THE BALTIC JOURNAL OF ROAD AND BRIDGE ENGINEERING
2019/14(3)

ISSN 1822-427X/eISSN 1822-4288
2019 Volume 14 Issue 3: 384–404
https://doi.org/10.7250/bjrbe.2019-14.449

LONG TERM BEHAVIOUR OF AN ASPHALT PAVEMENT STRUCTURE CONSTRUCTED ON A GEOGRID-REINFORCED SUBGRADE OVER SOFT SOILS

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Received 25 April 2019; accepted 29 May 2019

Abstract. Many roads with asphalt pavement are being reconstructed every year, as their quality becomes insufficient by the requirements. As it is well-known, old roads were built not in the very best quality, so doing reconstruction projects in the most cases there were required to deal with soft soils that are under the existing road structure. Geogrid reinforcement was widely used

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to solve issues of soft soil in Lithuania. There are projects where geogrid reinforcement is used to control road pavement roughness when there are layers of peat or silt under road structure instead of using concrete piles or geosynthetic-encased soil columns. This type of geogrid reinforcement application is unexplained in any normative-technical document but widely used in Lithuania. This application was usually made constructively without any calculations, choosing the reinforced solution by reducing the geogrid tensile strength or layer quantity compared to reinforced load transfer platform over piles. This paper evaluates the long-term influence of geogrid-reinforced subgrade on the roughness of asphalt surfacing and bearing capacity of the road structure when the soft peaty soils stratify in the deeper layers of the subgrade. There were compared the reinforced sections to adjacent sections to see the effect and fortunately a large number of adjacent sections were also strengthened, mostly by lime stabilisation. Therefore, this comparison allows making more insights on the long-term performance of the strengthened subgrade and influence on the road quality. This research gives recommendations on how the geogrids has to be selected to be used in this kind of application.

Keywords: bearing capacity, geogrids, geosynthetics, pavement roughness, soft soil, soil reinforcement, subgrade.

Introduction

Due to the deterioration of the Lithuanian road conditions, the asphalt pavement roads are being reconstructed every year. To prepare a reconstruction project of the road with the old asphalt surfacing, the designer has to evaluate geotechnical investigations. It is essential to understand the geotechnical conditions of the subgrade and this is quite hard when dealing with atypical situations. It is usual for a designer to find peat or silt layers under the subgrade of the existing road, especially when the road is crossing areas with lakes or swamps nearby. However, it is often quite hard to evaluate how to solve a soft soil problem in the most efficient way.

By the Lithuanian normative-technical documentation *ĮT ŽS17 Automobilių kelių* žemės *darbų atlikimo ir* žemės *sankasos* įrengimo *taisyklės* designer has two options to solve cases with peat and silt in the subgrade, either to dig it out and replace it with better quality soil, e.g. sand and gravel, or to install piled embankment. This problem of the soft peaty soil in the existing subgrade is actual not only in Lithuania but also in other countries (Poland, Latvia, Ukraine and others). Lithuanian road reconstruction projects had to deal with 0.4–1.4 m thickness of well-decomposed peat and (in some places) additional 0.7–1.5 m thickness of the silt layer that starts in 2.0–3.0 m depth from the top of the existing road structure. To install piles for such conditions is a costly solution, knowing that peat or silt has some level of consolidation. This condition is critical when there is a need to increase the quality of the roads when having the same budget for road maintenance (Vaitkus, Čygas, Motiejūnas, Pakalnis, & Miškinis, 2016). This problem remains significant. For this reason, after the geosynthetic materials were being started to be used in Lithuania, many road reconstruction projects with asphalt pavement have been implemented over ten years. Those projects used geogrid reinforcement instead of peat excavation and replacement or pile system installation (Wallbaum, Busser, Itten, & Frischknecht, 2014), various strength geogrids were used directly under the road structure or a bit lower, making the replacement with geogrid-reinforced frost-blanket course up to 0.6 m of the existing soil.

The expectations of using geogrid reinforcement for subgrade strengthening was that the reinforced soil under the road structure has to prevent road pavement from cracks, ruts, potholes or bumps that could be caused by the existing partially consolidated layers of soft peaty soil. This type of asphalt pavement structure strengthening is still being used. However, it is not described in the technical guide for geosynthetics used in the road soil work applications *MN GEOSINT ŽD 13 Geosintetikos naudojimo* žemės *darbams keliuose metodiniai nurodymai* (issued in Lithuania in 2013 by Lithuanian Road Administration under the Ministry of Transport and Communications) and neither normative documents of other countries (Vaitkus, Šiukščius, & Ramūnas, 2014) or in other design codes (Meyer & Elias, 1999).

Cuelho & Perkins (2016) performed large-scale field trials to identify the most critical geogrid properties for a sufficient stabilisation and (or) reinforcement function. These field trials concluded that the geogrids, which performed the best were rigid, had stiff junctions and enough tensile strength. However, this field trial is performed using unpaved road constructions and soft clay subgrade, as it is for most of the field trials.

Another type of test, using two layers of stiff geogrid, was performed to investigate the strain level in the geogrid reinforcement and the lateral movement of the entire structure due to post-construction settlement using a paved road structure (Vollmert, Emerslen, & Retzlaff, 2014). It showed that in the working phase, the plastic strains are tiny compared to the elastic strains even in very rigid structures. The study also showed that still a certain amount of plastic deformations are found even in very rigid structures. The tensile stresses must be absorbed to limit the amount of plastic deformation, even if they are developed at tiny strains. Moreover, that research had a geological condition, which had weak peaty clay or fine to coarse sand with some peat layers. However, it did not have more of the peat layers under the tested structure, and it cannot be a direct example of the problem described above.

Valero, Sprague, & Wrigley (2014) did a full-scale trafficking test of geogrid-reinforced subgrade using typical road structure with asphalt pavement. They indicated that all types of geogrid improve pavement-rutting resistance even under severe conditions. However, the subgrade was without any peat layers; it had moisture-sensitive silty sand.

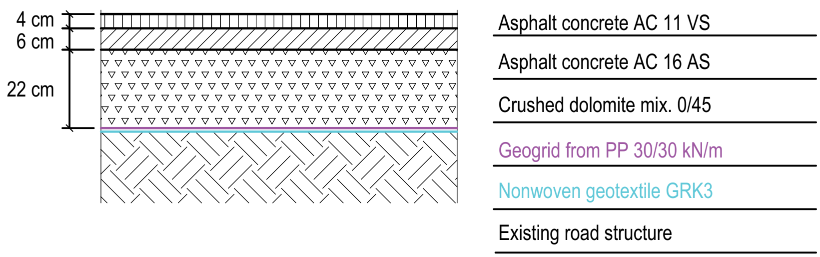
For this reason, large-scale test sections were used to determine whether the geogrid-reinforced subgrade is suitable, looking from the long-term perspective, to compensate for the compressible subgrade conditions. This research covered the International Roughness Index (IRI, m/km) measurements and bearing capacity measurements using Falling Weight Deflectometer (FWD). The aim was to analyse if asphalt pavement with geogrid reinforcement over partially consolidated peat has a trend to perform well after seven years of construction and how geogrid reinforcement influence the IRI (Šiukščius, Vorobjovas, & Vaitkus, 2017). It is also compared to the adjacent sections to identify how it performs in a general view of the road structure.

1. Tested road sections and designed solutions

To be able to get more reliable results, two different categories of roads were selected for the examination when estimating the geogrid influence on the pavement roughness (Šiukščius, Vorobjovas, & Vaitkus, 2018). The first road was the main road A6 Kaunas–Zarasai–Daugpilis (tested sections 66.20–68.76 km and 137.35–142.00 km). The second road was the national road No. 131 Alytus–Simnas–Kalvarija (tested sections 44.80–50.80 km and 52.45–57.12 km). Reconstruction of these roads was more than eight years ago. It was found that 11 sections have the situations as mentioned above, where there are filled soils over the peat or silt layers and where the geogrid reinforcement was used under the road structure.

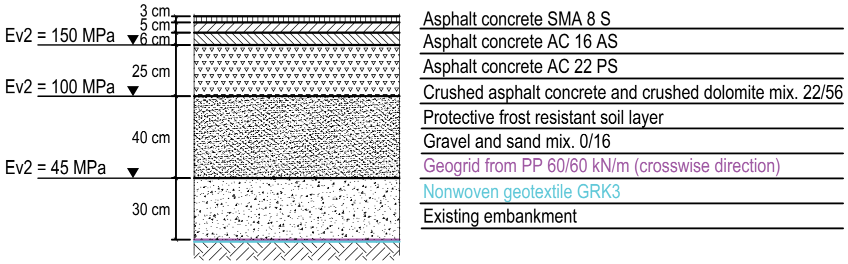
The worst geological situation is in the main road A6 section 67.26–67.45 km. A 0.9–1.4 m thickness of the peat layer, which is compressed until 30% and it starts in 2.3–3.4 m depth. Under the peat layer, in a 2.3–4.8 m depth, there is 0.7–1.5 m thickness of silt layer. Therefore, in total, there are up to 2.9 m of very soft peaty silty soil that is 1.98 m under the road structure. The majority of the sections has the geological situation where there are well decomposed (medium decomposed in the national road No. 131 (46.45–46.72 km)) 0.4–1.3 m thickness of soft peaty soil, and it starts in 2.0–3.1 m depth. Usually, the groundwater level is fully covering the soft peaty and silty soils, and, in some cases, is up to 0.5 m higher.

The road structures were devided into four types comparing the designed solutions based on the *ĮT APM 10 Automobilių kelių asfalto dangų priežiūrai skirtų medžiagų ir medžiagų mišinių panaudojimo ir jų sluoksnių* įrengimo *taisyklės and KTR 1.01:2008 Automobilių keliai*. The first and the weakest one is the road structure No. 1 for the main road A6 (67.26–67.45 km). A 30/30kN/m tensile strength polypropylene (PP) geogrid and a GRK3 class non-woven geotextile (mass per unit area no less than 150 g/m^2; resistance to static puncture no less than 1.5 kN by *MN GEOSINT ŽD 13*) were installed directly under the crushed dolomite mix 0/45 layer (Figure 1). The second road structure No. 2 is for the national road No. 131 (53.91–54.09 km, 55.00–55.09 km, and 56.74–56.94 km). A 60/60 kN/m tensile strength PP geogrid (crosswise) and a GRK3 were installed with a 0.3 m of soil replacement under the road structure (Figure 2). The third road structure No. 3 is for the national road No. 131 (45.965–46.140 km, 46.45–46.72 km, 46.865–46.950 km, 47.320–47.425 km, and 49.220–49.295 km). A 60/60 kN/m tensile strength PP geogrid (crosswise in two layers at every 0.3 m) and a GRK3 were installed with a total of 0.6 m of soil replacement under the road structure (Figure 3). The fourth road structure No. 4 is for the main road A6 (41.047–141.123 km). A 400/40 kN/m tensile strength polyester (PET) geogrid in crosswise direction, a 200/40 kN/m tensile strength PET geogrid along the road, and a GRK3 were installed with a 0.3 m of soil replacement under the road structure (Figure 4).



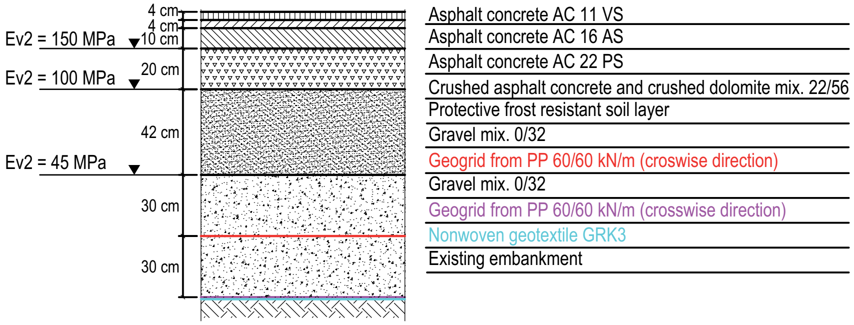
Note: main road A6 (67.26–67.45 km); measurements in cm.

Figure 1. Road structure No. 1



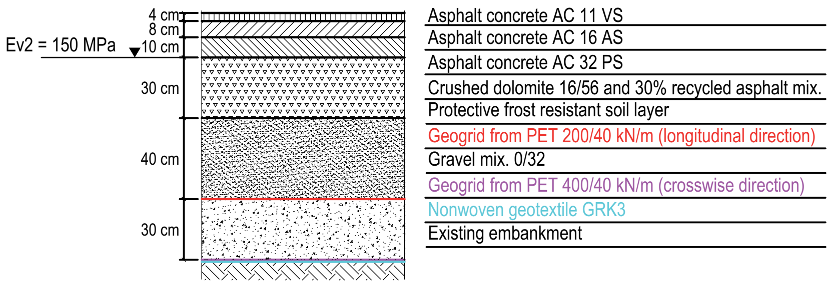
Note: national road No. 131 (53.91–54.09 km, 55.00–55.09 km, and 56.74–56.94 km); measurements in cm.

Figure 2. Road structure No. 2



Note: national road No. 131 (45.300–45.380 km, 45.965–46.140 km, 46.45–46.72 km, 46.865– 46.950 km, 47.320–47.425 km, and 49.220–49.295 km); measurements in cm.

Figure 3. Road structure No. 3



Note: main road A6 (141.047–141.123 km); measurements in cm.

Figure 4. Road structure No. 4

2. General research conditions

The road surface roughness is one of the main parameters that describe the driving comfort, and it is the indicator of the pavement condition. It is known that the asphalt pavement surface is also showing the crushed stone layer and frost-blanket course condition. If these layers are weak, the asphalt pavement becomes cracked or bumpy, and it has a negative influence on the IRI. The weak points are also the soft soils that are under the frost-blanket course, and the critical point is when the snow melts and the subgrade defrosts. At first, the remaining bearing capacity (Abu-Farsakh, Akond, & Chen, 2016) of the soils has to be checked to determine if the geogrid reinforcement is working correctly. On this purpose, the tested section FWD measurements were made on the most unfavourable time for the bearing capacity. That was in the spring of 2018, just a few days after the soils defrosted.

This research aims to indicate how geogrid-reinforced subgrade sections compare to typical subgrade sections without any required strengthening (≥ 45 MPa), lime stabilised and pile strengthened subgrade on the pavement roughness and bearing capacity. Besides, to find out how solutions of geogrid-reinforced subgrade differ from each other by IRI and FWD measurements, especially having cold climate influence (Want, Hoff, & Recker, 2016).

Before comparing the data, it is essential to know that geogrid has a lateral restraint effect (Sakleshpur Prezzi, Salgado, Siddiki, & Choi, 2017) to the limited soil layer thickness. It is usually about 0.6 m. The soil layer closest to the geogrid reinforcement is the primary layer for bearing capacity comparison. In a multilayer pavement system, the main characteristic of the base layer is its comparatively big bearing capacity. It widens the distribution of vertical loads and ultimately decreases the maximum vertical stresses acting at the base-subgrade interface (Zornberg, 2017) (Figure 4).

3. Research methodology and used equipment

Transport Competence Agency performed International Roughness Index measurements. The mobile road research laboratory RST-28 was used to take the IRI measurements. RST-28 laboratory is a mobile, multi-component pavement surface quality measuring unit, which uses 19 laser sensors, 2 accelerometers, 2 gyroscopes and 2 inclinometers that are mounted on the front measuring beam (laser frame). The measurements of the tested road sections were performed one year, four years and seven years after the road section reconstructions were finished. Measurements were taken in both driving lanes and for every driving track of the road measuring the IRI in the intervals at every 20 m.

Dynamic deflection measurement equipment, Dynatest 8000 FWD applies a dynamic load (duration 25–30 ms) that simulates the loading of a moving wheel. Deflection measurements have an absolute 2% ± 2 μm and standard comparative 1% ± 1 μm precision. The load used for the tests is 50 kN. During the tests, the asphalt surface temperature was varying from +13 °C to +22 °C. Comparing the deflection measurements, their values are reduced to the standard loading of 50 kN and a standard temperature of +20 °C. These deflection measurement values are used to calculate the bearing capacity E of the road structure layer.

Deflection measurements were carried out in both driving lanes, on the left driving track. Each road section having a different type of subgrade was tested by measuring three places in that distance, taking more than 25 m from the beginning and the end of the section. The air temperature was measured at the beginning of the deflection test. Falling Weight Deflectometer measurements of the tested road sections were performed eleven years for road structure No. 1, nine years for road structure No. 2, eight years for road structures No. 3 and No. 4 after the road section reconstructions were finished.

Statistical data analysis was performed using essential statistical parameters defining the research data: average and standard deviation. Average and standard deviation values were calculated for different types of road structures taking all the values available for tested sections grouping them to non-reinforced subgrade, geogrid-reinforced subgrade, lime stabilised and pile strengthened subgrade. One tested section includes all IRI values available in both lanes and all-wheel tracks and all FWD values available in both lanes on the left wheel track.

4. Comparison of the pavement roughness and bearing capacity

Test sections have a different type of subgrade. In total, there are four types of subgrade:

- the first one is when the subgrade has stable natural soils that need no strengthening (non-reinforced);
- the second has a geogrid-reinforced subgrade over a peaty silty soils layers;

- the third one has lime stabilised subgrade over natural or filled clayey soil;
- the fourth one has piled subgrade with geogrid-reinforced soil platform over piles in places where are very deep peat layers.

4.1. Main road A6 (66.20–68.76 km)

Geogrid-reinforced section compared to adjacent sections shows that measured IRI value of seven years after construction is below 2 m/km (required limit value for newly constructed asphalt pavement on main roads). It has better average IRI result than non-reinforced section (Figures 5–6). The adjacent sections are without additional strengthening. Section 67.45–67.64 km has a 0.4 m thickness of the frost-blanket course when others have the old road structure as a frost-blanket course. The road structure No. 1 has 30/30 kN/m geogrid reinforcement under crushed dolomite 0/45 layer and is the weakest structure from this research. The geological situation, as described above, is the worst in this research. However, this structure shows that even having a bearing capacity of crushed dolomite weaker by 18.18% (in this instance the geogrid has the most significant influence to the crushed dolomite layer $E2$) compared to a non-reinforced section the average value of IRI of seven years after construction is 9.29% better compared to non-reinforced section. Taking as a starting point the average value of IRI at the first-year, it has been seen that the average value of IRI of seven years after

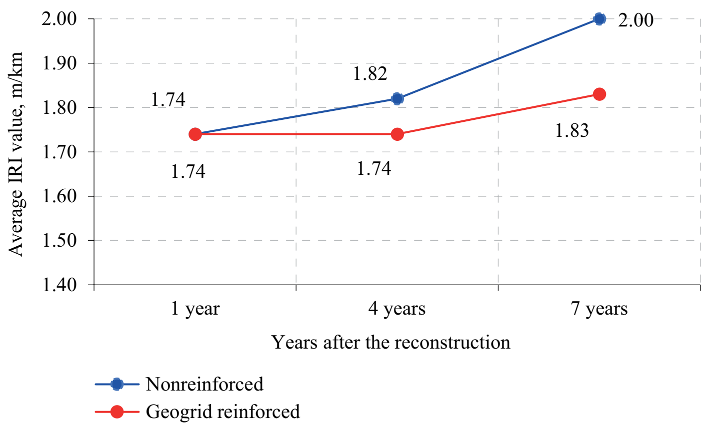


Figure 5. Average values of the International Roughness Index in the main road A6 (66.20–68.76 km)

construction increased by 14.94% in non-reinforced section and increased only by 5.17% in geogrid-reinforced section. The variation of min/max values and standard deviation are much higher for a geogrid-reinforced section (Table 1).

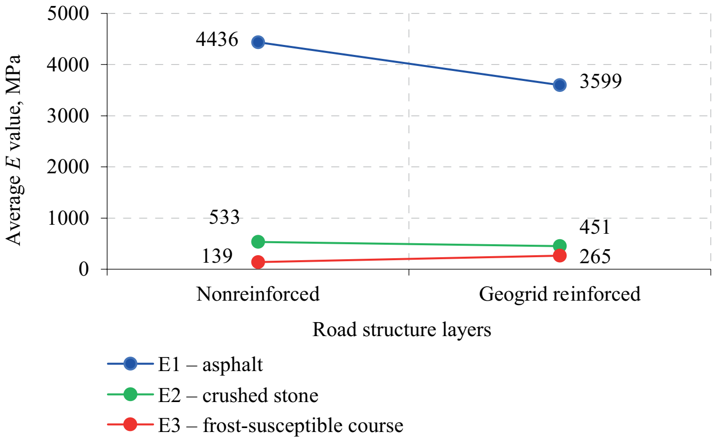


Figure 6. Average values of the bearing capacity in the main road A6 (66.20–68.76 km)

Table 1. Statistical values by subgrade type of measurements in the main road A6 (66.20–68.76 km)

Road structure type		International Roughness Index*, m/km			Bearing capacity for road structure layers, MPa		
		1 year	4 years	7 years	Asphalt	Crushed stone	Subgrade
Non-reinforced	minimum	0.00	0.52	0.55	2709	318	62
	maximum	6.82	5.01	6.75	6367	849	232
	standard deviation	0.83	0.80	0.98	1217	190	60
Geogrid-reinforced	minimum	0.96	1.02	0.93	3038	324	66
	maximum	4.64	4.34	5.87	3969	757	530
	standard deviation	0.73	0.61	1.04	386	164	210

Note: * at years after reconstruction.

4.2. National road No. 131 (52.45–57.12 km)

Geogrid-reinforced section compared to adjacent sections shows that measured IRI value of seven years after construction is far below 2.5 m/km (required limit value for newly constructed asphalt pavement on national roads). It has the best IRI average result (Figures 7–8). The geogrid-reinforced section has 0.4 m of the frost-blanket course and 0.3 m of the additional soil replacement when others have the old road structure as a frost-blanket course. The road structure No. 2 (53.91–54.09 km, 55.00–55.09 km and 56.74–56.94 km) has one 60/60 kN/m geogrid reinforcement under additional granular soil 0/16 layer. It is the third structure from this research by the total geogrid strength. At a depth from 1.1 m to 1.9 m under the geogrid reinforcement, there are up to 1.3 m of peat layers. Lime stabilised layers had 0.3 m thickness and had 3% of burnt lime.

Taking as a starting point the average value of IRI of seven years after construction for the geogrid-reinforced section it is 15.9% less than the average value of IRI for non-reinforced section and 21.59% less than the average value of IRI for by lime stabilised section. Taking as a starting point the average value of IRI of the first-year after construction it has been seen that the average value of IRI of seven years after construction increased only by 3.53% in geogrid-reinforced section, while this value increased by 10.87% in non-reinforced section and by 7.00% in lime stabilised section. The variation of min/max values and the standard deviation are given in Table 2. Falling Weight Deflectometer results show that the best IRI performer for this section (geogrid-reinforced subgrade) has the most significant average values of bearing capacity for crushed stone and frost-blanket course (in this instance the geogrid has the most

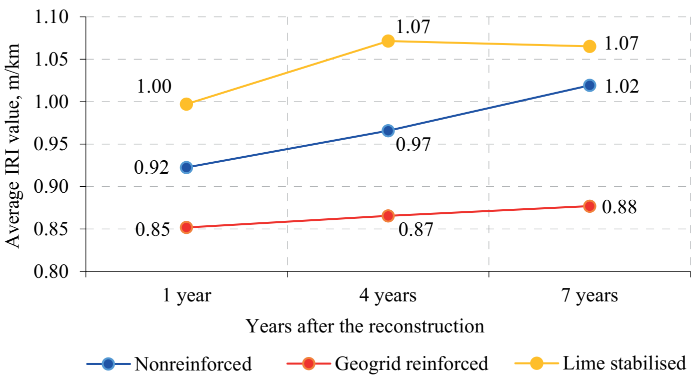


Figure 7. Average values of the International Roughness Index in the national road No. 131 (52.45–57.12 km)

significant influence to the frost-blanket course *E*3). It also shows that the structure having less IRI values is showing more significant values of bearing capacity for crushed stone and frost-blanket course.

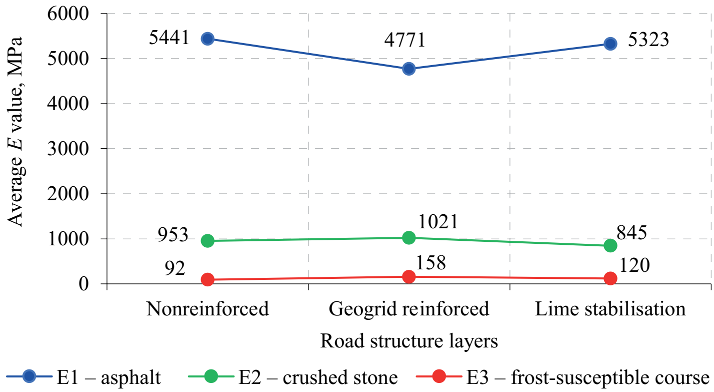


Figure 8. Average values of bearing capacity in the national road No. 131 (52.45–57.12 km)

Table 2. Statistical values by the type of subgrade structure of measurements in the national road No. 131 (52.45–57.12 km)

Subgrade structure type		International Roughness Index*, m/km			Bearing capacity for road structure layers, MPa		
		1 year	4 years	7 years	Asphalt	Crushed stone	Frost-blanket course
Non-reinforced	minimum	0.48	0.58	0.56	4349	682	73
	maximum	1.72	2.31	2.64	6612	1228	124
	standard deviation	0.27	0.32	0.37	845	186	18
Geogrid-reinforced	minimum	0.40	0.46	0.49	2653	292	65
	maximum	1.59	1.59	1.35	8410	1589	256
	standard deviation	0.22	0.20	0.20	1330	284	45
Lime stabilised	minimum	0.37	0.41	0.35	3250	687	98
	maximum	7.50	6.79	8.23	6822	1414	242
	standard deviation	0.66	0.69	0.69	910	212	45

Note: *at years after reconstruction.

4.3. National road No. 131 (44.80–50.80 km)

Geogrid-reinforced section compared to adjacent sections shows that seven years after construction measured IRI value is also below 2.5 m/km (required limit value for newly constructed asphalt pavement on national roads). However, it has significant IRI average result only compared to piled embankment section (Figures 9–10) while from lime stabilised and non-reinforced sections were received more significant results. All four different subgrade types were split into two groups showing similar geological situation:

A) non-reinforced and lime stabilised subgrades;

B) geogrid-reinforced and piled subgrades.

Group A has no peaty or silty soft soils under the structure while group B is used over soft peaty and silty soils having much more complicated conditions. Road structure layer thicknesses (asphalt concrete, crushed stone and frost-blanket course) are the same for all sections. The road structure No. 3 (45.965–46.140 km; 46.45–46.72 km; 46.865–46.950 km; 47.320–47.425 km, and 49.220–49.295 km) has two 60/60 kN/m geogrid reinforcement layers under additional granular soil 0/32 layer. It is the second structure from this research by the total geogrid strength. At a depth from 0.6 m to 1.7 m under the geogrid reinforcement there is up to 1.3 m peat layers. Lime stabilised layers had 0.3 m thickness and had 3% of burnt lime. Piled embankment sections have an additional 0.3 m 0/32 gravel layer between the road structure and pile caps.

Taking the average value of IRI seven years after construction for the geogrid-reinforced section as a starting point, it is 4.31% less than

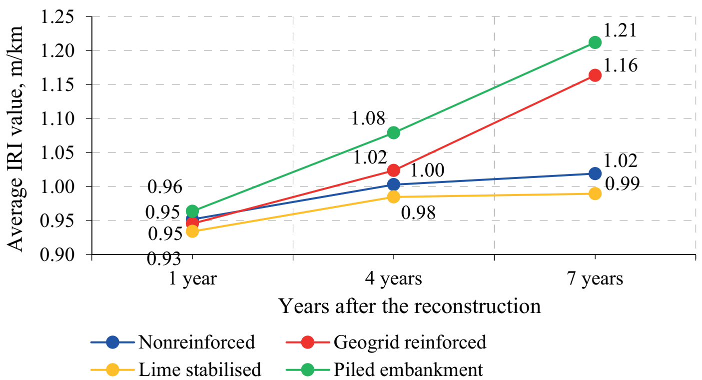


Figure 9. Average values of the International Roughness Index in the national road No. 131 (44.80–50.80 km)

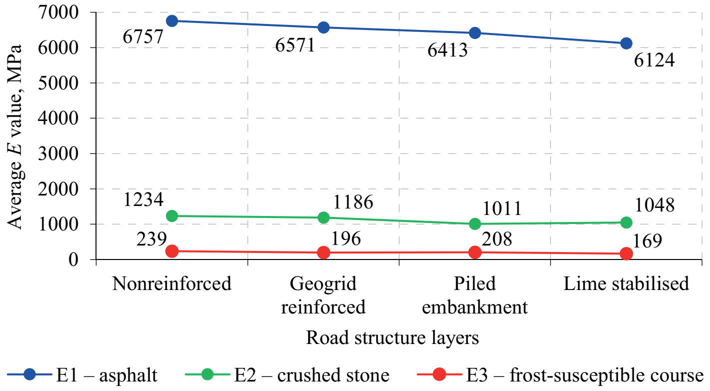


Figure 10. Average values of bearing capacity in the national road No. 131 (44.80–50.80 km)

Table 3. Statistical values by the type of subgrade structure of measurements in the national road No. 131 (44.80–50.80 km)

Subgrade structure type		International Roughness Index,* m/km			Bearing capacity for road structure layers, MPa		
		1 year	4 years	7 years	Asphalt	Crushed stone	Frost-blanket course
Non-reinforced	minimum	0.46	0.37	0.46	6757	1234	239
	maximum	1.97	3.00	1.78	6757	1234	239
	standard deviation	0.27	0.35	0.30	–	–	–
Geogrid-reinforced	minimum	0.41	0.43	0.48	2240	537	69
	maximum	1.95	2.57	2.97	9529	1882	306
	standard deviation	0.31	0.40	0.53	1529	335	48
Lime stabilized	minimum	0.32	0.40	0.35	2585	630	85
	maximum	3.94	3.31	3.39	10 250	1740	370
	standard deviation	0.35	0.38	0.37	1636	270	70
Piled subgrade	minimum	0.52	0.52	0.52	4046	676	148
	maximum	2.17	3.49	3.86	8262	1525	277
	standard deviation	0.28	0.41	0.58	1154	280	36

Note: * at years after reconstruction.

average value of IRI for piled subgrade section. However, 12.07% more than average value of IRI for lime stabilised section and 14.66% more for lime stabilised section. Taking the first-year average value of IRI as a starting point, it has been seen that seven years after construction geogrid-reinforced section average value of IRI increased by 22.11%, piled subgrade section increased by 26.04%, while non-reinforced section increased by 7.37% and lime stabilised by only 6.45%. The variation of min/max values and the standard deviation are given in Table 3. Falling Weight Deflectometer results show that the highest average values if the bearing capacity for crushed stone and frost-blanket course are for the geogrid-reinforced and piled subgrade sections (B group). Burnt lime stabilised sections has the smallest average values of the bearing capacity. Unfortunately, it is impossible to compare it to the non-reinforced section because it has only one measurement point (Figure 10).

4.4. Main road A6 (137.35–142.00 km)

This geogrid-reinforced section is in the least complicated geological conditions from all geogrid-reinforced sections in this research. From the bottom geogrid layer to the 0.4 m thickness peat layer, there are even 1.73 m filled soil layer. The road structure has the strongest geogrids in this research. Compared to adjacent sections geogrid-reinforced section shows that seven years after construction measured IRI value is also below 2 m/km (required limit value for newly constructed asphalt pavement on main roads). However, it has the worst IRI average result compared to other subgrade structure type sections (Figures 11–12). All four different subgrade types were split into two groups showing similar geological situation:

A) non-reinforced and lime stabilised subgrades;
B) geogrid-reinforced and piled subgrades.

Group A has no peaty or silty soft soils under the structure. Group B is used over soft peaty and silty soils having much more complicated conditions. Road structure layer thicknesses (asphalt concrete, crushed stone and frost-blanket course) are the same for all sections except for some parts of non-reinforced sections where there is existing road subgrade as a frost-blanket course The road structure No. 4 (141.05–141.12 km) has two geogrids 400/40 kN/m and 200/40 kN/m reinforcement under additional 0.3 m granular soil 0/32 layer. Lime stabilised layers had 0.3 m thickness and had 3% of burnt lime. Piled embankment sections have an additional 0.3 m 0/32 gravel layer between the road structure and pile caps.

The average value of IRI seven years after construction for the geogrid-reinforced section is 1.61 m/km. It is 10.56% more than average value of IRI for non-reinforced section, 14.91% more than a lime stabilised section and 22.36% more than average value of IRI for piled subgrade section. Taking the first-year average value of IRI as a starting point, it has been seen that seven years after construction geogrid-reinforced section average value of IRI increased by 15.83%, piled subgrade section increased by 7.76%, non-reinforced section increased by 6.67% while lime stabilised by 28.04%. The variation of min/max values and the standard deviation are given in Table 4.

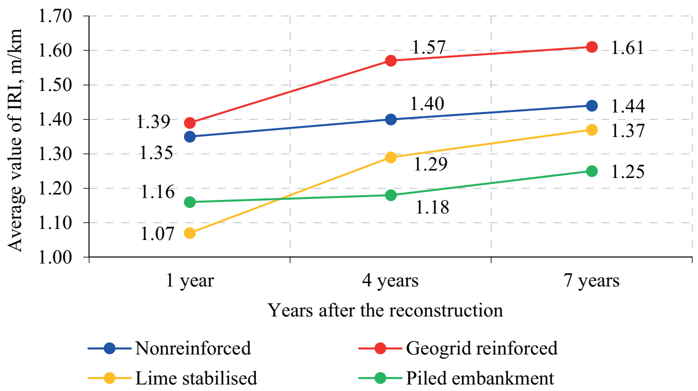


Figure 11. Average values of the International Roughness Index in the main road A6 (137.35–142.00 km)

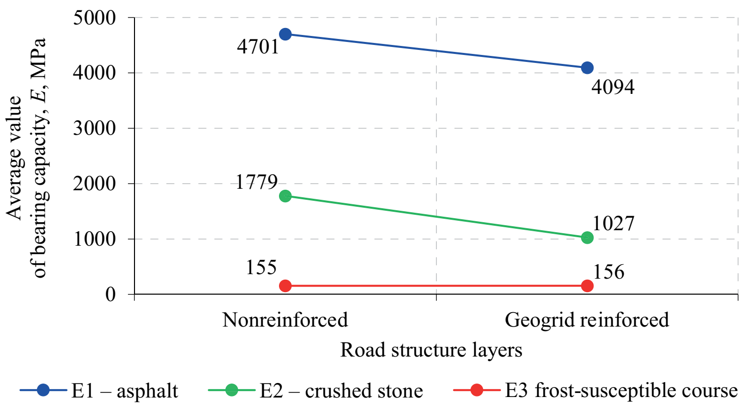


Figure 12. Average values of bearing capacity in the main road A6 (137.35–142.00 km)

Table 4. Statistical values by subgrade structure type of measurements in the main road A6 (137.35–142.00 km)

Subgrade structure type		International Roughness Index,* m/km			Bearing capacity for road structure layers, MPa		
		1 year	4 years	7 years	Asphalt	Crushed stone	Frost-blanket course
Non-reinforced	minimum	0.50	0.46	0.54	3541	1190	110
	maximum	5.75	3.83	7.08	6701	2416	234
	standard deviation	0.66	0.44	0.73	1099	363	39
Geogrid-reinforced	minimum	1.03	0.98	0.95	2706	780	75
	maximum	1.64	2.70	2.65	6287	1225	235
	standard deviation	0.18	0.43	0.45	1264	156	69
Lime stabilized	minimum	0.52	0.73	0.67	–	–	–
	maximum	1.82	3.30	2.95	–	–	–
	standard deviation	0.26	0.52	0.49	–	–	–
Piled subgrade	minimum	0.56	0.44	0.59	–	–	–
	maximum	2.64	2.49	2.68	–	–	–
	standard deviation	0.35	0.33	0.37	–	–	–

Note: * at years after reconstruction.

Falling Weight Deflectometer results show that the average value of the bearing capacity in the geogrid-reinforced subgrade section for the crushed stone layer is less by 73.22%. However, for the frost-blanket course, it is bigger by 0.64% (in this instance, the geogrid has the most significant influence on the frost-blanket course bearing capacity $E3$). Unfortunately, there is no data for bearing capacity for lime stabilised and piled subgrade sections.

5. Geogrid evaluation

Statistical analysis is used for all types of structures to see if pavement deterioration tendency for geogrid-reinforced subgrade section is similar to non-reinforced subgrade section pavement deterioration, which is the control section. Statistical analysis of the IRI and bearing capacity values was performed to obtain the coefficient of variation (CV) values to be able to compare the results of the test. The smaller the coefficient of variation, the more precise is the result of the test (IRI and FWD for each type of structure); for IRI, it means that the pavement is smoother, and for FWD, it means that the pavement is more homogeneous. While the aim is to compare asphalt pavement surface roughness and bearing capacity for the geogrid-reinforced subgrade with the non-reinforced subgrade sections, the statistical analysis covers only these two types of subgrade. Table 5 shows that road structure No. 1 has quite a similar CV for both subgrade types, except the bearing capacity for the frost-blanket course because the geogrid is installed under a crushed stone layer. The coefficient of variation for IRI shows an excellent precision result for road structures No. 2 and No. 4. In general, comparing the precision of the results, there is no significant difference between both subgrade types at each road structure type.

As for the geogrid, the main parameters for a soil stabilisation/reinforcement is to have a stiff aperture, maintain high tensile strength at low elongations and to have adequate long term design strength (Cuelho, Perkins, & Morris, 2014). In addition, the optimum nominal aperture size has to be about four times of medium grain size of the fill material (Mehrjardi & Khazaei, 2017). All geogrid-reinforced sections had geogrids that were made from PP or PET bars welded injunctions (laid geogrids), which means – stiff geogrids. It is feasible to adopt the

Table 5. Values of the variation coefficient in the tested road sections

Road structure		Road structure parameter		
		Asphalt layer roughness IRI, m/km	Crushed stone	Frost-blanket course
			Bearing capacity	
			E2, MPa	E3, MPa
No. 1	A	0.568	0.364	0.792
	B	0.490	0.356	0.432
No. 2	A	0.227	0.208	0.285
	B	0.363	0.195	0.196
No. 3	A	0.457	0.228	0.357
	B	0.294	–	–
No. 4	A	0.280	0.152	0.442
	B	0.507	0.204	0.252

Note: A – geogrid-reinforced subgrade; B – non-reinforced subgrade.

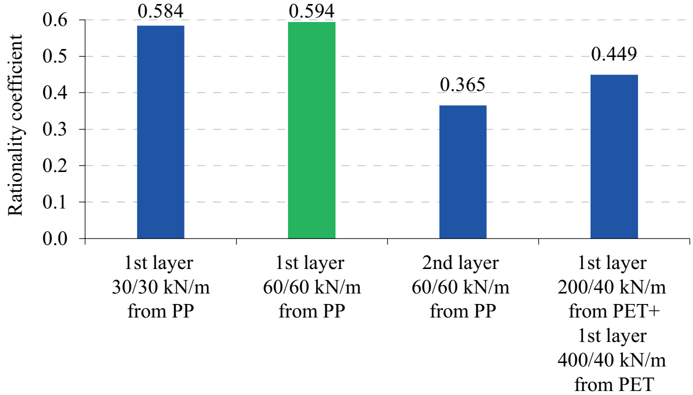


Figure 13. Rationality coefficients for geogrid structure types

total tensile strength at 1% elongation and long-term design strength values as the main geogrid parameters for four types of geogrid-reinforced constructions having these parameters.

To be able to choose the best option for the subgrade reinforcement with geogrids a Simple Additive Weighting (SAW) method was used evaluating the criteria of IRI, geogrid tensile strength at 1% elongation, geogrid long term design strength and geogrid price. Every criterion has its importance coefficient used for the decision matrix and calculation. The result of the calculation is rationality coefficient. The higher the rationality coefficient, the more rational is the reinforcement type. The best option for the geogrid reinforcement in this research is one geogrid layer 60/60 kN/m from PP (Figure 13).

It is stated that using two layers of geogrid reinforcement trying to improve the long-term performance of the road structure over the peaty soils, which lay more in-depth in the subgrade, is irrational.

Conclusions and recommendations

1. This research proves that geogrid reinforcement is sufficient to be used over a well-decomposed peat and silt layers, which lays deeper in the subgrade to maintain the International Roughness Index at a similar level compared to strong non-reinforced subgrades.
2. Average International Roughness Index values for geogrid-reinforced subgrade sections vary from 0.88 m/km to 1.83 m/km when for non-reinforced sections it vary from 1.02 m/km to 2.00 m/km. This statement leads to a conclusion that even having much worse geological situation, geogrid-reinforced sections overall performs

slightly better than non-reinforced sections. This conclusion means that geogrids are reducing fatigue of the structure by absorbing cyclic loading forces. This geogrid feature is compensating for poor subgrade properties to maintain a designed lifetime of road structure.

3. Calculated variation coefficients for International Roughness Index shows that the stability and precision of test results are better for geogrid-reinforced subgrade sections at road structures No. 2 and No. 4, but worse at road structures No. 1 and No. 3 compared to non-reinforced subgrade sections. As for bearing capacity of crushed stone and frost-blanket course, geogrid-reinforced subgrade sections at road structures No. 1 and No. 2 are slightly worse and for structure No. 4 slightly better for crushed stone layer compared to non-reinforced subgrade sections. Overall, geogrid-reinforced subgrade sections over peat and slit soils show International Roughness Index and bearing capacity results in a similar level as for non-reinforced subgrade sections over firm soils.
4. The research covers only a stiff laid geogrids that were installed in the subgrade, and it proves that geogrid stiffness, high tensile strength at low elongations and adequate long-term design strength are the key parameters to describe the geogrid performance.
5. The purpose of using geogrid reinforcement over up to 3 m thickness well-decomposed peat layers, was to avoid the excavation of peat and soil replacement piled subgrade installation due to the money savings for investor and significantly shorter installation time (depending on the area, saves up to few months) for the contractor. The research shows that the solution is working as it was expected theoretically.

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