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The cyclic loading resistance of old railway track sub-ballast materials at different water contents

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ABSTRACT

Water content is one of the most important factors influencing the performance of earth structures. It is well known that the water content of sand has a significant effect on its shear strength and its resistance to cyclic loading. In this study, the loading resistance of four different sand materials was investigated in a cyclic load triaxial test at different water contents. Three of the four material samples were taken from the sub-ballast layer of an existing Finnish railway track. The laboratory tests confirmed that the resistance to cyclic loading decreased with an increasing saturation level for all tested materials. The weakest material in the cyclic loading triaxial test had the most uniform grain size distribution with a small median grain size. The calculation of the vertical stress increase in the sub-ballast layer revealed that even a fine-grained sand can withstand the train load well when the rolling stock is mostly passenger traffic with an axle load of 160 kN and the sub-ballast layer is not completely saturated. However, heavy freight traffic with axle loads of 225 kN and 250 kN can approach the bearing capacity of a weak sub-ballast material if the water content of the upper part of the sub-ballast layer is high. This study has shown that the top part of the sub-ballast layer should be kept below 60–70% saturation level to avoid the development of excessive permanent deformation.

Introduction

Over time, rolling stock will cause permanent deformation of railway track. The deformation rate depends on several different factors, and appropriate models of the critical components of the track are needed to predict them [17]. The stiffness of subsoil is the most significant factor in terms of permanent deformation, but the thickness of sub-ballast layer has also been found to play a significant role in the stiffness of the entire track [21]. As a result of climate change, floods, heavy rainfall, and in some places extreme drought are predicted to increase worldwide [28]. In Finland for instance, annual precipitation is projected to increase by several percent depending on the calculation model [20]. A combination of cyclic loading, fine-grained soil, and excessive water content in the structural layers has been found to be very damaging to track durability [15].

It is known from previous studies [13] that the functionality of track drainage in Finland still needs much improvement. These factors have led to the situation where the Finnish Transport Infrastructure Agency and the Tampere University initiated a research project to investigate the effects of track water content on loading resistance to identify the potential benefits of improved drainage. As part of the study, the shear strength of four sub-ballast material specimens were tested at different water contents in static triaxial tests. Three samples were from the sub-ballast layer of an old Finnish railway track while one sample was a reference material that fulfils the current grading requirements. Fig. 1.1 summarizes the maximum shear strengths obtained in static triaxial tests as a function of the water content. The maximum shear strength started to increase as a result of suction effect when the water content decreased below 7%. That corresponds to a degree of saturation of less than 50% with the materials studied. At higher water contents, the maximum shear strength remained constant, which, however, does not correspond to the real situation in a track environment where the loading is cyclic. More detailed results of static triaxial tests are presented in the article “Determining Soil Moisture Content and Material Properties with Dynamic Cone Penetrometer” [12]. Similar results have also been observed elsewhere, such as in the study of Trinh et al. [29] for a worn ballast layer material, the static shear strength of which increased significantly with decreasing water content.

Because of the above perspectives, it is necessary to find out how the sub-ballast materials used in old Finnish railway tracks perform with

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water contents close to the saturated state. The following research questions were set:

(1) To what extent do the properties of the sub-ballast materials of typical existing Finnish tracks weaken under cyclic loading when the water content increases close to the saturated state?
(2) What influence do the parameters describing the granularity of the material (fines content, median grain size, uniformity coefficient) have on the material's resistance to the cyclic loading at different water contents?
(3) Is it possible to make a quantitative estimate of the influence of rolling stock axle load on the permanent deformations of sub-ballast?
(4) Is the improvement of track drainage still an adequate method in the light of this study's results?

Theoretical framework

Material properties that influence soil resistance to cyclic loading

According to Li and Selig [15], cyclic loading and fine-grained materials with excessive water content establish a poor combination in terms of track geometry stability. The combination of soil and water is very complex and there are many different factors that have an effect on soil's capacity to withstand the external loading at different water contents. Typically, the considered situations are divided into saturated or unsaturated states. Especially in a saturated or almost completely saturated state, there is a risk of an increase in pore pressure, which can lead to a collapse in the soil strength.

With unbound material, coarse granularity generally improves the material's ability to withstand external loading, while uniformly grained and fine grained (silty) soils have usually been considered unsuitable for continuous cyclic loading. Crushed rock aggregates also differ from natural materials because the contacts between the particles are different. Crushed rock aggregates are formed from sharp-edged particles that do not slide as easily as rounded natural sand particles. The shape of particle size distribution curve, which also indicates the compaction characteristics of the material, also affects the resistance to cyclic loading. Materials with a high dry bulk density also generally have a high stiffness and shear strength. This is explained by the fact that the grain structure is more stable as the smaller particles fill the voids between the large particles. However, a well-graded and very dense particle structure can result in low water permeability and make the material susceptible to the development of excess pore water pressure when exposed to cyclic loading. For this reason, some studies have recommended that the material should be sufficiently permeable under cyclic loading [1,10,14,27].

Under static load, the matrix suction pressure, which depends on the degree of the saturation, increases soil shear strength by increasing the effective stresses. Much research has been done on the subject, but estimating the additional shear strength caused by matrix suction has proven difficult. One of the best known methods is that of Fredlund et al. [6], which adds the influence of matric suction as a part of normal stress in the traditional Terzaghi formula, but other methods also exist. The direction of change in water content is also important for the development of soil strength properties, as during the hysteresis of water content the suction pressure is higher in the drying direction compared to hydration [6,7,8,30,31].

The ability of a material to withstand cyclic loading has been studied from several different perspectives. High-amplitude loading, which often occurs in earthquakes, can lead to rapidly developing large pore water pressures and total soil liquefaction. On the other hand, loading with a lower amplitude at high number of repetitions can cause long-term deformations, which cause maintenance problems, for example, on railways [32]. Typically, fine-grained sands and silty sands have been found to be sensitive to cyclic loading [14].

Trinh et al. [29] examined the properties of a worn French ballast layer, which in a way acted as a substructure layer on the track, under cyclic loading at different water contents. This material, which contained stones of 25–60 mm (44%), sand and a lot of fines (18% smaller than 100 μm), clearly deformed increasingly with increasing water content. In the experiments, they found an increase in permanent axial deformation from 0.4% to 1.4% as the water content increased from 4% to 6%. In the saturated state, the specimen collapsed with a rather small number of load repetations. The effect of water content on the performance of the substructure layers therefore cannot be ignored. Suiker

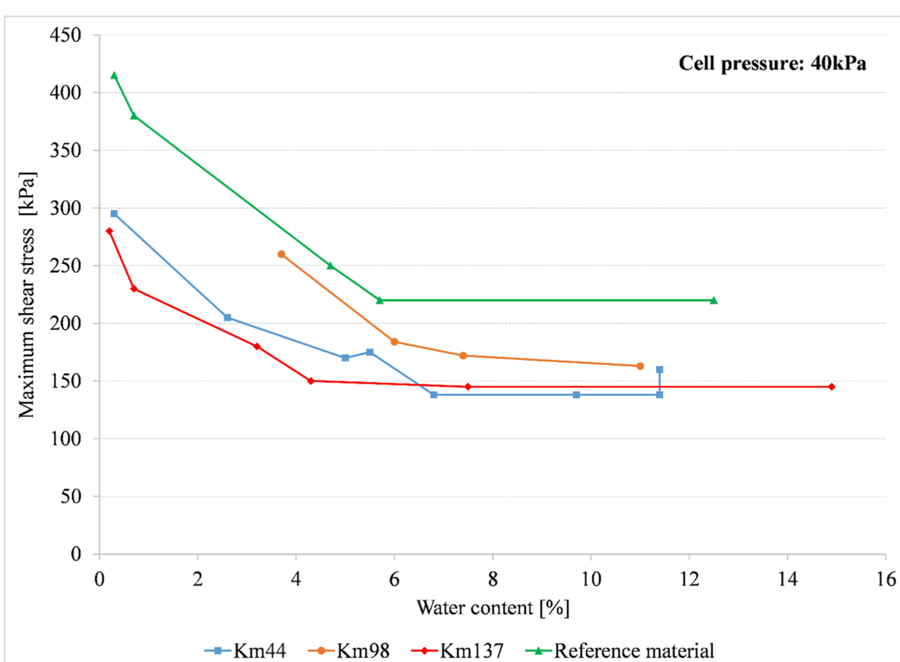

Fig. 1.1. The Results of the static triaxial tests. Three of the samples were taken from the track sub-ballast layer of an old Finnish track at kilometer poles 44, 98 and 139, respectively [12].

et al. [24] have also examined the performance of substructure material and support layer materials using both static and cyclic loading triaxial tests. The average grain size d_{50} of the substructure material they used was 0.75 mm, the coefficient of uniformity was about 11, and the fines content was about 2%. In the test process, the confining pressure was either 41.3 kPa or 68.9 kPa and the cyclic deviator stress in relation to the maximum value of deviator stress at failure in monotonous loading triaxial test ranged from 0.495 to 0.975. In this kind of loading arrangement, they found that the cyclic loading increases both the strength and stiffness of the substructure material, i.e., the cyclic loading at the applied levels did not result in immediate collapse of the test specimen. At higher loading levels some momentary deformations occurred, but their growth leveled off. In their experiments, Suiker et al. used the optimum water content of 5.5% determined for the material.

Traffic loads on track substructure

The interaction between the track and the rolling stock is complex. The quasi-static approach has been applied to in the traditional dimensioning, in which a load surcharge caused by a dynamic effects has been added on top of the static load. The frequency of the dynamic load varies from 0.5 Hz to up to 2000 Hz [3]. In the Netherlands, it has been estimated that it would be possible to reduce the degradation of the network geometry by up to 23%, mainly by controlling the dynamic load [23]. It is obvious that the momentary dynamic loads vary along the railway line, and especially in the vicinity of different transition zones (tunnels, bridges, railway switches, embankments) the increased dynamic load caused by rolling stock has also increased the deformation [18].

In order to be able to estimate the risk for permanent deformations in track substructure it is necessary estimate the amount of vertical stress increase that takes place in the substructure. For Finnish track structure layer thicknesses, the matter has been clarified by Kolisoja et al. [11]. In that study the effect of increasing axle loads to 250 kN was modeled with the BISAR, a multi-layer linear elastic analysis software delivered by oil company Shell. The results of the study are illustrated in Fig. 2.1, which shows both the modeling results and the measurements of vertical stress increases during the passage of a test train with an axle loads of 250 kN. Measured vertical stresses up to 80 kPa occurred at a depth of 0.5 m from the bottom surface of the sleeper. At 1.0 m from the bottom of sleeper, the vertical stress increases were only 20–30 kPa. The stresses are very similar to the vertical stresses estimated later with a more advanced 3D FEM model [19] and shown in Fig. 2.2. The results of FEM modelling indicate that at the top of sub-ballast layer vertical stress increase is about 80 kPa, but with depth the stress increase dampens rapidly.

Vertical stress distribution in track substructure has also been studied elsewhere in full-scale laboratory experiments. Feng et al. [5] have measured stresses in structures caused by 170 kN and 220 kN axle loads

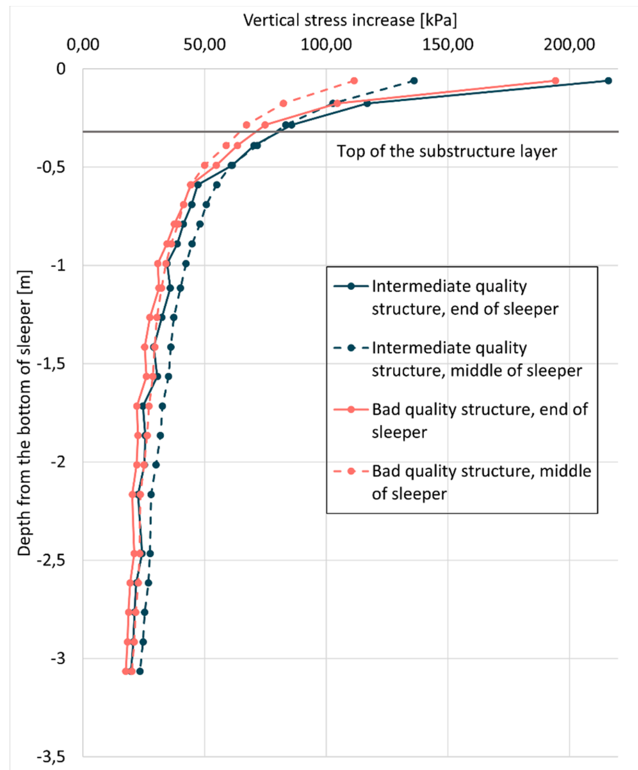

Fig. 2.2. FEM modelling results of vertical stresses caused by a 250 kN axle load in track embankment as a function of depth [19].

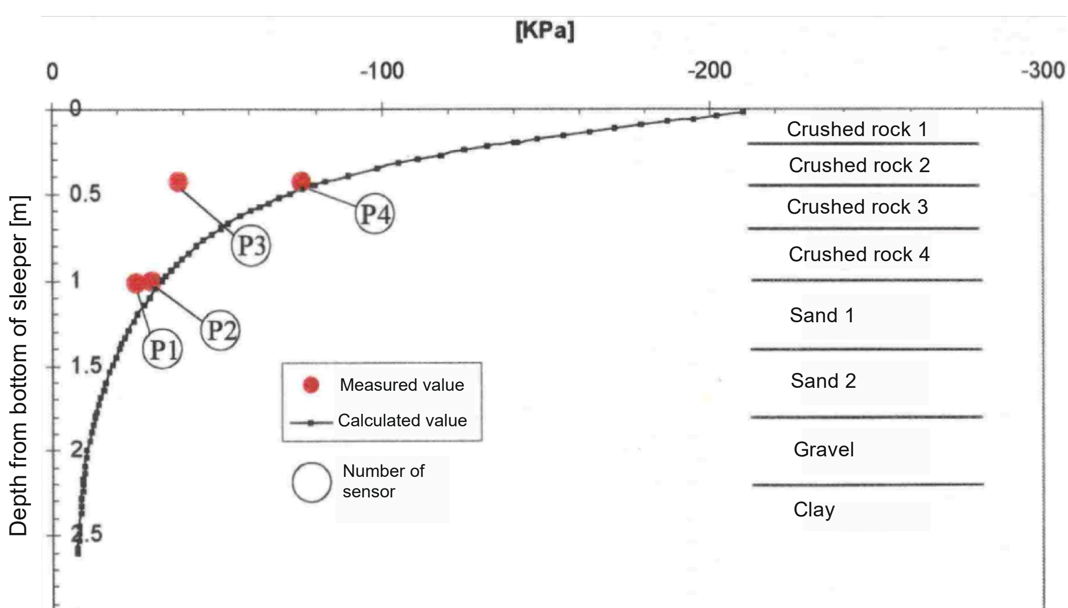

Fig. 2.1. Calculated and measured vertical stresses as a function of depth below the sleeper under a 250 kN axle load [11].

at different speeds in the full-scale laboratory test arrangement. At an axle load of 170 kN, they found a 37–81 kPa stress increase at bottom of the ballast layer. In the substructure layer, vertical stresses of 18–49 kPa were observed. At a higher axle load of 220 kN, below the ballast layer, vertical stresses of 47–109 kPa were observed. The ballast layer under the sleeper was 0.3 m and the substructure layer was 0.7 m thick. The amount of vertical stress increase depends also on the sideway location. The highest stresses in the structure were measured from the rail line and the lowest below the center of sleeper. Shahu et al. [21] found a vertical stress of 40–90 kPa at a depth of 0.4 m below the bottom of the sleeper with an axle load of 290 kN. Trinh et al. [29] concluded that the vertical stress of substructure is 40–90 kPa with the axle loads used in France. It can therefore be concluded that for a substructure, a vertical stress increase of 40–80 kPa is an appropriate estimate of the operational situation, and this range can be used to evaluate the laboratory results.

In addition to vertical stresses, there are horizontal stresses in the track embankment. The magnitude of the horizontal stress in this case was estimated using a previously developed FEM model [9]. Based on those analyses, 30 kPa was chosen as the confining pressure to be used. The same 30 kPa confining pressure has been used also in the study of ballast materials, which has been found to be close to the in-situ situation [29]. On the other hand, Touqan et al. [26] used a 90 kPa confining pressure and a vertical stress of 300 kPa. That is considerably higher than the vertical stress increases applied to the substructure in a static loading condition in Finland. The material used in Torqan et al. study was also clearly coarser ($d_{50} = 7.4$ mm) compared to the sands used in this study.

The loading frequency used in the cyclic loading test series of this study, 5 Hz, was the same as that of Suiker et al. [24] and Trinh et al. [29]. This loading frequency is not far from the loading frequency caused by the bogies of train wagons at the speeds used in Finland. However, the speed of rolling stock on the track varies, as do the distances between wheelsets and bogies. In addition, the rolling stock causes track loads at different frequencies. Some studies have found that low dynamic frequencies are mainly causing the excessive deformation [23]. One difference between the in-situ situation and the laboratory tests lies also in the length of the load pulse series, as in Finland there is no continuous load of 10,000 pulses on the track, and there is always some time interval between trains. These discrepancies would play a significant role if the loads were to cause pore pressure build-up in the materials.

Materials and methods

Materials

The laboratory test series of this study included four different track substructure materials, three of which were taken from the sub-ballast layer of a southern Finnish track section. The samples were collected from the depth of 0.55 m to 1.35 m below the top surface of sleepers. A significant part of the Finnish rail network was built at the turn of the 19th and 20th centuries using available local materials that may not meet current material requirements. For this reason, a reference material with a low fines content and fulfilling the current granularity requirements for the substructure layer in Finland was included in the laboratory tests. The grain size distribution curves of the test materials are shown in Fig. 3.1 and the parameters describing their granularity in Table 3.1. The Km137 material is remarkably uniformly graded. The grain size distribution curves of the reference material and the Km137 sample are similar in shape, but there is a significant difference in the mean grain size, as d_{50} of Km137 is 0.4 mm and that of the reference material is 1.1 mm. The Finnish sands are usually rounded due to their glaciation-time formation history, and they usually consist of hard minerals like quartz and feldspar. The reference material particle shape was somewhat more angular than that of other samples.

Test specimen preparation

Test were conducted by using a specimen diameter of 200 mm and height of 400 mm. Due to the limited volume of material samples, the same material had to be used multiple times. After drying and cooling, the samples were moistened in a concrete mixer to a water content of

Table 3.1
Grading parameters from tested materials.

Sample	Average particle diameter d_{50} [mm]	Coefficient of uniformity [–]	Content of fines <0.06 mm [%]
Reference material	1.1	4.7	2.5
Km44	0.7	10.0	4.9
Km98	0.5	10.0	6.7
Km137	0.4	3.5	3.7

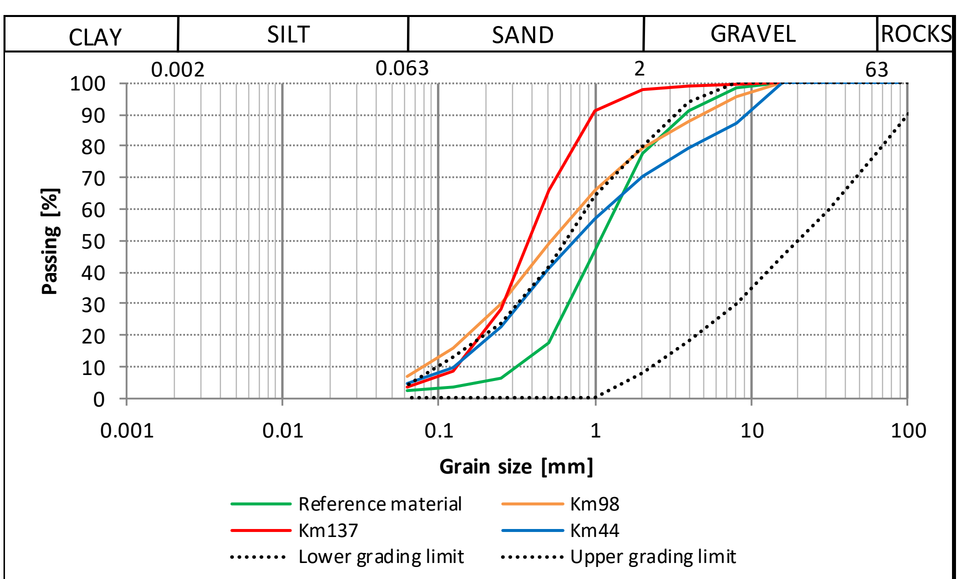

Fig. 3.1. The measured grain size distributions of test materials. Dashed lines describe the grading limits of Finnish Transport Infrastructure Agency for sub-ballast material.

7%, which was considered to be a suitable compaction water content based on Proctor compaction tests. However, this water content turned out to be slightly too high in some of the specimens and water was leaking out during the compaction work. Approximately 30 kg of sample material was required for each triaxial test specimen. Compaction took place in a steel mold with a vibratory compaction device in four 100 mm layers. The compaction time was about 20 s per layer, which produced the maximum compaction achieved by that method. The specimens were extruded from the steel mold into a rubber membrane, displacement sensors were installed on the specimen surface, and the specimen was placed inside the test cell. Fig. 3.2 shows the triaxial test equipment used for the large-scale cyclic loading test.

Testing principles

Cyclic load triaxial tests were performed as drained tests, i.e., water was allowed to drain from the specimen through the top outlet of the test cell. The tests were divided into three different series:

- In the A-series tests, the water content was the compaction water content from start to finish.
- In the B-series experiments, the specimen was prepared and conditioned at the compacting water content. The specimen was then saturated by feeding in water from the bottom of the cell. The resilient and permanent deformation test series were performed in this state.
- The C-series specimen was conditioned and saturated like in the B-series tests, but then the specimen was let to drain gravitationally before testing.

The saturation in the B- and C-series tests was carried out by introducing water from a water tank at a height of about 1.5 m into the base of test specimen. The time used for the saturation process varied considerably due to the different water permeabilities of the materials. The reference specimen and specimen Km137 were easily saturated, but the saturation of specimens Km44 and Km98 took longer. Correspondingly, more water remained in these materials in the C-series tests after saturation and gravitational drying.

The loading process started with cyclic conditioning. The purpose of the conditioning was to remove any gaps between the loading cap and test specimen and to ensure coherence of the test specimen. The conditioning phase consisted of a cyclic vertical stress of 150 kPa applied during a 70 kPa confining pressure. The conditioning pulses were applied as long as permanent deformations developed, but not to more than 2000 load pulses. In general, significant deformations slowed down very rapidly at the beginning of the conditioning phase.

Fig. 3.2. Large-scale test equipment used in the cyclic load triaxial test. Specimen dimensions were d = 200 mm and h = 400 mm.

In the resilient deformation tests, a series of 100 pulses was applied to the material at a frequency of 1 Hz at different confining pressures. The loading procedure was based on the low stress level specification of EN 13286-7 [4], but the highest deviatoric stresses at all confining pressures were skipped to avoid too early destruction of the specimen. The deviator stresses used are listed in Table 3.2. The load series was interrupted if there was a permanent axial deformation of more than 0.25%. As a cumulative maximum permanent axial deformation in the resilient deformation test series, 0.5% was allowed, which means a permanent compression of 2 mm with a 400 mm high specimen.

As stated before, a confining pressure of 30 kPa was used in the permanent deformation tests. The specimens were subjected to a 10,000 pulse load series starting from a deviator stress of 20 kPa. After each series of pulses, the deviator stress was increased by 10 kPa until the specimen collapsed or the specimen deformations became critical to the test equipment.

Results

This chapter presents the results concerning resilient deformation behavior and permanent deformation test series performed for 13 different test specimens. The water contents of the specimens are reported as saturation degrees measured after the test. The specimen was disassembled in three parts to determine the water contents in the top, middle, and bottom parts of test specimen. These water contents have been averaged and compared to the calculated maximum water content. The calculated maximum water content has been determined using the dry bulk density and the porosity calculated on the basis of the typical solid density of Finnish rock materials (2650 kg/m^3). The saturation degrees are shown in Table 4.1. Minus and plus signs after the saturation degrees are indicating the direction of latest water content change during test specimen preparation procedure. Thus the plus sign indicates that water content has been increasing from compaction water content and the minus sign indicates that test specimen has been drying from the saturation water content. In some of the test specimen there was water content variation with depth. That inevitable phenomenon was especially observed in the most coarse grained materials due to the effect of gravitation. This might have caused different behavior in different parts of the specimen and therefore the permanent deformations have been determined based on the full height of test specimen.

The results of the resilient deformation tests are summarized in Fig. 4.1, in which the resilient modulus values obtained at different water contents have been presented as a function of the sum of principal stresses. The highest resilient moduli values were obtained with the highest dry density specimens of Km44 and Km98. The differences

Table 3.2
The confining pressures and deviatoric stresses during the resilient deformation tests. The test was done according to EN 13286-7 [4].

	Confining pressure [kPa]	Deviatoric stress [kPa]	Number of pulses
Series 1	20	20	100
	20	30	100
	20	50	100
Series 2	35	50	100
	35	80	100
Series 3	50	80	100
	50	115	100
Series 4	70	115	100
	70	150	100
Series 5	100	150	100
	100	200	100

Table 4.1
Dry densities and water contents of tested specimens.

Test label	Dry density [g/cm^3]	Void ratio	Saturation degree [%]	Water content bottom [%]	Water content middle [%]	Water content top [%]
Reference material						
1A1*	1.768	0.50	40	8.7	6.3	6.2
1A2	1.786	0.50	40	8.7	5.6	4.8
1B	1.733	0.53	70+	17	7.6	17
1C	1.782	0.49	30-	6.6	4.9	4.3
Km137						
2A	1.764	0.50	35	7.4	7.0	5.8
2B	1.751	0.51	65+	14.1	13.1	8.0
2C	1.733	0.53	50-	13.4	8.3	5.4
Km98						
4A*	2.083	0.27	60	6.9	6.3	4.7
4B	2.083	0.27	70+	7.0	7.0	6.7
4C	2.062	0.29	55-	6.5	6.2	5.5
Km44						
3A	2.071	0.28	65	7.1	6.7	5.1
3B	2.137	0.24	80+	7.4	6.5	6.9
3C*	2.069	0.28	70-	7.4	7.3	6.3

* Resilient deformation test was not successful because of sensors failure.

between moduli values are not as great as observed differences in cyclic loading tests, but the measured moduli values are generally lower in the samples of high saturation degree.

The results of the cyclic loading tests are reported as the rate of accumulation of axial strain per load pulse. The advantage of that approach is that the permanent deformation developed in the track structure can then be roughly estimated when the average axle load and traffic volumes of the rolling stock on the track are known. The axial strain rate has been calculated based on the difference of vertical displacement readings at pulses number 50 and 9950, because during the pauses between the pulse series, the specimen was found to recover temporarily. The accumulation rate of axial strain has been calculated only for full-length pulse series, i.e. those in which the test specimen collapsed have not been considered. The deformations shown in this way are summarized in Fig. 4.2. Two types of collapse mechanisms were observed in the tests, as the reference material endured for a long time with low permanent deformations until the specimen became fragile and broke down, whereas in the Km44 and Km98 specimens in particular, the development of axial strain started quite early and increased continuously with increasing vertical stress.

Discussion

In the cyclic loading tests performed, there were clear differences in the loading resistance of the tested materials. The collapse mechanisms were also different for the materials, as the collapse of the reference material was fragile, while the collapse of the other materials was more gradual. The best cyclic load resistance was achieved with the driest specimens and the reference material was by far the most durable. Correspondingly, the highest rates of axial strain accumulation were measured in the specimens with the highest water content. In static triaxial tests, matrix suction began to increase the shear strength of test materials below saturation degree of 50%. Lower than 50% saturation degrees were observed in the cyclic loading test specimen 1A1, 1A2, and 1C of the reference material and in test 2A of the Km137 material. The differences observed in cyclic loading tests at saturation degrees of more than 50 % are not due to the effect of matrix suction.

The specimens did not achieve a calculated 100% saturation degree. It is obvious that with a gravitational saturation process, air easily remains in some of the pores of the specimen, and this takes a long time to dissolve. In the tests performed, the saturation time varied according to the material and for the Km44 and Km98 materials, the saturation process lasted for several days, while in the reference material the water flowed through the material in less than half an hour. This was expected because the wide grain size range combined with the higher fines content in the Km44 and Km98 material samples results in low water permeability. It is also possible that the oven drying of the Km44 and Km98 materials made the silt/clay they contain very slowly saturable. It is therefore likely that with a significantly longer saturation time or other saturation methods, the air trapped in the pores would have been removed more efficiently and the loading resistance of the materials in high saturation degree would have been even weaker than what was now measured. In Finland, in-situ sub-ballast saturation degree have been measured to vary from 30 to 100 % depending on the depth and site drainage properties. More precise analysis of in-situ saturation degrees in railway substructures will be reported in an upcoming paper.

In the predicted operating vertical stress range of 40–80 kPa, the differences between the materials narrowed, but there were still clear differences. Different degrees of saturation were also found to influence the rate of deformation developed in the specimen in the operating stress range. Based on the results, a simplistic calculation was made of the total deformations formed in the sub-ballast layer. It was found that the vertical stress increase caused by passenger train axle loads is so small (near the lower limit of the operating vertical stress range) that the deformation developed in all of the materials remains very small even if the materials are close to the saturated state. This can also be clearly seen from Fig. 4.2, because with a vertical stress increase of less than 50 kPa, the axial strain accumulation rates were very low. The situation changed in the case of a vertical stress increase of the order of about 80 kPa, corresponding to an axle load of 250 kN. In this case, clear differences were observed between the materials so that much faster deformation began to occur in the materials at high saturation degree. In particular, the specimen km137 in high saturation degree caused a multiple times annual deformation in this calculation compared to the other materials.

The ability of materials to withstand cyclic loading cannot be solely predicted by using the resilient moduli. The observed differences in resilient moduli values between the different saturation levels were small. Densely packed materials km44 and km98 performed best in the resilient deformation tests, but they were still weaker than the reference material in the cyclic test. It is therefore obvious that the short-term loading series of the resilient deformation tests, with a maximum of 100 pulses, does not provide a reliable prediction of cyclic loading resistance. On the other hand, in a real loading situation, there are always intervals between trains, so a continuously propagating cyclic test series of 10,000 pulses can also overestimate the development of permanent deformations. Intervals in the cyclic loading series allow time for pore water pressure to dissipate.

Vertical cyclic loading in the triaxial test cell is a well-established test method, but it does not fully describe the situation in the actual operating environment. In a railway environment, the movement of rolling stock causes principal stress rotation. This has been investigated, for example, by Mamou [16], Cai et al. [2], and Thevakumar et al. [25]. Their studies have shown how the rotating load axis can indeed play a significant role in the deformation behavior of granular materials. This is something that should be considered more closely if laboratory tests are aimed to be used to accurately estimate permanent deformations.

The fines contained in the granular material have a divaricate effect on its performance. The fines impede the flow of water and thus easily increase the water content of the structure, but on the other hand, Soliman and Shalaby [22], for example, observed in their experiments how the loading resistance of gravel materials improved with a reasonable amount of fines. They described the phenomenon as being due to the fact that the round-grained gravel needs some fines to prevent

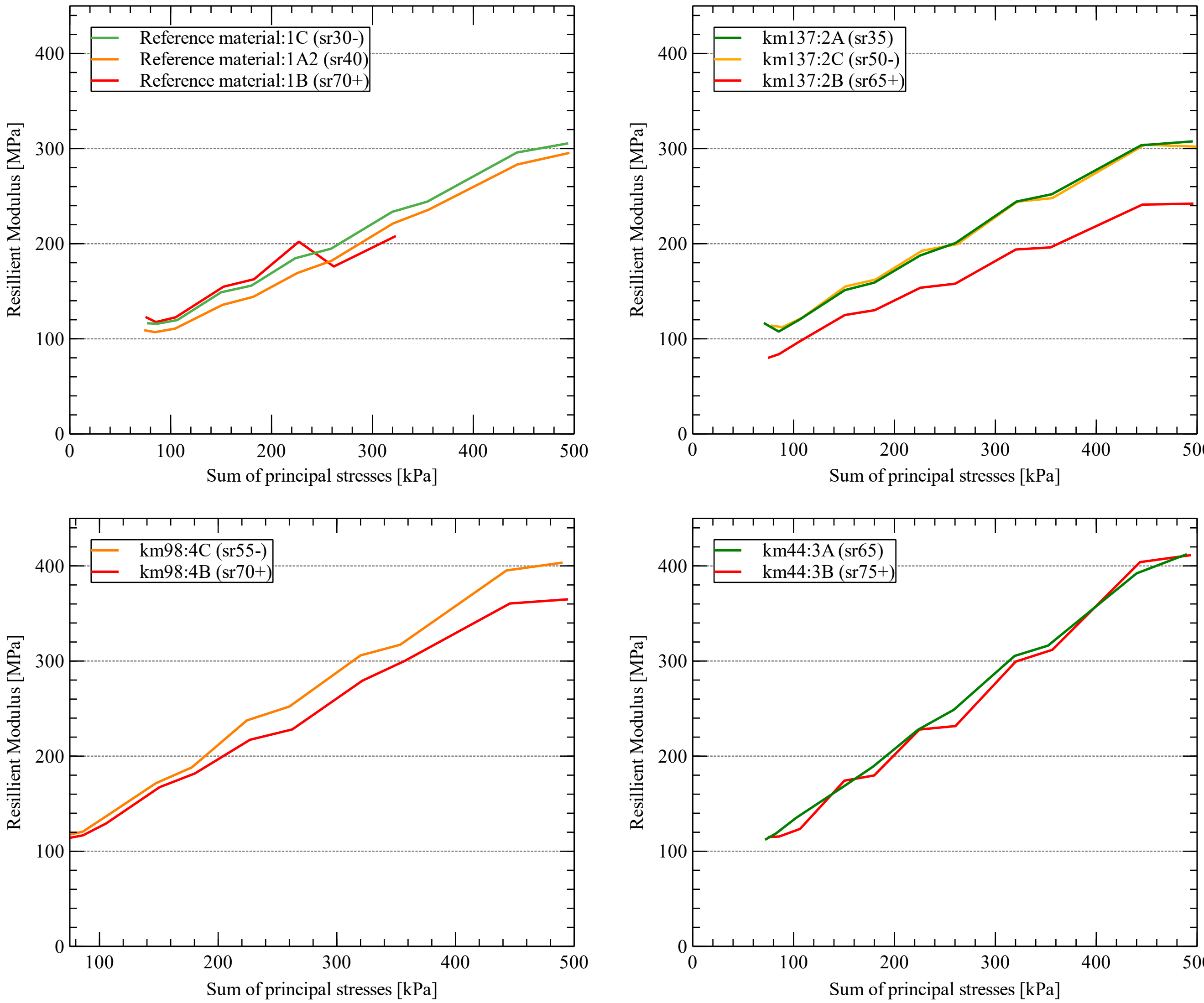

Fig. 4.1. Measured resilient modulus values of the tested specimens.

the particles from slipping past each other. This may explain the previously mentioned difference in the failure mechanisms of the specimens, as there was no fragile breakdown behavior in the specimens km44 and km98, which occurred in the reference material.

Conclusion

This study was part of a larger project on track drainage. The study provided indications of how the water content of the track substructure has an effect on its loading resistance. This is especially emphasized just below the ballast layer. Based on the results, drainage improvements should be directed to sites where the water level is exceptionally high. If the substructure is not saturated with water or the material is not exceptionally sensitive to the effects of water, it is unlikely that the development of deformations of the track will be significantly reduced by improving the drainage. The finding fits well with the work of Trinh et al. [29], who depict that previously track deformation has been attributed to poor drainage in France. For this reason, the importance of drainage has been emphasized in the modernization of tracks required by rolling stock with higher axle loads and speeds, but on the other hand, it has been observed how even older structures can perform quite well without proper drainage. Therefore, they also ended up stating how material-specific sensitivity to water content should be taken into account in track maintenance and action planning.

Answers to the research questions:

- In all four materials examined, the loading resistance decreased with increasing water content. Therefore, a high saturation degree condition should be avoided. It can be concluded that if the material meets the current granularity requirements of the Finnish Transport Infrastructure Agency, its ability to withstand the cyclic load is sufficiently good at different water contents. If the material is on the finer side of the required granularity range, it is likely to have problems with its performance, especially at high water contents.
- The best-performing reference material, which clearly meets the current granularity requirements, withstood the cyclic loading tests best. The material performed well, although its dry density is low and close to the dry density of the sample Km137. In Finland, according to current regulations, the median particle size d_{50} of the sub-ballast layer must be at least 0.6 mm. Based on the study, risks of deformation increase significantly if the average grain size of the material is too small. Especially the small average grain size, low dry density, and low uniformity coefficient are a risky combination. Material with too low median grain size and uniform grain size distribution, such as Km137, should not be subjected to loads caused by heavy

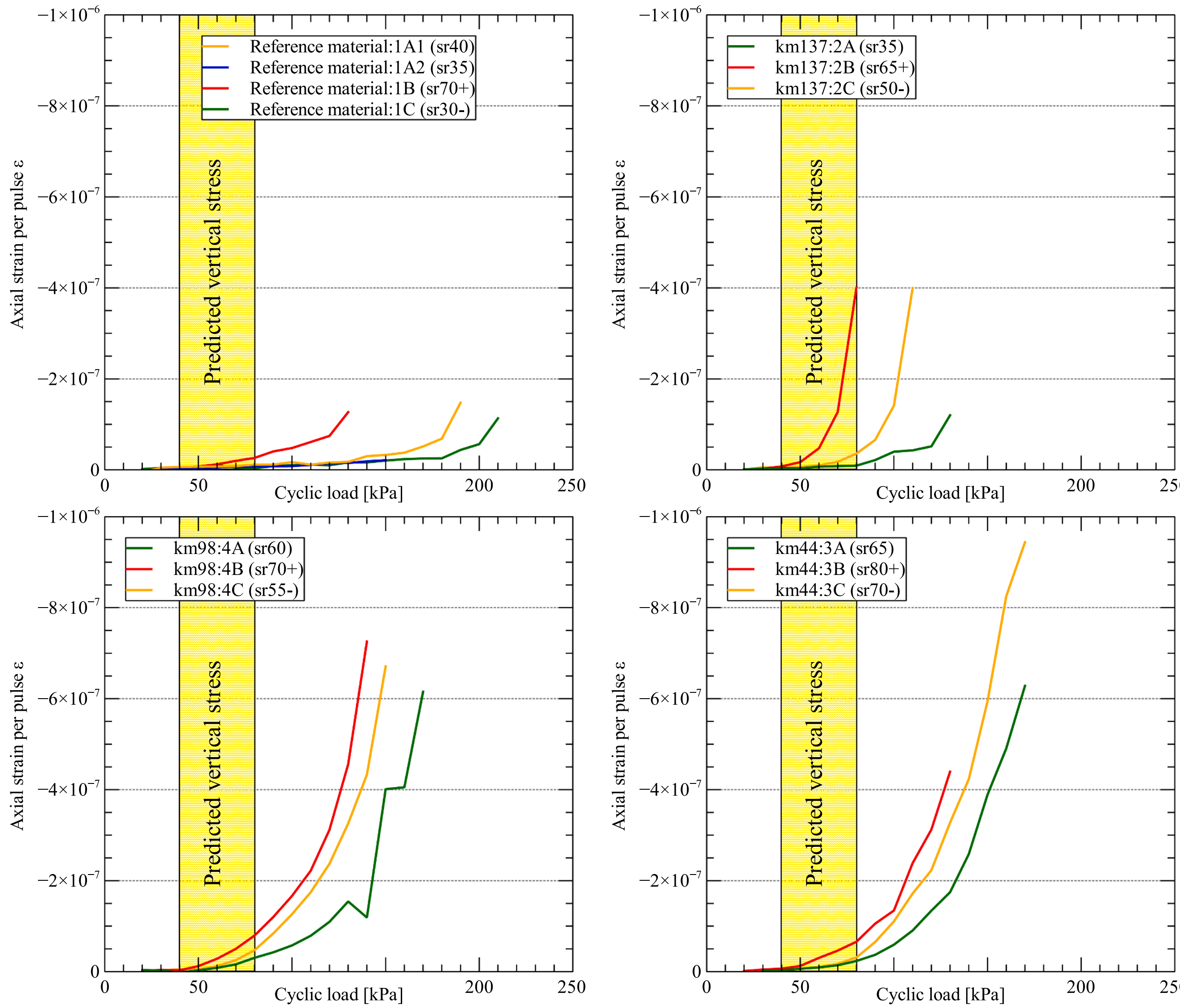

Fig. 4.2. Accumulation rate of axial strain per load pulse. The yellow area in the graphs represents the predicted level of vertical stresses in the sub-ballast layer. A confining pressure of 30 kPa was used in all cyclic loading tests. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

axle loads in a saturated state. Moderate (less than 5%) fines contents are unlikely to cause problems.

- Based on the conducted tests, the differences in the functionality of the substructure materials in Finland are small at axle loads of about 160 kN typical for passenger traffic. This is natural, since at the depth of the sub-ballast layer, the increase in vertical stress at this axle load is small. The situation is different in freight traffic, where vehicles with axle loads of both 225 kN and 250 kN are used. Already the 225 kN axle load vehicles start to fully utilize the strength properties of substructure materials, especially with the low-quality materials mentioned above. With axle loads higher than this, the situation becomes obviously more critical. On the other hand, in Finland, traffic with an axle load of 250 kN travels mainly on high-quality sections of track which are well-built with proper drainage systems. In addition, it is also necessary to take into account the discontinuity points of the track, where the dynamic load increase can be significant and thus more of material's load resistance capacity is utilized than in line parts.
- Efficient drainage and a reasonable water content increased the loading resistance capacity of the materials in laboratory tests. Thus, the structural layers of track should be drained properly. However, it is likely that sites with unevenness problems are multi-problematic and the benefits measurable by improving drainage alone may be small unless the track sub-ballast layer is nearly fully saturated.

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CRediT authorship contribution statement

Juha Latvala: Investigation, Data curation, Writing – original draft. **Pauli Kolisoja:** Supervision. **Heikki Luomala:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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