Experimental study on compaction and bearing capacity of railway track subballast

A. Kalliainen, O. Peltokangas, H. Luomala & A. Nurmikolu
Department of Civil Engineering, Tampere University of Technology, Tampere, Finland

ABSTRACT: Density is one of the most important material properties affecting the mechanical properties of granular materials. A poorly compacted railway substructure is more likely to suffer from the accumulation of permanent deformation during its service life. Problems can be avoided by using proper materials and methods during construction. The materials used in railway track substructure layers are typically natural sands and gravels, but their availability is increasingly being limited to more and more local pits. That has made the use of crushed rock aggregates more prevalent. Crushed rock aggregates, especially, must be relatively uniformly graded and coarse-grained. This particular grading is necessary to avoid the frost heave action caused by gradual fouling of the material during its planned service life of 100 years. Due to the uniformly graded materials the compaction of subballast layers has been found difficult. That could lead to an unevenly compacted structure causing excessive permanent deformations and local variations in the strength and bearing capacity of the embankment. A joint research project of the Laboratory of Earth and Foundation Structures at Tampere University of Technology and the Finnish Transport Agency studied the above problem by building a series of full-scale test embankments. The subgrade conditions, grading and the quality of material, thickness of the compacted layer, and construction methods were systematically varied in various test sections. The results obtained from the full-scale construction site were compared to those from model scale in laboratory conditions. All results indicate that grading and moisture content of the material determine the amount of compaction needed for sufficient density and bearing capacity. This paper reveals the effect of modification of compaction procedures on density and bearing capacity values based on laboratory and full-scale tests.

KEY WORDS: Compaction, bearing capacity, density, railway track subballast

1 INTRODUCTION

Density has for long been regarded one of the most important factors influencing the long-term behaviour of granular materials and the development of permanent deformations (Allen 1973, Marek 1977, Barksdale 1991). Resistance to permanent deformation under repetitive loading improves considerably as density increases. The effect of density on the stiffness of a material skeleton of granular material can be explained by means of particle-level considerations: the denser the material is compacted, the more distinctly particles have contact points with adjacent particles (Brecciaroli and Kolisoja 2006). The force exerted on a single particle contact point by a certain external load decreases, when the number of particle contacts increases. The effect of density on resilient stiffness has been less thoroughly studied.

However, many researchers (Allen and Thompson 1974, Rada and Witczak 1981, Kolisoja 1997) have suggested that resilient modulus generally increases with increasing density.

The subballast of a Finnish railway track structure consists of two layers: an intermediate and an insulation layer. An insulation layer 1-1.5 metres thick is required for protection against the effects of seasonal frost. Substructure layers are typically made of natural sands and gravels. The use of crushed rock aggregates has recently gained ground because the availability of natural materials has been increasingly limited to local pits (Nurmikolu 2005).

1.1 Quality control methods for compaction of subballast

Density can be measured by a volumeter or a nuclear density gauge, and the received density values are usually compared to the standard or modified Proctor compaction test result. The water volumeter test is an approved method for testing the density of sands and gravels in Finland. It has been considered a very accurate method when the maximum grain size of the material is relatively small.

The plate loading test (PLT) is another quality control method widely used in Finland. In PLT the surface of a layer is loaded with several loading steps and the deflection of the surface is measured and the deformation modulus is calculated on the basis of load and deflection. Modulus E_{v2} from the second loading and the ratio E_{v2}/E_{v1} between E_{v2} and the modulus from the first loading are considered the quality control parameters of density.

1.2 Requirements for Finnish subballast layers

In the case of an insulation layer constructed of natural sand or gravel aggregates, the average degree of compaction must be ≥ 95% while the requirements for an insulation layer of crushed rock aggregates are $E_{v2} \geq 160$ MPa and $E_{v2}/E_{v1} \leq 3$. In the case of intermediate layers, the requirements, average degree of compaction ≥ 95% or $E_{v2} \geq 180$ MPa and $E_{v2}/E_{v1} \leq 2$, are equal for all allowable materials. In many cases some of these values, especially the requirement for the ratio E_{v2}/E_{v1}, has not been achieved. It must be noted that the Finnish requirement is considerably higher than, for example, the highest requirement of 120 MPa given for main lines by Göbel et al. 1996. Consideration of frost protection in track design typically makes Finnish subballast layers rather thick: from 1.5 to 2.1 metres depending on geographical location.

2 CONSTRUCTION OF TEST EMBANKMENTS

Due to the problems and difficulties met at some railway construction sites, the compaction properties of subballast materials, quality control methods and compaction practices were studied at a full-scale construction site near the city of Seinäjoki in western Finland. Compaction practices and properties were tested on two test embankments about 200 metres long consisting of 14 different sections built of both crushed rock aggregate and natural sand and gravel materials. One test embankment (TS1-TS7) was located on soft subsoil and another similar test embankment (TS8-TS14) on stiff subsoil. The effect of layer thickness was studied using three different lifts as illustrated in Figure 1.

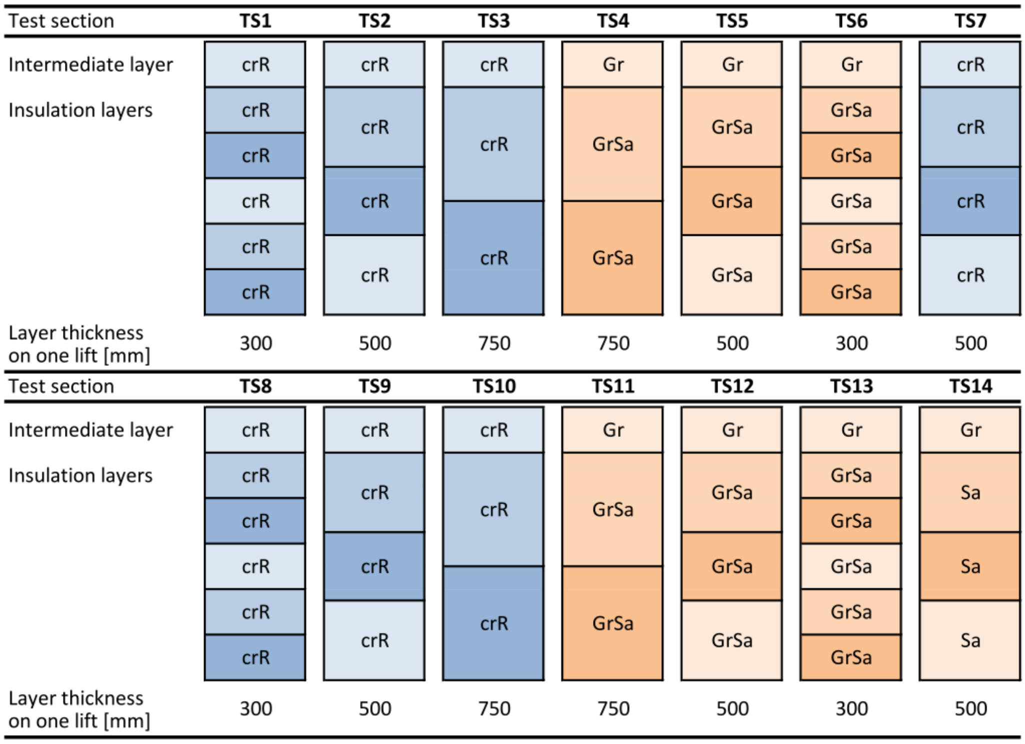

Figure1: Longitudinal profile of test embankments. Test sections 1-3 and 7-10 were built of crushed rock aggregate (crR) and the others of natural sand (GrSa) and gravel (Gr) materials. After testing the material of the intermediate layers of test sections 4-6 and 11-14 was replaced with the same crushed rock aggregate used in the other sections.

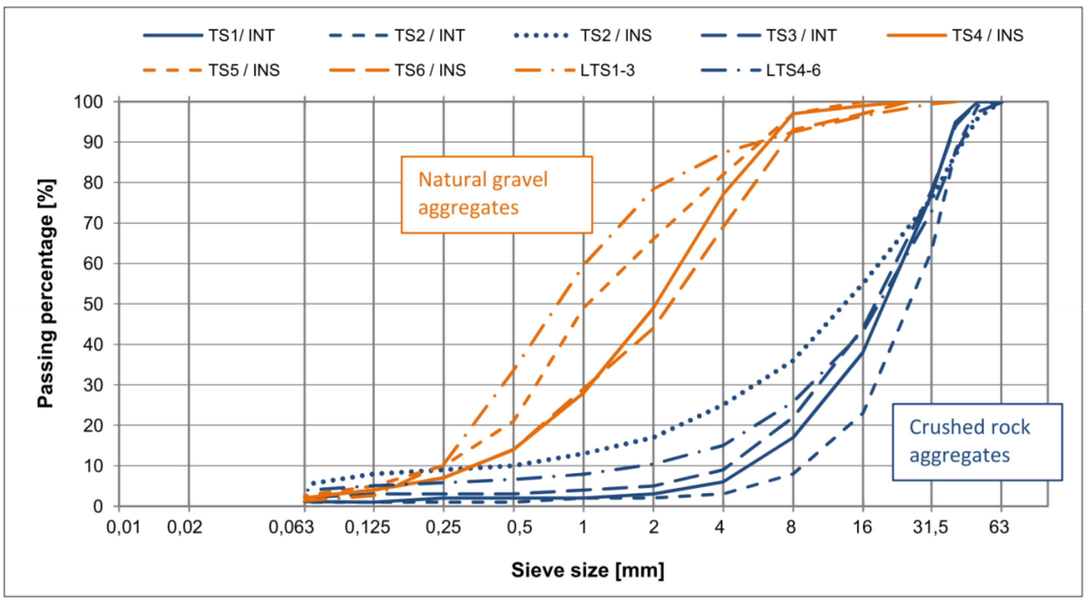

Figure2: Grading curves of materials used in test embankments (TS1-TS6) and laboratory tests (LTS1-3 and LTS4-6). INT stands for intermediate layer and INS for insulation layer.

The grading curves of the subballast materials used in the test embankments are shown in Figure 2. The crushed rock materials were manufactured at the same pit with the same crushing settings, yet the scatter of grading was rather large. The tolerance of grading requirement curves for crushed rock aggregate is very narrow and the grading of samples tapped most of it. Grading of the gravel was much more fine-grained, but the requirement for a natural material is also more fine-grained. The samples represented the fine-grained side of the requirement.

Due to the large scatter of grading, the variation in the reference densities defined with the modified Proctor test for crushed rock aggregate was quite large: from 20.8 to 23.4 kN/m^3. The reference densities defined with the modified Proctor test for gravelly sand, gravel and sand were 19.8, 21.1 and 17.7 kN/m^3 respectively.

The test sections were built layer by layer and density and deformation modulus were measured several times during compaction. The earthwork was performed with excavators, and two single drum rollers, weighing 8 and 12 tonnes, were used for compaction. Some of the layers were moisturised well, some slightly, and some were compacted with their natural water content. The use of excavators instead of bulldozers seemed to increase the risk of sorting of the material.

3 FIELD MEASUREMENTS

During the first field measurements in autumn 2009, density was measured using a water volumeter and a Troxler nuclear density gauge. Deformation modulus was measured using PLT.

3.1 Nuclear density gauge tests

The results of the density measurements on the crushed rock aggregate using a nuclear density gauge were surprising. The degree of compaction was poor and the values decreased as construction proceeded (Figure 3). The action was unexpected and the reason for it not readily understandable. Water content of the crushed rock material varied from 0.5 to 2.9% but did not correlate very well with the degree of compaction. The trend of measurement results was highly similar with soft and stiff subsoil. Compared to the modified Proctor test results, the average degrees of compaction at a measurement depth of 250 mm measured from the top of every lift were 91% on soft soil and 87% on stiff subsoil, and below all expectations.

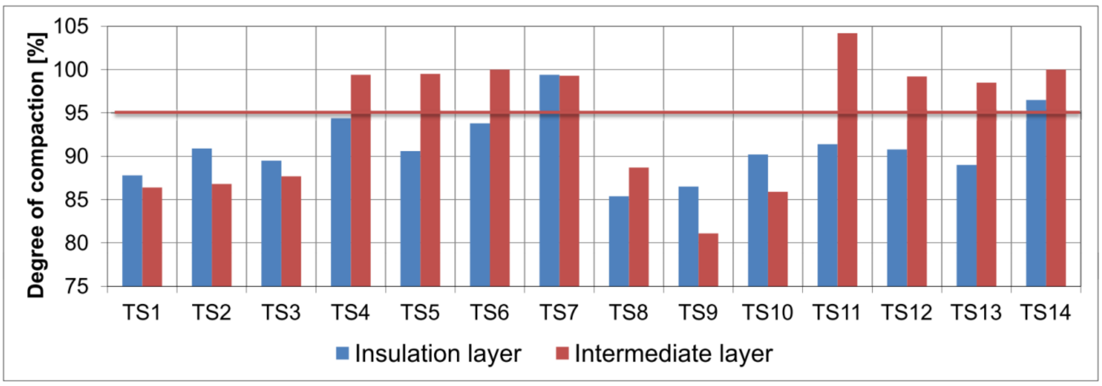

Figure3: Degree of compaction measured with nuclear density gauge at a depth of 250 mm in test sections 1-14.

The effect of depth on measurement results was a key factor for understanding the decreasing trend of density. The deeper from a certain surface level the nuclear density gauge value was measured, the better it appeared to be, and the difference was remarkable. This finding led to the hypothesis that compaction work sorts the grading of material in the vertical direction. The more the layers were compacted, the more sorting occurred, because thicker and stiffer layers took more compaction energy and the vibration had higher magnitude. Vibration caused the small particles and fines of the aggregate to fall deeper into the compacted layer and the surface of the layer became very open-graded. The density measurements made after different numbers of roller passes supported the hypothesis. After 6-8 passes, density no longer improved and the trend was almost decreasing.

The natural sand and gravel material was found much simpler from the quality control point of view. The scattering of the results measured with the nuclear density gauge was smaller, and the values generally increased along with compaction work. Density improved as long as compaction continued, and the results for the embankment on the stiffer soil were higher. Even though density values increased, the results for the insulation layers constructed of gravel did not satisfy the 95% requirement for degree of compaction whereas the results for intermediate layers of most sections did (Figure 3). As regards measurements on natural sand and gravel, density results at the measurement depth of 250 mm were without exception higher than results at a depth of 100 mm. This gave rise to the suspicion that the nuclear density gauge apparatus itself is more or less depth dependent.

3.2 Plate loading tests

As in the case of density measurements, the plate loading tests did not satisfy the minimum acceptable quality control value of 180 MPa for intermediate layers with the exception of few test sections. Figure 4 shows the average moduli values for test sections 1-14 measured from top of the insulation and intermediate layers. In some sections the moduli values measured from insulation layers made of crushed rock aggregate reached the requirement of 160 MPa, while moduli values for insulation layers made of natural sand appeared to be notably low. Measured E_{v2}/E_{v1} ratios typically varied between 4 and 6, and none reached the desired maximum value of 2 or 3.

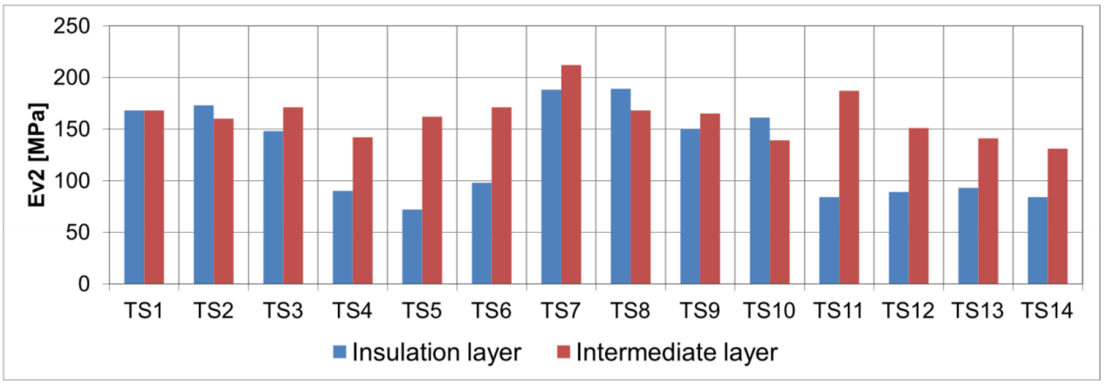

Figure4: Average E_{v2} moduli from the plate loading tests on test sections 1-14.

4 LABORATORY TESTS

4.1 Laboratory tests in general

Due to the problems discovered during the first field measurements and earlier projects, the compaction of subballast materials was studied in a laboratory to determine whether it is possible to meet the requirements under controlled conditions. The laboratory test structures, 6 in total, were built in two test series in a pit measuring about 2.5 m x 2.5 m. The subgrade of the structures was 4 metres thick and made of fine sand. The subgrade modulus of 75MPa of the test pit correlated with the subgrade conditions of test sections 8-14 at the Seinäjoki test site.

The three test structures (LTS1-LTS3) of the first series were built of gravelly sand and second series of three structures (LTS4-LTS6) of crushed rock aggregate. The grading of both materials is shown in Figure 2.

All laboratory test structures were compacted in 6 lifts to give an overall structural thickness of approximately 890 mm in the case of LTS1-LTS3 and 810 mm with LTS4-LTS6. A very light 100 kg vibrating plate was used in the compaction work and a uniform number of 8 passes was done for each layer. The first pair of test structures of both series (LTS1 and LTS4) were compacted with approximately the natural water contents of 1.5% and 0.5%, respectively. Optimum water content was the target with the compaction of the second pair (LTS2 and LTS5). An attempt was made to bring the water content of the third pair of test structures above the optimum level, but especially in the case of the crushed rock aggregate, water retention capacity of material appeared to be inadequate. The water contents of sand structures LTS2 and LTS3 were 10.8% and 12.3%, respectively while the water contents of structures LTS5 and LTS6 made of crushed rock aggregate were 3.3% and 3.2%, respectively.

Five nuclear density gauge measurements and four plate loading tests were typically performed on top of completed test structures. The results presented are averages of these measurements. Any exceptions are mentioned later with detailed results.

4.2 Laboratory tests with gravelly sand

Because nuclear density gauge measurements were relatively easy to perform on sand structures, five additional density measurements were made on top of the fourth layer. The reference density defined with the modified Proctor test for sand was 19.21 kN/m^3. The requirement of a 95% degree of compaction was achieved only in some measurements (Figure 5). The clear correlation between the degree of compaction and measurement depth was surprising, although expected in light of the first field measurements. The decreasing trend in results according to water content was not expected either. It may be caused by the nuclear density gauge, because a highly similar trend was discovered during field measurements.

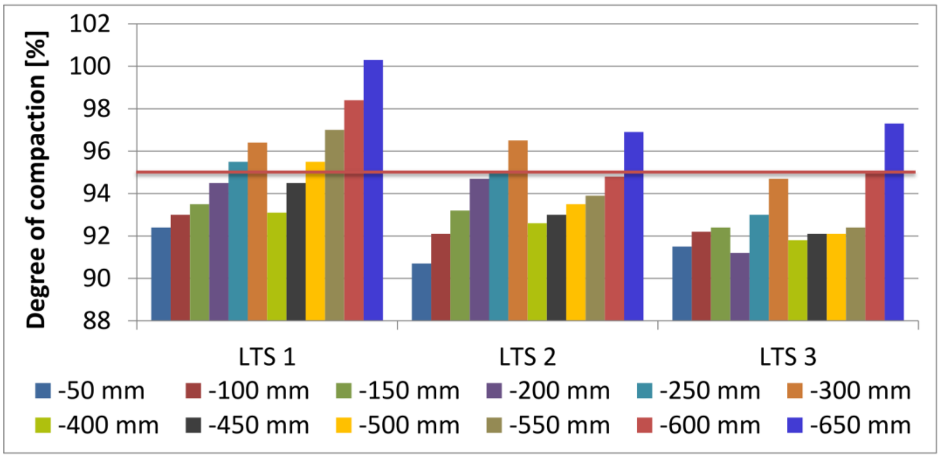

Figure5: Degree of compaction of natural gravelly sand in LTS1-LTS3 according to nuclear density gauge measurements. Measurements between -50…-300 mm were made from the top of the completed test structures and measurements between -410…-660 mm from the top of the fourth layer.

The plate loading test results for test structures made of gravelly sand are shown in Figure 6. It can be seen that even with the probably minor lateral support provided by the test pit, the results did not meet the minimum acceptable quality control value of 180 MPa. The increase in water content did not have a major effect on moduli values, but seemed to improve the E_{v2}/E_{v1} ratio. Since the material was compacted in a test pit under optimal conditions, it can be assumed that the moduli values reached in the tests are relatively close to the maximum capacity of the material.

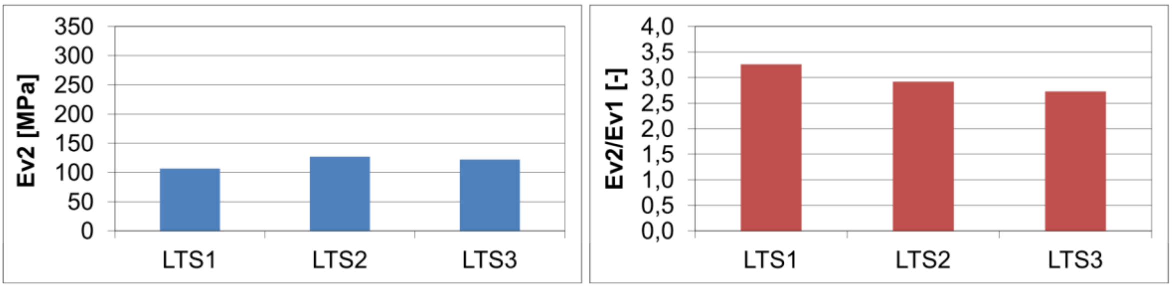

Figure6: E_{v2} moduli and E_{v2}/E_{v1} ratios of the plate loading test on laboratory test structures 1-3.

4.3 Laboratory tests with crushed rock aggregate

The reference density value of 20.76 kN/m^3 was used for laboratory test structures LTS4-LTS6 made of crushed rock aggregate. The modified Proctor test for coarse-grained materials of large maximum grain size is difficult to execute and the results are slightly unreliable since the results of different Proctor tests differed by more than 10%. As shown in Figure 7, the requirement of 95% degree compaction was only achieved at the measurement depth of 300 mm. The effect of measurement depth was not as clear as with the sand material, yet similar. Plate loading test results on crushed rock aggregate easily exceeded the requirement of 180 MPa with all test structures (Figure 8). Watering had a notable effect on both E_{v2} moduli and E_{v2}/E_{v1} ratios.

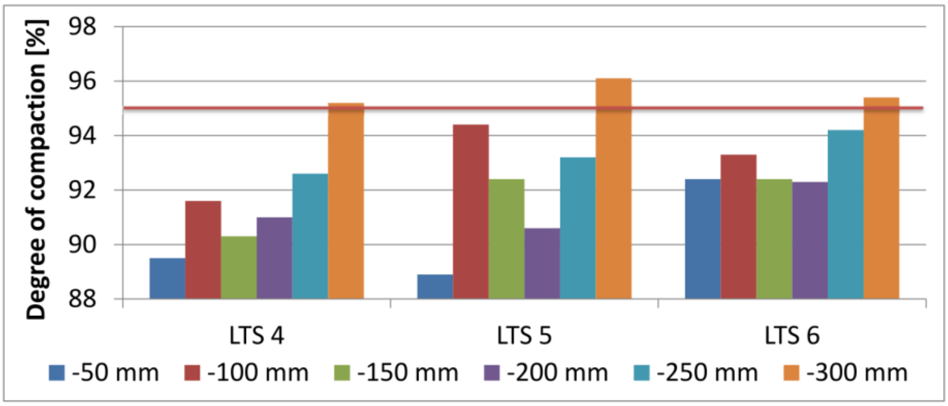

Figure7: Degree of compaction of crushed rock aggregates in LTS4-LTS6 according to nuclear density gauge measurements. All measurements were done from the top of the completed test structures.

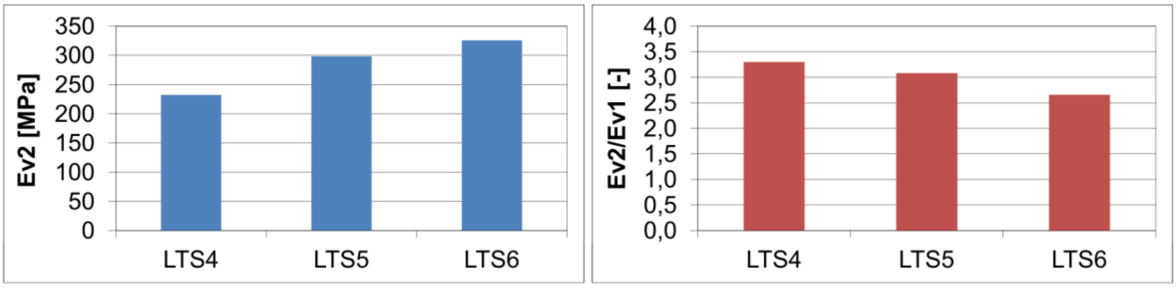

Figure8: E_{v2} moduli and E_{v2}/E_{v1} ratios of the plate loading tests on laboratory test structures 4-6.

During the construction of laboratory test structure 6, additional plate loading tests were performed on top of the second (270 mm) and the fourth (540 mm) layer to determine the effect of layer thickness on modulus values (Figure 9). The results showed that high modulus values are achievable even with relatively thin layers.

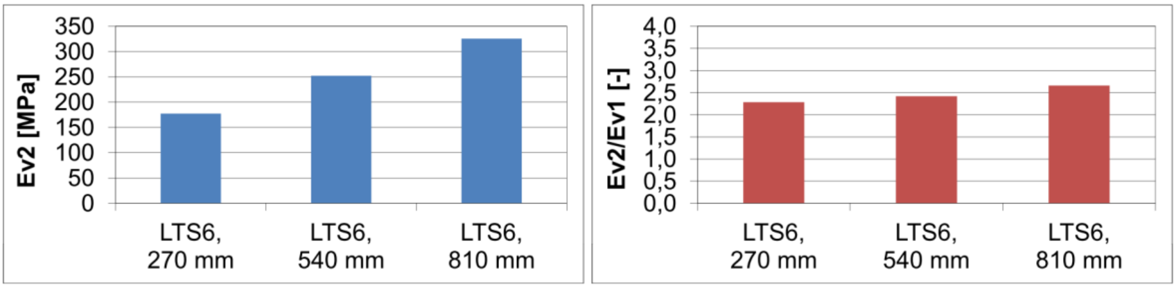

Figure9: E_{v2} moduli and E_{v2}/E_{v1} ratios of the plate loading tests on laboratory test structure 6.

5 ADDITIONAL FIELD MEASUREMENTS

Encouraged by the promising results with crushed rock aggregate in the laboratory, additional measurements were performed on test sections 8-14 in summer 2010. Test sections 1-7 had already been covered with a loading berm and were unavailable for testing. The first additional measurements were made at a distance of 1-2 metres from the edge of the embankment on both sides. Measurements taken before moistening and re-compaction indicated that moduli values for structures constructed of crushed rock aggregates had held steady, but values for sand test sections 12-14 had notably improved since the construction stage of the previous autumn. Similar improvement did not occur in test section 11 which was originally moistened less and compacted in thick 750 mm lifts.

Moistening and re-compaction had a clear effect on E_{v2} moduli values which improved for every test section. In spite of improved moduli values, the 180 MPa requirement seemed achievable only in isolated test sections and measurement points. Since the test embankment had been exposed to rain and melt water during winter, the surface of the structure was very coarse-grained. Therefore, the effect of filler stone, particle size 0/16 mm, was studied by compacting it on top of the coarse-grained layer of test sections 8-10. A very smooth surface was achieved with the use of filler stone making it easy to place the loading plate on the surface. The use of filler stone had no significant effect on moduli values, but the measured values were unexpectedly high, 210 to 280 MPa, on both the coarse-grained and filler stone surface. It was concluded that high moduli values were either linked to having the measurement points placed on the centreline of the embankment or with static compaction without vibration done after the normal compaction procedure.

The effect of the location of the measurement point on the cross-section of the test embankment and static compaction were studied further in all test sections 8-14. Especially in the case of test sections 8-10 built of crushed rock aggregate, the location of the measurement point made a clear difference as measured moduli values increased and E_{v2}/E_{v1} ratios decreased towards the centreline of the embankment (Figure 10). The effect was not as clear with test sections 11-14 made of natural sand, but moduli values measured 2.5 m from the centreline were generally lower than those measured closer to the centreline.

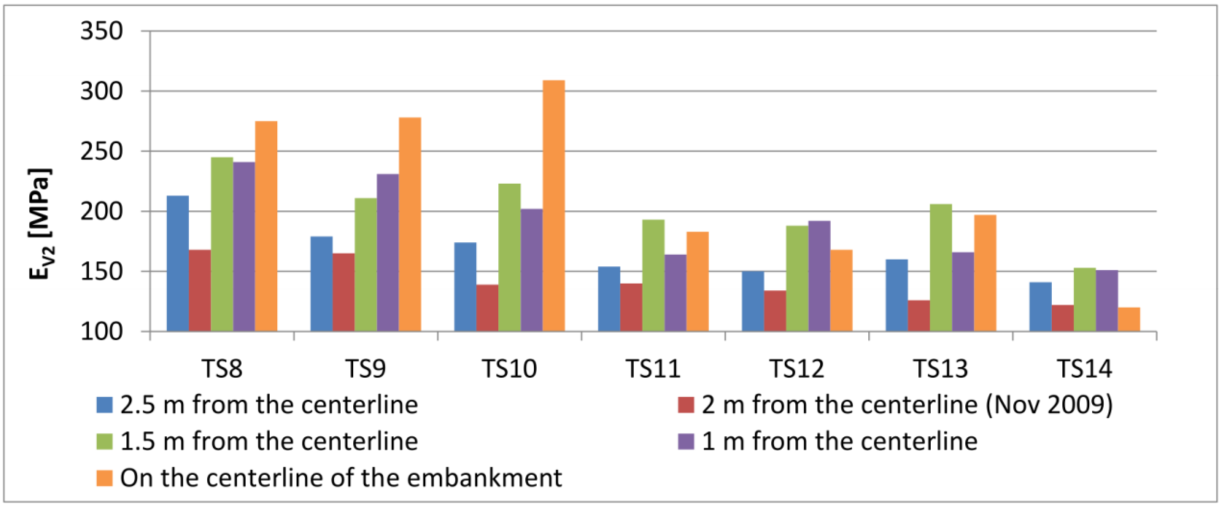

Figure10: Measured E_{v2} moduli values of the plate loading tests in the cross-section of the test embankment in test sections 8-14.

Static compaction performed after the normal compaction procedure improved moduli values in all test sections (Figure 11). The E_{v2}/E_{v1} ratios were also notably smaller after static compaction. It should be noted that static rolling does not improve the functionality of the layer, but it levels the surface and makes it more solid, which produces higher measurement results.

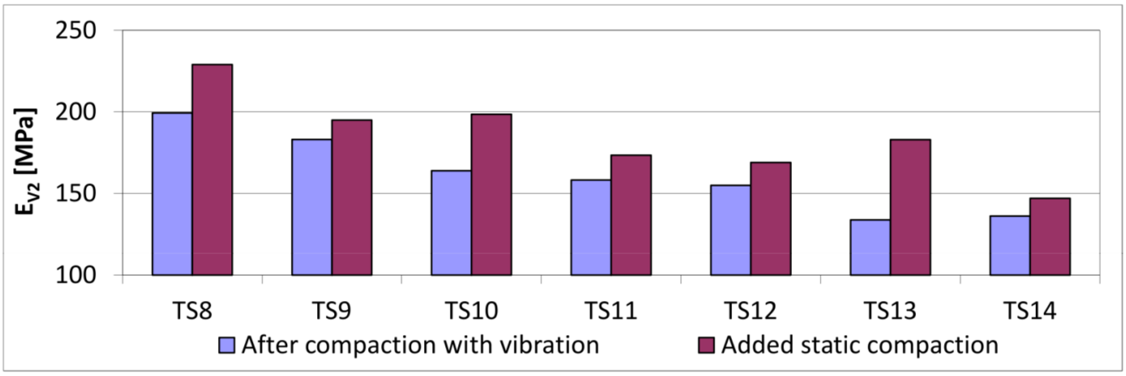

Figure11: Re-measured average E_{v2} moduli values of plate loading tests before and after static compaction without vibration.

6 CONCLUSIONS

Several factors can affect the quality of the subballast layers during the construction process. The most significant factors were found to be grading, sorting and water content of the material, thickness of the compacted layer and the procedure followed in the compaction work. Sorting of the material led to an inhomogeneous structure, which was found to make controlling of density and bearing capacity difficult. The materials used in the subballast layers compacted most effectively with the optimum water content. Crushed rock aggregates, in particular, required moistening before compaction for the optimal result. The most effective layer thickness of compaction depended on the type of roller used, but relatively thin layers were found optimal in all cases. It was found advantageous to start compaction of crushed rock aggregates by moistening and static compaction to avoid sorting of the material in the vertical direction during the compaction procedure.

Based on the obtained results, the plate loading test proved to be the most reliable method for quality control. Repetition of the measurements was found acceptable and additional compaction energy increased bearing capacity systematically. On the other hand, the ratio between the second and the first loadings proved unsuitable, at least with crushed rock aggregates. Thus, the recommendations concerning the quality requirements of compaction were given in terms of the bearing capacity value derived from the plate loading test. Nuclear density gauge measurements were found more complicated in the case of aggregates of a large maximum grain size due to the difficulty of determining the optimal density of these types of materials.

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