Degradation of ballast and crushed rock subballast in Finnish railways

Dégradation du ballast et du sous-ballast des voies ferrées finlandaises

A. Nurmikolu & P. Kolisoja
Tampere University of Technology, Tampere, Finland

ABSTRACT
The degradation of aggregate is the factor that normally determines the service life of the ballast bed. Quite recently the use of crushed rock aggregate has expanded also to the structural layers beneath the ballast bed (subballast). To ensure sufficient frost protection for the track, the thickness of subballast in Finland is normally as much as 1.5-2.0 metres. The ballast degradation occurring in an actual track structure over decades was studied by sampling and extensive series of laboratory tests with a special view to the quality of fines. Many properties of the mineral fines of the analysed ballast samples generally differed relatively little from each other. Degradation of ballast aggregates results mainly from mechanical fragmentation and attrition caused by traffic loads and tamping, and in a few cases possibly from frost weathering. The chemical weathering after crushing of the ballast of Finnish railways is generally insignificant. In the absence of long-term use experiences, the research strived to forecast the degradation of the subballast crushed rock aggregates in cyclic loading apparatus with three separate loading plates. A total of 35 long-term cyclic loading tests equivalent to about 150-300 MGT were carried out varying grain size distribution, strength of the aggregate, amount of fine material and water in the aggregate, loading level and flexibility of the bottom. In the water saturated state the degradation of crushed rock aggregate was dramatically strong. Grading of crushed rock aggregate had a significant impact on the degradation.

RÉSUMÉ
La détérioration des agrégats est le facteur qui détermine généralement la durée de vie du lit du ballast. Récemment, l'utilisation des agrégats de roches concassées a été étendue aux couches des structures sous-jacentes au lit de ballast (sous-ballast). Pour assurer à la voie ferrée une protection suffisante contre le gel, l'épaisseur du sous-ballast est en Finlande d'environ 1,5 à 2 mètres. La dégradation du ballast s'accumulant sur les structures réelles de voies ferrées durant plusieurs décades a été etudiée à l'aide de prélèvements effectués, et de nombreuses séries de tests ont été organisées en laboratoire, tout particulièrement en ce qui concerne la qualité des minéraux amendés. De nombreuses propriétés des minéraux amendés prélevés sur des échantillons du ballast ne montraient de l'une à l'autre que de faibles différences. La degradation des agrégats du ballast est due principalement à la fragmentation mécanique et à l'attrition résultant du passage des charges et du roulement, mais aussi dans quelques cas à l'usure causée par le gel. L'usure chimique après écrasement du ballast des voies ferrées finlandaises est en général non significative. Faute d'expériences sur l'usure à long terme, les objectifs de l'étude ont été la prévision de la dégradation des roches concassées des agrégats du sous-ballast dans un appareil à chargement cyclique muni de trois plaques de chargements séparées. Trente-cinq tests de chargement cyclique, équivalant à 150-300 tonnes, ont été effectués en variant la distribution des tailles des grains, la résistance des agrégats, la somme de matières fines et d'eau dans les agrégats, le niveau de chargement et la flexibilité du fond. Dans l'état de saturation d'eau, la dégradation des agrégats de roches concassées s'est avérée extrêmement forte. La gradation des agrégats de roches concassées a eu un impact significatif sur la dégradation.

Keywords : Railway track, cyclic loading, crushed rock aggregate, ballast, subballast, degradation, fouling, grading, fines, mineralogy

1 BACKGROUND

Coarse-grained and uniformly graded crushed rock aggregate, ballast, is traditionally used in the uppermost structural layer of a track. The loading environment of the ballast bed is well described by Simon et al. (1983) who state that the ballast, in particular, is subjected to the heaviest stress levels and environmental loading of all aggregates used in construction. Sustained tendency towards higher axle loads further increases the loading applied to structural layers. At the same time the smoothness requirement of railway tracks is extremely high and is tightening along with increasing train speeds, which are in many cases prerequisite for competitiveness of environmentally friendly rail traffic. Therefore, it is not surprising that the degradation of aggregate is the factor that determines the service life of ballast bed.

A literature review by Nurmikolu (2005) showed that very many studies dealing with the degradation of ballast have been published. As a result of ballast degradation its water retention, deformations and frost susceptibility increase (Nurmikolu & Kolisoja 2008). Finally, the effectiveness of the maintenance performed to keep the track geometry at an acceptable level decreases to the extent that, instead of tamping, the most economical alternative is to clean the ballast with a special sieving machine in the field. An earlier study (Nurmikolu et al. 2001) estimated, based on field and laboratory analyses, the effect of the strength of aggregate on the service life of ballast. However, the researched data on the degradation mechanism of ballast and the effect of the resulting fines on the behaviour of the ballast bed has been scarce. In this study, the mechanism of ballast degradation occurring in an actual track structure over decades was considered by extensive sampling from ballast bed and series of laboratory tests.

The use of crushed rock aggregate has expanded also to the structural layers beneath the ballast bed as the use of gravel and sand resources has been effectively restricted due to environmental aspects. A 100 year service life is required of the substructure meaning that the traffic and environmental loading on it last essentially longer than the 40 year service life of the ballast layer. Moreover, the finer-grained grain size distribution

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of frost protection and intermediate layer (subballast) aggregates makes them more vulnerable to degradation by environmental loads due to their larger grain surface area. To ensure sufficient frost protection of the track, the thickness of the structural layers beneath the ballast bed is normally 1.5-2.0 metres in Finland. Thus, the amount of material used for subballast is substantial and the consequences of any possible incorrect material selections may be dramatic. The cleaning of degraded aggregate requires machinery and work effort of greatly higher costs compared to ballast layer material. In the absence of long-term use experiences, the study strived to forecast the degradation of the frost protection and intermediate layer crushed rock aggregates in a laboratory-scale cyclic loading apparatus with three separate loading plates.

2 TEST PROGRAMME

2.1 *Sampling from ballast bed and standard laboratory tests*

To assess the quality and harmfulness of generated fines it is necessary to consider degradation in an actual loading environment. The sampling point in ballast bed cross-section has been found to have a decisive impact on the produced degradation estimate (e.g. Klassen et al. 1987). In Finland the samples taken to determine need for ballast cleaning are taken from the point shown in figure 1.

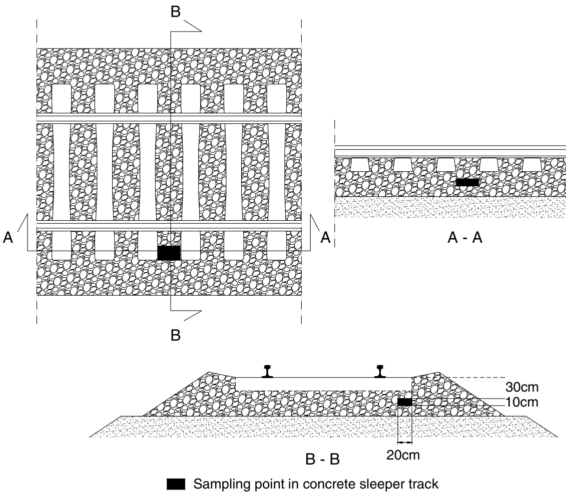

Figure 1. Sampling point of ballast bed samples.

Laboratory investigations were focused on 36 degraded ballast bed samples which had been in service without cleaning mainly over 30 years or subject to 100-350 million gross tonnes of train loading. An attempt was made to cover a wide range of typical ballast aggregates by geographically distributed sampling at different points of the railway network. Grading, impact and abrasive strength, water absorption, freeze-thaw resistance and frost heave susceptibility of the samples were tested. In addition, the fines were examined as to water adsorption, specific surface area, pore size distribution, mineralogy and loss on ignition. Surface texture of some fines was viewed by a Scanning Electron Microscope. Results from extensive laboratory frost heave testing are presented elsewhere (Nurmikolu 2005, Nurmikolu & Kolisoja 2008). Besides ballast samples, seven fresh, unused crushed rock aggregates from the quarries and eight natural gravels and sands, mostly from the substructure of the track, were examined as reference materials in the case of subballast structures.

A broad basis of comparison for the degradation of the examined samples was provided also by grading data of more than 1500 ballast samples taken primarily in 1990s for the needs of renovation planning from almost every track section of Finnish rail network. Currently the need for sampling has been substantially reduced due to great progress in ground penetrating radar analysis (Silvast et al. 2007, 2009).

2.2 *Cyclic loading test arrangement*

Laboratory-scale cyclic loading equipment was developed to simulate the degradation of crushed rock aggregates used in the track structure. The arrangement enabled the simulation of loading cycles corresponding to decades of train traffic in a test lasting a few weeks. A key point in the development of the test arrangement was to allow the principal stress directions in the aggregate to rotate corresponding to an overhead moving train loading in the real track structure (figure 2). Also Momoya & Sekine (2005) found a test arrangement simulating a *moving* wheel loading absolutely necessary in analysing the deformations from an actual train loading. The rotation of the direction of loading could be arranged by using three separate loading cylinders in turns to simulate the situation under a track section spanning three sleeper intervals (figure 3).

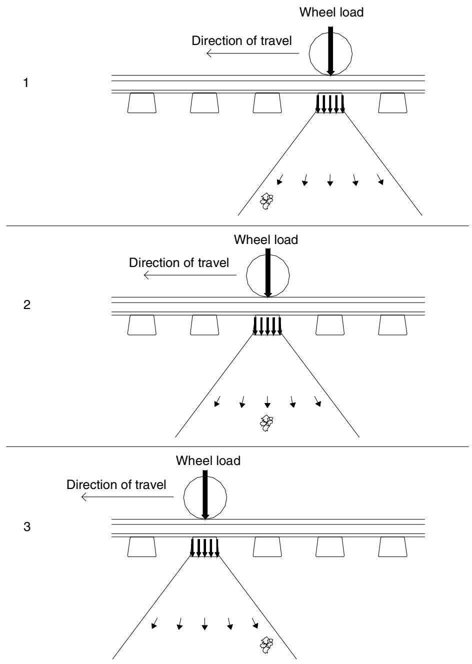

Figure 2. Principle governing change of the major principal stress direction affecting a given particle group as the train travels forward.

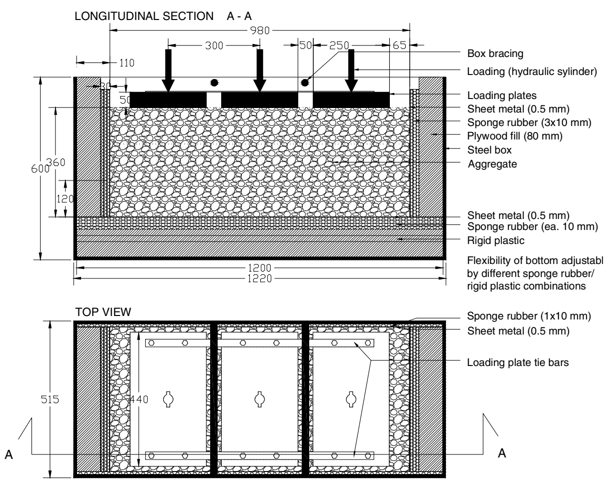

Figure 3. Test box prepared for cyclic loading tests.

In the absence of long-term use experiences, the research strived to forecast especially the degradation of the frost protection and intermediate layer (subballast) crushed rock aggregates. A total of 35 long-term cyclic loading tests equivalent to about 150-300 million gross tonnes traffic were carried out varying grain size distribution, strength of the aggregate, amount of fine material and water in the aggregate, loading level and flexibility of the bottom. Besides degradation analysis (wet sieving before and after the test), recoverable and permanent displacements were measured in various levels of test materials. Test arrangement and test programme are more detailed described by Nurmikolu (2005).

Considering the correspondence of the equipment to the actual loading situation, the biggest drawback was the problem of the interface between the aggregate and the box that in some cases caused considerable unrealistic degradation. Problems in the simulation of the behaviour of the subgrade are also related to this issue. The movable wall solution suggested by Indraratna and Salim (2003) could be applied in the development work of the loading arrangement. Because of these constraints, the loading arrangement can be regarded as a model test with distinct drawbacks, and the obtained degradation results cannot under any circumstances be applied as absolute values to the conditions of the actual track structure. However, it was considered more useful to compare the effect of different variables on the degradation of the aggregate and its ability to distribute loads with the present equipment instead of further development of the equipment.

3 RESULTS AND DISCUSSION

The properties of the mineral fines of the ballast samples generally differed relatively little from each other. However, some single divergent samples and especially the presence of organic matter widened the range of the test results (table 1). In the case of gravels and sands, the overall deviation in the properties of mineral fines was much wider (Nurmikolu 2005).

Table 1. Means and ranges of test results on ballast samples. The parameters of the right-hand column exclude samples from the Tmj-Raa railway section in case they deviated strongly from the mean.

	N	Mean	Range	Mean excl. Tmj-Raa	Range excl. Tmj-Raa
Water absorption, 4/31.5 mm (%)	26	0.20	0.08-0.80	0.16	0.08-0.28
Water absorption, 0.063/4 mm (%)	5	0.68	0.26-1.63	0.44	0.26-0.69
Freeze-thaw fouling, 4/8 mm (%)	9	1.04	0.21-4.91	0.56	0.21-0.88
Freeze-thaw fouling, 8/16 mm (%)	9	0.45	0.12-2.58	0.19	0.12-0.31
Specific gravity, 4/31.5 mm (t/m^3)	26	2.83	2.63-3.03		
<0.02 mm share of fines (%)	36	55	42-69		
<0.002 mm share of fines (%)	36	11	8-17		
Loss on ignition (%)	36	5.1	1.7-13.1	4.8	1.7-7.6
Specific surface area (m^2/g)	36	6.49	2.63-22.2	5.80	2.63-13.8
Spec.surf.area after ignition (m^2/g)	13	3.78	2.62-5.83	3.58	2.62-5.03
Water adsorption (%)	36	2.82	1.39-9.23	2.61	1.39-4.50
Total pore volume (ml/g)	32	0.509	0.43-0.66		
Adsorption pore volume (ml/g)	32	0.069	0.05-0.10		
Wall surface area of pores (m^2/g)	32	7.14	4.31-10.1		

In general, most of the fines in the ballast samples consisted of the most common rock minerals, quartz, feldspars and amphiboles, whose average share in the mineral fines of the samples was established at about 80 % (figure 4). This was a positive finding in the respect that despite thousands of times larger specific surface area of fines, in comparison to coarse grains, hard minerals appear resistant to chemical weathering in the structure even in the form of fines.

To compare the degradation behaviour in cyclic loading tests, reference parameters were determined from the change in the percentage passing the *i* mm sieve before and after the test results (ΔP_i) as shown in equations 1 and 2. The reference parameters for displacements were the permanent displacement of the loading plates and the recoverable displacement of the loading plates during a loading pulse.

$$Hi_{25/16/8/4mm} = \frac{\Delta(P_{25}) + \Delta(P_{16}) + \Delta(P_8) + \Delta(P_4)}{4} \quad (1)$$

$$Hi_{0.063/0.125/0.25mm} = \frac{\Delta(P_{0.063}) + \Delta(P_{0.125}) + \Delta(P_{0.25})}{3} \quad (2)$$

As seen from the results presented in table 2 (Nurmikolu 2005), the degradation situation is the most disastrous when the aggregate is in a water-saturated state. In the worst case, the slurry in the water gets in a constant pumping motion in the pore space between coarse grains. The selection of grain size distribution has a marked impact on degradation as well as the loading level, since increasing it from 150 kPa to 225 kPa increased degradation 3.5- to 5-fold in the comparisons.

Table 2. Summarised cyclic loading test data and resulting degradation and deformation parameters. The most important variations in test conditions of each test are shown in boldface.

Test conditions and aggregate									Result parameters			
Test	Load (kPa)	No. of cycles ($\cdot 10^6$)	Bottom rubber (mm)	Aggregate source	Grading (mm)	Water *)	Ballast grading	Tamping simulation	$Hi_{25/16/8/4mm}$	$Hi_{0.063/0.125/0.25mm}$	Recoverable displacement of loading plate (mm)	Permanent displacement of loading plate (mm)
1	300	0.3	50	A	4/32				2.3	0.6		
2	300	6.0	20	A	4/32				0.9	0.2	2.1	3.3
3	300	1.3	40	A	4/32				1.2	0.4	2.6	
4	225	6.0	50	**A**	4/32				7.8	5.6	3.6	22.8
5	225	6.0	50	B	**2/50**				0.4	0.2	2.5	3.4
6	225	6.0	50	B	2/50	**S**			0.3	0.3	2.5	2.1
7	225	3.6	50	B	**4/32**						2.4	5.1
8	225	6.0	50	B	**8/40**				0.8	0.1	2.6	3.6
9	225	6.0	50	**A**	**4/32**				1.3	1.3	3.0	7.8
10	225	6.0	50	**A**	**4/32**				1.0	0.6	2.9	4.8
11	225	6.0	50	B	**0/40**				0.3	1.1	2.4	3.1
12	225	6.0	**100**	B	8/40				0.9	0.2	3.6	4.0
13	**300**	**0.5**	50	B	**0/50**	**S**			2.4	9.6	5.5	
14	225	3.0	50	B	0/50	S			1.7	8.8	4.5	16.6
15	225	3.0	50	**C**	0/50	S			2.1	9.3	5.4	22.5
16	225	3.0	50	**D**	0/50	S			3.4	10.9	5.5	32.3
17	150	3.0	50	B	0/50	**7%**			0.4	2.2	2.6	7.8
18	150	3.0	50	**D**	0/50	**7%**			1.1	2.7	2.6	12.3
19	225	3.0	50	B	4/32				6.6	3.0	2.4	27.3
20	**300**	3.0	**30**	B	**16/63**		**x**		0.8	0.3	3.3	5.7
21	**300**	3.0	**30**	B	**16/63**		**x**	**x**	13.1	2.0	3.1	
22	**225**	**6.0**	50	B	0/50	**5%**			1.0	0.2	2.9	10.6
23	225	3.0	50	B	4/32				5.0	2.8	1.8	16.4
24	225	3.0	50	B	**0/50**				2.3	1.9	2.5	9.5
25	**150**	3.0	50	B	4/32				1.7	1.0	1.2	11.1
26	225	3.0	50	B	4/32				9.1	3.5	2.1	23.7
27	225	3.0	**10**	B	4/32				2.3	1.0	1.5	16.9
28	**300**	3.0	**10**	B	4/32				5.7	2.1	1.8	26.4
29	225	3.0	50	B	**4/63**				3.4	3.0	2.8	13.9
30	225	3.0	50	B	**1/40**				6.2	2.9	2.1	14.4
31	225	3.0	50	**A**	0/40				1.7	1.5	2.9	7.3
32	225	3.0	50	**D**	0/40				1.2	1.0	3.0	5.1
33	225	3.0	50	**E**	0/40				4.8	2.5	2.3	20.8
34	225	3.0	50	**C**	0/40				4.7	2.3	2.2	16.5
35	225	3.0	50	**F**	0/40				8.3	2.6	2.0	19.7

*) The S in the test setup column refers to a water saturated state

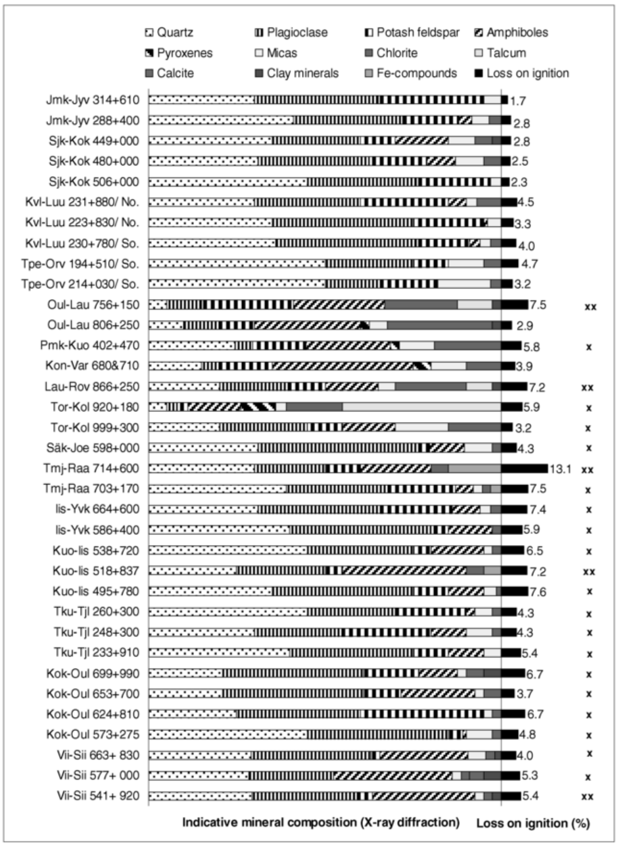

Figure 4. Indicative assessments of relative shares of minerals (%) in fines of ballast samples based on X-ray diffraction analysis and their losses on ignition (%). x: X-ray diffraction results indicated abundant presence of iron compounds and/or organic matter. xx: X-ray diffraction results indicated highly abundant presence of iron compounds and/or organic matter.

4 CONCLUSIONS

The degradation of the ballast of the Finnish rail network is largely due to the mechanical breakage and abrasion of ballast grains from traffic loading and tamping. Tamping is a very important factor in the degradation of ballast. Applicability of alternative methods, such as stoneblowing, should be further considered. The chemical weathering after crushing is generally insignificant in the ballasts used in Finnish railways, and should it occur it is limited primarily to the surfaces of grains.

The recommendations made for the grading, strength and mineralogy of frost protection and intermediate layer crushed rock aggregate (subballast) have been incorporated into the material requirements of the Finnish railways. If the recommended crushed rock aggregate is used, its degradation in a way that decisively deteriorates the performance of the structure was deemed improbable as a result of train loading of a few hundred million gross tons at today's or slightly higher axle loads. This requires, however, that the drainage of the structure functions.

In many cases ballast has degraded especially under rails and at the ends of sleepers. Such uneven degradation of ballast can be critical for stresses in concrete sleepers. When assessing the performance of ballast, the sampling level should be selected considering, on the one hand, the detrimental effect of fines independent of the elevation as to water retention and frost susceptibility and, on the other hand, the pore space required, especially in the upper sections of the ballast bed, to ensure deformation properties and the efficiency of ballast tamping.

Despite the relatively small losses on ignition, the effect of humus accumulated in the ballast bed over decades has a very big impact on the water adsorption of the fines of a material. The very large specific surface areas of the fines of some ballast bed samples before ignition decreased after ignition to the level normal for mineral soils. Hard rock minerals, quartz, feldspars and amphiboles, made up, on average, 80 % of the fines of degraded ballast bed samples which indicates the resistance to chemical weathering also as they occur as fines.

In the cyclic loading test arrangements the ability of aggregate to distribute loading correlates very closely with its ability to resist degradation. In the water saturated state the degradation of crushed rock aggregate was dramatically strong in cyclic loading tests. Thus, the functioning of track drainage is of utmost importance in preventing degradation of crushed rock aggregate. Grading of crushed rock aggregate had a significant impact on the degradation observed in cyclic loading tests. Uniformly graded aggregates degraded clearly more than more broadly graded aggregates. In the case of aggregate strength properties, the correlation with degradation occurred in the case of dry state cyclic loading tests mainly between the results of tests depicting impact resistance and in the case of water saturated state tests with results depicting abrasion resistance.

Measurement data on track geometry and corresponding properties of ballast should be examined together in order to estimate the economic cleaning limit of ballast bed. The aim should be to link geometry errors, their repeatability and the efficiency of tamping to the properties of ballast. Also, the impact of the structural and environmental factors independent of ballast aggregate quality on the degradation of ballast should be examined.

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