Density and Bearing Capacity of Railway Track Subballast

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Abstract

Density is one of the most important material properties affecting the mechanical properties of granular materials. Poorly compacted railway substructure is more likely to be exposed to the accumulation of permanent deformation during its service life. The materials used as subballast are uniformly graded and compaction of these materials is difficult. This may lead to unevenly compacted structure and local variation of the strength and bearing capacity of the embankment. In this study the compaction properties were studied by building a series of full-scale test embankments. The subgrade conditions, grading and quality of material, thickness of compacted layer and construction methods were varied. The measurements confirmed that there are very few suitable methods for reliable quality control of the compaction of coarse grained crushed rock aggregates.

1. Introduction

The subballast of Finnish railway tracks consists of two layers: an intermediate and an insulation layer. The severity of the winter season defines the thickness of the insulation layer which is typically 1-1.5 metres [1, 2]. From the quality control point of view, the density and bearing capacity of rather thick structure layers constructed of coarse and uniformly graded granular materials may be difficult to monitor. The density of the unbound material layer is often considered the most important factor influencing material performance [3]. Direct density measurements can be made by a volumeter or a nuclear density gauge. The plate loading test (PLT) is another quality control method used in Finland. In the PLT, loading is done twice and the modulus \( E_{v2} \) from the second loading cycle is compared with the modulus \( E_{v1} \) obtained from the first loading. Modulus \( E_{v2} \) and the relationship \( E_{v2} / E_{v1} \) are considered the quality control parameters of density. In many cases the requirement \( E_{v2} / E_{v1} \leq 2 \) for the intermediate layer and in some cases \( E_{v2} \geq 180 \) MPa has not been met. It should be noted that the Finnish requirement is considerably higher than the highest requirement of 120 MPa set for main lines in Germany 1996. [4]

2. Materials and methods

The compaction properties of the subballast materials were studied on a full scale construction site near the town of Seinäjoki in western Finland. The compaction practice and properties were tested in two test embankments about 200 m long that had 14 different sections built of both crushed rock aggregate and natural sand. One test embankment was on hard subsoil, the other on soft soil. The effect of layer thickness was studied by using three different increments. Table 1 shows the structure of the test embankment. The layers of the test sections were built one by one and their density and moduli values were measured several times during compaction. Two different single drum rollers, weighing 8 and 12 tonnes, were used for compaction. Density was measured by a water volumeter and the Troxler nuclear density gauge. Moduli values were measured by PLT, a falling weight deflectometer (FWD), and a light-weight deflectometer. Some of the layers were moisturised thoroughly, some slightly while some were compacted at their natural moisture content. The grading curves of subballast materials used in this study are shown in Figure 1. The grading requirement for crushed rock aggregate material is very narrow, and the grading of actual samples covers almost the entire grading area. The materials were manufactured at the same pit with the same crushing settings, but still the scatter of the grading was rather large. The grading of gravel was finer as is the requirement for natural material grading. The samples represent the fine side of the requirement.
Table 1. Longitudinal profile of test embankments. Sections TS1-TS7 were on soft soil while almost similar sections TS8-TS14 were on stiff subsoil. Test sections 1-3 and 7 were built of crushed rock aggregate (crR) and test sections 4-6 of natural sand (grSa) and gravel (Gr) materials.

<table>
<thead>
<tr>
<th>Test section</th>
<th>TS1</th>
<th>TS2</th>
<th>TS3</th>
<th>TS4</th>
<th>TS5</th>
<th>TS6</th>
<th>TS7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intermediate layer</td>
<td>crR</td>
<td>crR</td>
<td>crR</td>
<td>Gr</td>
<td>Gr</td>
<td>Gr</td>
<td>crR</td>
</tr>
<tr>
<td>Insulation layers</td>
<td>crR</td>
<td>crR</td>
<td>grSa</td>
<td>crR</td>
<td>grSa</td>
<td>grSa</td>
<td>crR</td>
</tr>
<tr>
<td>Layer thickness of one increment</td>
<td>300 mm</td>
<td>500 mm</td>
<td>750 mm</td>
<td>750 mm</td>
<td>500 mm</td>
<td>300 mm</td>
<td>500 mm</td>
</tr>
</tbody>
</table>

The total length of the test embankment was 180 m and it included seven 20-m test sections. Thickness of the intermediate layer was 300 mm and a 1500 mm thick insulation layer was built with 2-5 increments depending on the section. Intermediate layers built of gravel in the beginning were replaced by crushed rock at the end of the study.

Figures 1a and 1b. The grading curves of compacted materials. The natural sand/gravel aggregates in the insulation (INS) layers were significantly more fine-grained (Fig. 1a) than the crushed rock aggregate used for the insulation and intermediate (INT) layers (Fig. 1b).

3. Results

3.1 Nuclear density gauge tests

The results of density measurements on the crushed rock aggregate using the nuclear density gauge were unexpected. The degree of compaction was poor and values decreased layer after layer as construction proceeded (Figure 2a). The reason for the unexpected behavior was not readily understandable. The water content of the material varied between 0.5 and 2.9 %, but did not correlate very well with the degree of compaction. The trend of measurement results was highly similar in the case of soft and hard subsoil, but the average degree of compaction measured at a depth of 250 mm was slightly better in the soft soil. In comparison with the modified Proctor test results, the actual numbers were 91 % in the soft soil and 87 % in the stiff subsoil, which were against all expectations.

The effect of depth on measurement results was a key factor in understanding the decreasing trend of density. The deeper the measurement was taken, the higher the density. The trend was probably partially due to the measurement method itself, but the finding led to a hypothesis that the compaction work sorts the material in the vertical direction. The more the layers were compacted, the more sorting occurred, because thicker and stiffer layers took more of the compaction energy resulting in stronger vibration. Due to vibration the small particles and fines of
the aggregate sank 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 gave support to the hypothesis (Figure 2b). After 6-8 passes density did not improve any further; in some cases it even decreased. However, the scattering was remarkable despite the special measuring tubes that enabled exact repetition of the measurements [5].

Figure 2a. Degree of compaction of crushed rock aggregates in test sections 1-3 (on the left). Figure 2b. Degree of compaction of crushed rock aggregate in relation to roller passes in test sections 8-10 (on the right).

The natural gravel material used as a reference material was found much simpler from the quality control point of view. The scatter of nuclear density gauge results was lower, and the values generally increased as compaction work proceeded. Density improved as long as compaction continued, and the embankment on the stiffer subsoil gave higher results.

3.2. Plate loading tests

After a normal compaction procedure, the PLTs did not attain the minimum acceptable quality control value $E_{v2}=180$ MPa. After moisturising, re-compaction and static compaction, 180 MPa was achieved with crushed rock aggregate and in some cases also with natural sand (Fig 3a). Another interesting outcome of the PLTs was that, according to the measurement results, the modulus value varies, especially in test sections built of crushed rock aggregates, notably in the cross-section of the embankment. According to the PLTs, the test sections built of crushed rock aggregate were not significantly stiffer than the corresponding test sections built of natural sand material.

Figure 3a. The measured $E_{v2}$ modulus, and Fig 3b. The average relationship $E_{v2}/E_{v1}$ of the plate loading tests on test sections 8-14.
The compaction of the crushed rock aggregate was studied in laboratory conditions after the building of the test sections to clarify the reasons for the poor density and low moduli values measured on the test site. The results clearly indicated the important role of optimum water content during compaction. In addition, the compaction method seemed to have an effect on the measured modulus. After the normal compaction procedure, the test sections were first observed once and then compacted with a static roller load, and then observed again. The results illustrated in Figure 3b clearly indicate the high importance of the proper compaction method. Static rolling does not improve the performance of the crushed rock aggregate layer, but it levels the surface and makes it more solid, which produces the higher measurement results. An important finding was also that the modulus relationship requirement \( E_{V2}/E_{V1} \leq 2 \) appears unachievable and the measured value depends on how the surface is compacted before the test. Therefore, it is questionable whether the relationship \( E_{V2}/E_{V1} \) should play an essential role in the quality control of railway embankments.

5. Conclusions

The requirement for the grading set mainly to ensure the non-frost-susceptibility of the material causes that the crushed rock aggregate used as subballast material in Finland is a rather difficult material to handle and compact properly; it is also really tricky from the quality control point of view. The best compaction result is achieved when the layer is constructed by bulldozing, the material is well moistened, a proper layer thickness according to the weight of the roller is selected, and compaction is finished before the fines in the upper part of the layer begin to sink deeper into the compacted layer.

Conducting quality control measurements is a demanding task because coarse and uniformly graded material is not suitable for many test methods. The nuclear gauge can be used, but definition of the reference density may be unreliable. The tests showed that the degree of compaction varied a lot and the values measured on the test site were relatively low.

The plate loading test was found to be the most reliable method for determining compaction quality. It does not measure the degree of compaction, but stiffness of the structure, and gives reliable results for coarse materials. The highest moduli values were observed in the middle of the embankment, and static rolling before the test was found to improve the results. On the other hand, the relationship \( E_{V2}/E_{V1} \) was found unreliable for crushed rock aggregate, because the value can vary widely, and the absolute value is usually much higher than the present requirement.

6. Acknowledgements

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7. References


