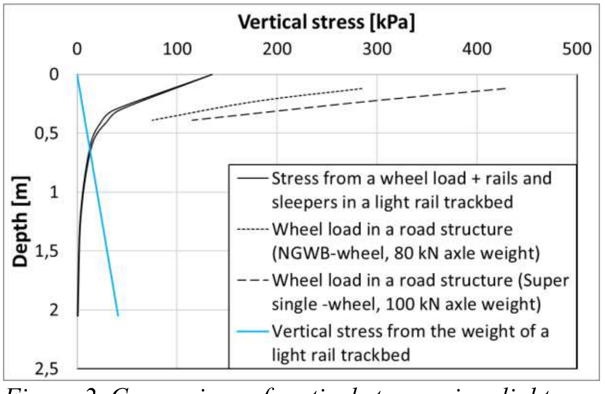

Figure 2. Comparison of vertical stresses in a light rail trackbed and a road structure (Linden 2018)

As can be seen from Figure 2, the vertical stresses in a light rail trackbed are noticeably smaller than the stresses in a thin paved road structure. This is due to the more even distribution of the wheel load onto a trackbed compared to a road structure. In the structural layers under a slab track the stresses would be even smaller than in a ballasted trackbed under sleepers. It should be noticed though, that the pavement of the road on which the stresses were measured from was rather thin. In a road with thicker pavement the stresses would probably be a bit lower.

The stresses that a moving wheel load causes in a ballasted trackbed differ from the stresses in a road base also in the nature of the stress. When a wheel load moves on a road, the strains it induces in the road structure shift smoothly from one stress state to another. When a wheel load moves on a ballasted track, the stiffness of the track varies depending on the rail support and the sleepers (Kalliainen et al. 2014). This causes a dynamic component to the vertical load, which is received by the ballast material.

3 MATERIAL PROPERTIES OF CRUSHED CONCRETE AGGREGATE

Crushed concrete aggregate (CCA) is a recycled material made out of waste concrete. It can be used as a replacement for natural aggregates. In practice the main difference between CCA and crushed natural rock is the self-hardening property of the CCA. As concrete is crushed into smaller pieces, new surfaces of un-hydrated cement are exposed. With compaction and proper after-treatment, the hydration reaction begins again leading to the CCA layer hardening. Self-hardening improves the compressive strength of the aggregate and the load-bearing capacity of the structure that it is in.

In Finland, crushed concrete aggregate is classified in four categories depending on the source and quality of the material. The raw material used in category I CCA is mostly composed of leftover concrete from concrete product manufacturing, mainly hollow-core slab factories (Forsman &

Höynälä 2000). In categories II-IV the concrete comes from the concrete industry or demolition sites. The requirements for CCA in different categories are presented in Table 1.

Table 1. Properties of CCA in categories I, II, III and IV (rows 1-9 SFS 5884 2018 and InfraRYL 2017; rows 1-5, 7 and 9-10 Finnish Road Administration 2005 and 2007, rows 6 and 8 are slightly updated to SFS 5884 and InfraRYL)

Category	**I**	**II**	**III**	**IV**
1. Material source	Concrete industry	Concrete industry / demolition sites	Concrete industry / demolition sites	Concrete industry / demolition sites
2. Self-hardening properties	Hardens	Hardens	Uncertain	Uncertain
3. Grain size distribution [mm]	[1]	[1]	[1]	Varies
4. Frost susceptibility	No	No	No	Varies
5. Compressive strength (28d) [MPa]	≥ 1.2	≥ 0.8	-	-
6. Maximum percentage of crushed bricks [weight-%]	10	10	10	30
7. Maximum percentage of other materials [weight-%] [2]	0,5	1	1	1
8. Floating materials [cm^3/kg] [3]	5	10	10	No harmful amount
9. E-modulus [MPa]	700	500	280	-
10. n = E/E_A max [4]	10	10	6	-

[1] The aggregate needs to comply with the Finnish general requirements for infrastructure construction (InfraRYL) regarding the application
[2] Timber, plastic etc.
[3] For example cellural plastics, mineral wool
[4] E/E_A = Ratio of material modulus to the Odemark bearing capacity of its foundation. If the ratio E/E_A is greater than the value given in the table, a smaller modulus value $E = n \times E_A$ is used in the design.

As can be seen from Table 1, impurities contained in the CCA weaken its technical properties. Category I CCA, for which the raw material comes from the concrete industry has the least amounts of other materials than concrete in it. In categories II-IV some or all of the material comes from demolition sites, so it isn't as pure. Some technical properties of CCA determined in different studies are summarized in Table 2.

Table 2. Properties of classified crushed concrete aggregate (Helsinki et al. 2018)

Property	**Value range**
Optimal water content, w_{opt}	8–12 %
Maximum dry unit weight	17.5–20.5 kN/m^3
Minimum dry unit weight	12.7–14.5 kN/m^3
Specific gravity	2.55–2.65 t/m^3
Capillarity, H_c	0.20–0.25 m
Water permeability, k	10^{-5}–10^{-4} m/s
Acidity, pH	11–12.5
Friction angle	40°

4 CRUSHED CONCRETE AGGREGATE AS A CONSTRUCTION MATERIAL

Trial road sections utilizing crushed concrete aggregate have been monitored for over 20 years in Finland. The results of these follow-up studies have been positive. Higher values of bearing capacity have been measured for the structures with CCA than for the reference structures constructed with crushed rock (Dettenborn 2013; Dettenborn et al. 2015). The road sections with CCA reached about 15–25 % greater bearing capacity values than the reference sections after 13–15 years. The hardening process is fastest in the first 2–5 years after construction.

The workability of hardened CCA in road structures and the effects of the material on different aspects of infrastructure maintenance has also been studied in Finland. These studies have shown that even CCA layers that have been hardened under very heavy traffic loads can be excavated by ordinary machines. When compacted back to the structure, CCA reaches 70 % of its original compressive strength in about 28 days. (Ramboll Finland Oy 2014)

Due to the hardening and chemical properties of CCA there are some limitations for its use with water supply and sewage system components. By following these restrictions CCA can be used in an urban setting with dense pipe and cable networks as well as in a plain embankment.

5 CONCLUSIONS

Crushed concrete aggregate has been used in road and street construction in Finland since the early nineties. The experiences have been positive and the structures have worked well. The calculated vertical stresses caused by a train load in a light rail trackbed are noticeably lower than the stresses measured from a real road embankment under traffic load. This suggests that CCA could be used in light rail construction as well as in road and street construction.

There are some open questions concerning the suitability of CCA right under the sleepers in a ballasted track. The wheel load effects the ballast in a different way than it would in a flexible pavement structure like a road. The loading is more cyclical and may have an abrasive effect on the CCA. The durability of CCA in this kind of a situation hasn’t been studied. Under the concrete slab of a slab track the train load is obviously distributed more evenly compared to a ballasted track with sleepers, and such wear would not be an issue.

More research is also needed on the effects of using CCA in the intermediate layer under the ballast. Technically CCA is suitable for use in the intermediate layer, but there is a risk that it would have a negative effect on the durability of the ballast material. Creating a “sandwich-structure“ containing crushed rock aggregate in the ballast layer between two more rigid layers; the sleepers and the slab-like layer of hardened CCA, might increase the grinding effect in the ballast thus increasing the need for tamping.

Based on the current research and experiences from using CCA in road and street structures, it can be assumed, that CCA is a suitable material to be used in the lower structural layers of a ballasted track and in all the layers underneath the concrete slab in a slab track. The good geotechnical properties of CCA are best utilized in the layers closer to the top, though. The components of a ballasted light rail track and a slab track are presented in Figure 3 with colour-coding showing the suitable structural layers to use CCA in according to existing research.

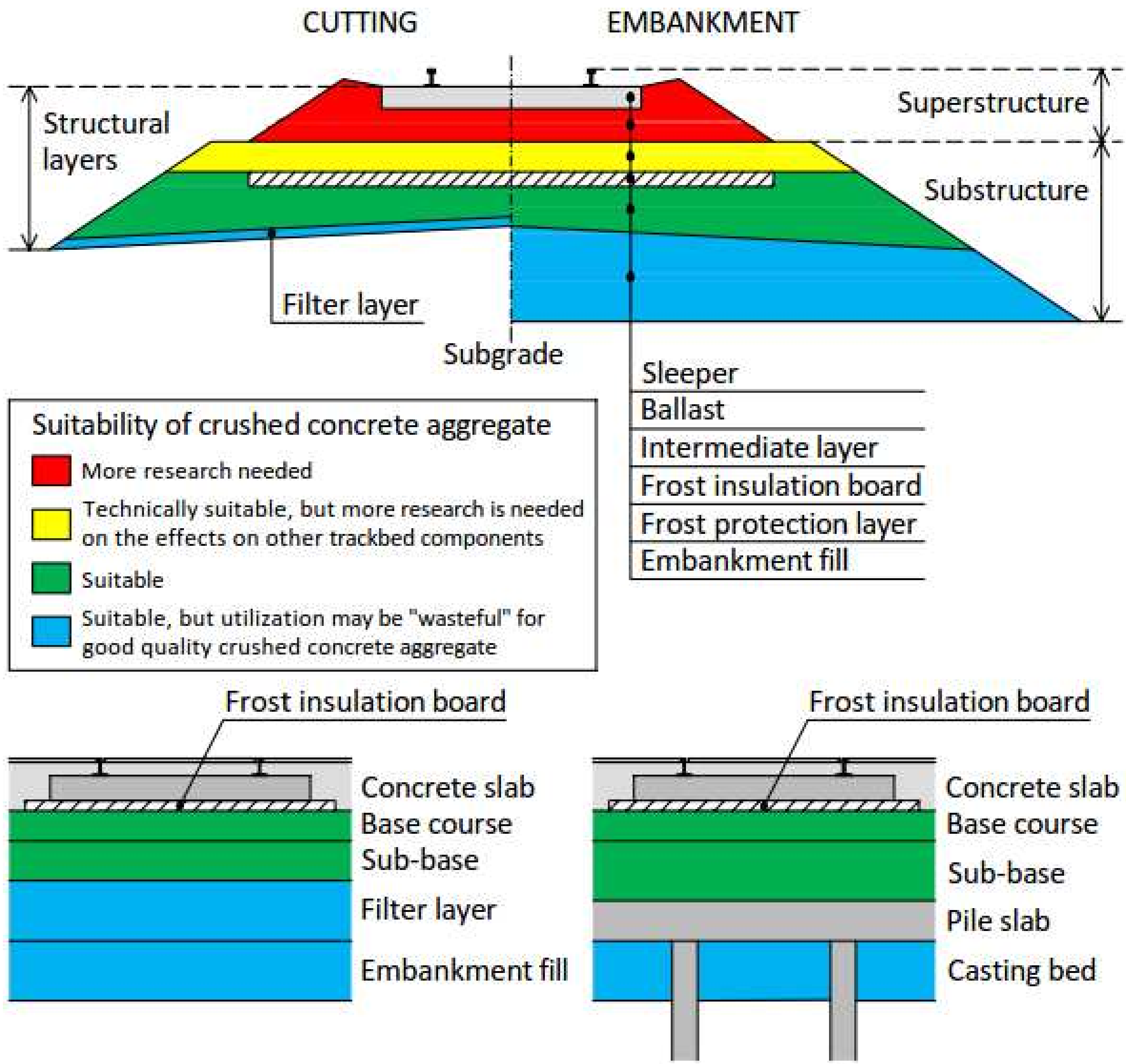

Figure 3. Components of different types of light rail tracks and the suitability of CCA use in the various layers (Linden 2018)

6 ACKNOWLEDGEMENTS

The research presented in this paper was supported financially by the cities of Helsinki, Espoo and Tampere, Helsinki City Transport (HKL) and Ramboll Finland Oy.

7 REFERENCES

Dettenborn, T. 2013. *Crushed concrete long-term behaviour* (in Finnish, Betonimurskerakenteiden pitkäaikaistoimivuus), Master's thesis, Aalto University, Espoo (in Finnish). 36 p.

Dettenborn, T., Forsman, J., Korkiala-Tanttu, L. 2015. Crushed concrete in road structures – two decades of experience. *Proceedings of* *the Institution of Civil Engineers*. Paper 1500005. ICE Publishing. 8 p.

European Union. 2008. *Directive 2008/98/EC of the European Parliament and of the Council*.

Finnish Road Administration. 2005. *Information for road design no. 71D, The modules and durability models used in road superstructure design* (in Finnish, Tietoa tiensuunnitteluun nro 71D, Tien päällysrakenteen mitoituksessa käytettävät moduulit ja kestävyysmallit). Finnish Road Administration. 13 p. Available (ref. 30.10.2018): https://julkaisut.liikennevirasto.fi/thohje/tts71d.pdf

Finnish Road Administration. 2007. *Using by-products in road structures, Directive for planning phase* (in Finnish, Sivutuotteiden käyttö tierakenteissa. Suunnitteluvaiheen ohjaus), Finnish Road Administration, Helsinki. 80 p.

Finnish Transport Agency. 2018. *Technical guidelines for track design, part 3, Track structure* (In Finnish, Ratatekniset ohjeet, osa 3, Radan rakenne), Finnish Transport Agency directive 13/2018, Finnish Transport Agency, Helsinki.

Forsman, J., Höynälä, H. 2000. Reclaimed Crushed Concrete, chapter in publication *By-products and Recycled Materials in Earth Structures, Materials and Applications*. Edit. H. Mäkelä & H. Höynälä. National Technology Agency, Technology Review 92/2000, Helsinki. 97 p.

Geological Survey of Finland. 2017. *Crushed rock aggregate* (in Finnish, Kalliokiviaines), www-page (ref. 21.11.2017): http://www.gtk.fi/_system/print.html?from=/geologia/luonnonvarat/kalliokiviaines/index.html.

Haakana, V. 2014. *Impact of heavy vehicle's tire configuration on road distress* (in Finnish, Raskaiden ajoneuvojen rengastuksen vaikutus tierasitukseen), Master's thesis, Tempere University of Technology, Tampere. 89 p.

Helsinki, Espoo, Tampere, Turku and Vantaa cities. 2018. *Crushed concrete aggregate in municipal earth construction, Guidelines for design, construction and maintenance* (in Finnish, Betonimurske kaupunkien julkisessa maarakentamisessa, ohje suunnitteluun, rakentamiseen ja ylläpitoon). Draft 10/2018. 25 p.

InfraRYL 2017. *General requirements for infrastructure construction: 20000 Super- and substructures* (in Finnish, Infrarakentamisen yleiset laatuvaatimukset: 20000 Päällys- ja pintarakenteet), Rakennustieto. 413 p.

Kalliainen, A., Kolisoja, P., Nurmikolu, A. 2014. *Three-dimensional railway track structural model and load carrying capacity of a railway track* (in Finnish, Radan 3D-rakennemalli ja ratarakenteen kuormituskestävyys), Finnish Transport Agency, Helsinki. 174 p.

Linden, T. 2018. *Utilization of Crushed Concrete Aggregate in Light Rail Construction* (In Finnish, Betonimurskeen käyttö raitiotierakentamisessa), Master's thesis, Tampere University of Technology, Tampere. 110 p. + app. 6 p.

Raide-Jokeri. 2015. *Project plan* (In Finnish, Hankesuunnitelma). 82 p. + app. 5 p.

Raitiotieallianssi. 2016. *Tampere light rail design principles* (In Finnish, Tampereen raitiotien suunnitteluperusteet). 91 p.

Ramboll Finland Oy. 2014. *Field and laboratory studies of crushed concrete aggregate* (in Finnish, Betonimurskeen kenttä- ja laboratoriotutkimukset). Report 24.10.2014. 16 p. + app. 23 p.

SFS. 2018. *SFS 5884, Factory Production Control of crushed concrete for earth construction* (in Finnish, Betonimurskeen maanrakennuskäytön laadunvalvontajärjestelmä), Finnish Standards Association SFS, Helsinki.