VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

FACULTY OF ENVIRONMENTAL ENGINEERING

DEPARTMENT OF ROADS

INVESTIGATION OF THE INFLUENCE OF SUBGRADE‘S STABILIZATION ON THE DECREASE OF BEARING CAPACITY OF THE ROAD PAVEMENT STRUCTURE DURING THE SPRING THAW PERIOD

Innovative Road and Bridge Engineering study program

Master‘s thesis

Author: Laurynas Juodis, IKTmfu-20

Lecturer: Prof Dr Audrius Vaitkus

VILNIUS 2022

VILNIUS GEDIMINAS TECHNICAL UNIVERSITY
FACULTY OF ENVIRONMENTAL ENGINEERING
DEPARTMENT OF ROADS

RIGA TECHNICAL UNIVERSITY
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DEPARTMENT OF ROADS AND BRIDGES

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(Date)

Civil Engineering study field

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OBJECTIVES FOR MASTER THESIS

................No. ....
Vilnius and Riga

For student Laurynas Juodis
(Name, Surname)

Master Thesis title: Investigation of the influence of subgrade‘s stabilization on the decrease of bearing capacity of the road pavement structure during the spring thaw period

Approved on 21 December, 2021 by Dean‘s decree No. 115ap
(day, Month) (year)

The Final work has to be completed by 7 January, 2022
(Day, Month)

THE OBJECTIVES:

Analysis of relevant scientific and technical literature on the performance and design of road structure subgrade, including the interaction of different soils and environmental conditions as well as existing practical methods for ensuring sufficient bearing capacity of the road pavement structure and subgrade. Design of the plan for experimental part by selecting roads of the same category in which different subgrade soil treatment methods were applied. Performance of experimental investigation by measuring bearing capacity of selected road sections. Analysis and interpretation of experimental data including evaluation of pavement structure bearing capacity dependency on subgrade characteristics. Conclusions and recommendations on the effectiveness of subgrade soils treatment methods in ensuring the bearing capacity and durability of the pavement structures.

Consultants of the Master Thesis: ……………………………………………………………….………………

....……...............
(Title, Name, Surname)

Academic Supervisor .... Prof dr Audrius Vaitkus
(Signature) (Title, Name, Surname)

Objectives accepted as a quidance for my Master Thesis

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(Student‘s signature)

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Vilniaus Gedimino technikos universitetas
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Antrosios pakopos studijų **Inovatyvios kelių ir tiltų inžinerijos** programos magistro baigiamasis darbas 3 (keliai)

Pavadinimas **Žemės sankasos sustiprinimo įtakos kelio dangos konstrukcijos laikomosios gebos sumažėjimui pavasario atlydžio laikotarpiu tyrimas**

Autorius **Laurynas Juodis**
Vadovas **Audrius Vaitkus**

Kalba: anglų

Anotacija

Vadovaujantis nacionalinėmis projektavimo taisyklėmis sankasos stiprumas visiems keliams turi būti projektuojamas lygiai toks pats (45 MPa (keliams), 30 MPa (pėsčiųjų takams)) su nuostata, kad šis stiprumas niekada nepasieks žemesnių reikšmių nei yra nustatyta projekte. Tačiau sankasos stiprumas pavasario polaidžio metu dažniausiai stipriai nukrenta, kas lemia per didelius dangos konstrukcijos įlinkius ir greitesnį jos nusidėvėjimą. Šio baigiamojo magistro darbo tikslas yra nustatyti kaip kinta dangos konstrukcijos laikomoji geba pavasario polaidžio metu esant skirtingiems sankasos pagerinimo būdams, o taip pat įskaitant ir natūralius sankasos gruntus. Mokslininkai teigia, kad dangos konstrukcija labiausiai pažeidžiama esant švelniai žiemai, kai ledo gabaliukai tankiausiai susiformuoja viršutiniuose dangos konstrukcijos sluoksniuose ir dėl per didelio vandens kiekio drenažo tinkluose vykstant greitam pavasario polaidžiui. Autoriaus atliktas 7 skirtingų kelių ir 2 sezonų tyrimas parodė, kad visos dangos konstrukcijos laikomoji geba daugiausia priklauso nuo asfalto dangos ir visos dangos konstrukcijos storių. Rezultatai parodė, kad žemiausia E600,sub modulio reikšmė lyginant su visa dangos konstrukcija buvo užfiksuota ties sankasos riba nepriklausomai nuo dangos konstrukcijos struktūros. Sankasos laikomoji geba išreikšta E600,sub moduliu kito nuo 159 MPa iki 219 MPa sausuoju metu ir nuo 131 MPa iki 189 MPa pavasario polaidžio metu. Sankasos pagerinimas arba sustiprinimas sumažina standumo skirtumus esančius dangos konstrukcijos paviršiuje pavasario polaidžio ir sausojo rudens periodo metu, taip sušvelninant sezoniškumo įtaką dangos konstrukcijos eksploatacinėms savybėms. Keliuose, kuriuose nėra atliktas sankasos pagerinimas, skirtingų sezonų paviršiaus standumas skiriasi 32%, o keliuose, kuriuose sankasa yra pagerinta - 8%. Analizė parodė, kad sankasos deformacijų modulis pavasario polaidžio metu vis tiek dažnai nukrenta žemiau 45 MPa, net jeigu ir buvo atliktas sankasos pagerinimas. BMD apimtis – 100 psl., 55 paveikslai, 13 lentelių ir 53 literatūros šaltiniai.

Prasminiai žodžiai: Cemento rišiklis, grunto jautrumas šalčiui, gruntų pagerinimas, gruntų sustiprinimas, hidrauliniai kelių rišikliai, įlinkio dubens indeksai, įlinkio dubuo, kalkių rišikliai, krintančio svorio deflektometras, laikomoji geba, laikomosios gebos grafikas, pagrindo kreivumo indeksas, pavasario polaidis, paviršiaus kreivumo indeksas, sankasa, sankasos stiprumo indeksas.

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Master Degree Studies **Innovative Road and Bridge Engineering** study programme Master Graduation Thesis 3 (Roads)

Title **Investigation of the Influence of Subgrade's Stabilization on the Decrease of Bearing Capacity of the Road Pavement Structure during the Spring Thaw Period**

Author **Laurynas Juodis**
Academic supervisor **Audrius Vaitkus**

Thesis language: English

Annotation

All road pavement structures according to national regulations are designed on the same strength of subgrade (45 MPa (roads), 30 MPa (pathways)), with the provision that the strength of subgrade does not decrease lower than the design limit value. Usually happens that subgrade strength during the spring thaw period decreases dramatically thus leading to insufficient (not supplying design criteria) pavement structure deflection and faster deterioration. The purpose of this master’s thesis is to investigate how bearing capacity changes during spring thaw dependent on pavement structures subgrade improvement type including natural subgrade case. Researchers note that pavement structure is being highly deteriorated during mild winter when the densest quantity of ice lenses forms in upper pavement structure layers and during the rapid spring thaw due to excess moisture content in the drainage. The author experimental research in 7 different roads sections and 2 seasons presented that the bearing capacity of the whole pavement structure is mainly dependent on asphalt layer thickness and thickness of the whole pavement structure. Results revealed that the subgrade area, compared to pavement structure layers, expresses the lowest E600,sub modulus values independently from road structure composition. The bearing capacity of the measured subgrade expressed with E600,sub modulus, varied from 159 MPa to 219 MPa in the dry autumn period and from 131 MPa to 189 MPa in the spring thaw period. Subgrade soil improvement or stabilization reduces the seasonal impact on the pavement structure performance by reducing the difference of the stiffness at the surface of the pavement structure during spring thaw and dry autumn periods since the difference of stiffness on unimproved roads is 32% and 8% on improved roads. The analysis presented that the deformation modulus of the subgrade still often decreases below 45 MPa during the spring thaw period even if the subgrade was improved. Master's thesis consists of 100 pages that include 55 figures, 13 tables and 53 references.

Keywords: Base curvature index, bearing capacity, bearing capacity plot, cement binders, deflection basin, deflection bowl, deflection bowl indexes, falling weight deflectometer, frost susceptibility, hydraulic road binders, lime binders, soil improvement, soil stabilization, spring thaw, subgrade, subgrade strength index, surface curvature index.

Vilniaus Gedimino technikos universiteto egzaminų sesijų ir baigiamųjų darbų rengimo bei gynimo organizavimo tvarkos aprašo
2 priedas

(Baigiamojo darbo sąžiningumo deklaracijos forma)

VILNIAUS GEDIMINO TECHNIKOS UNIVERSITETAS

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BAIGIAMOJO DARBO (PROJEKTO) SĄŽININGUMO DEKLARACIJA

2022 m. sausio 06 d.

Patvirtinu, kad mano baigiamasis darbas tema „Žemės sankasos sustiprinimo įtakos kelio dangos konstrukcijos laikomosios gebos sumažėjimui pavasario atlydžio laikotarpiu tyrimas“ patvirtintas 2021 m. gruodžio 21 d. dekano potvarkiu Nr. 115ap, yra savarankiškai parašytas. Šiame darbe pateikta medžiaga nėra plagijuota. Tiesiogiai ar netiesiogiai panaudotos kitų šaltinių citatos pažymėtos literatūros nuorodose.

Parenkant ir įvertinant medžiagą bei rengiant baigiamąjį darbą, mane konsultavo mokslininkai ir specialistai: profesorius daktaras Audrius Vaitkus. Mano darbo vadovas profesorius daktaras Audrius Vaitkus.

Kitų asmenų indėlio į parengtą baigiamąjį darbą nėra. Jokių įstatymų nenumatytų piniginių sumų už šį darbą niekam nesu mokėjęs (-usi).

Laurynas Juodis

(Parašas) (Vardas ir pavardė)

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LIST OF ABBREVIATIONS

BCI – base curvature index;

CBR – California bearing ratio;

E_{V1} – deformation modulus of the subgrade which is determined during the first test by compressing subgrade with step plate;

E_{V2} – deformation modulus of the subgrade which is determined during the second test by compressing subgrade with step plate;

FWD – falling weight deflectometer;

F1 – frost unsusceptible soil;

F2 – low or moderate frost susceptibility soil;

F3 – high frost susceptibility soil;

KPT SDK 19 – Lithuanian rules for the design of road standard pavement structures;

MN GPSR 12 – Lithuanian methodological instructions for the improvements and stabilization of soils;

SCI – surface curvature index;

SI – soil improvement;

SQI – soil qualified improvement;

SS – soil stabilization;

SSI – subgrade strength index;

ε_t – tensile strain at the bottom of the asphalt bound layer.

LIST OF GLOSSARIES

Bearing capacity plot – a line drawn through all bearing capacity values measured at various offsets (including zero) from the load centre;

Deflection bowl – a line drawn through all deflections measured at various offsets (including zero) from the load centre;

Deformation modulus – an indicator of soil resistance to deformations, MPA;

Dry autumn period – specifically for this research, a period from 2021-09-13 to 2021-09-17;

Geotextile – is permeable fabrics which, when used in association with soil, can separate, filter, reinforce, protect, or drain;

Pore water pressure – refers to the pressure of groundwater held within a soil or rock, in gaps between particles (pores);

Settlements – refers to the mechanical process by which soil changes volume gradually in response to a change in pressure;

Spring thaw period – specifically for this research, a period from 2021-04-02 to 2021-04-08;

Subbase – pavement structure layer which thickness and thermal properties of substances ensures the resistance to the negative impact of frost;

Subgrade – soil structure that performs the base (foundation) function of the pavement structure.

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INTRODUCTION

Relevance of the topic - In 2019, the Lithuanian road administration released new pavement structure design rules. These rules indicate the need to apply pavement structure subgrade stabilization for all roads that are built on frost susceptible soils. The purpose of this master's thesis is to investigate how bearing capacity changes during spring thaw dependent on pavement structures subgrade improvement type including natural subgrade case.

Problem – All road pavement structures according to national regulations are designed on the same strength of subgrade (45 MPa (roads), 30 MPa (pathways)), with the provision that the strength of subgrade does not decrease lower than the design limit value. Usually happens that subgrade strength during the spring thaw period decreases dramatically thus leading to insufficient (not supplying design criteria) pavement structure deflection and faster deterioration. Current practice shows that this problem could be managed by a few techniques: drainage (ditches) or subgrade soil improvement.

Research object – The performed analysis of the Master's thesis covers Lithuanian Regional roads No. 1125, No. 2006, No. 2008, No. 3118, No. 3131, No. 3425, and No. 5120. These roads have a design load that reach up to 0,18 mln. ESAL's. The subgrade is made out of different soil types with different frost susceptibility levels. Subgrades were unimproved, improved and stabilized by using lime, cement or hydraulic road binders. Selected roads are situated in the 1,30 – 1,60 m frost depth zones.

Aim – Define the seasonal variation of asphalt pavement structure bearing capacity dependency on spring thaw and type of subgrade soil improvement on Regional roads.

Tasks:

1. Literature review (articles, technical regulations, etc.) on road structure subgrade design and performance.
2. Analyse spring thawing rate throughout the years and its effect on various types of pavement structure soils, their relevant performance dependence from moisture content, and frost susceptibility.
3. Define the pavement structure subgrade soil improvement types and methods
4. Perform experimental investigation on measuring bearing capacity of pavement structure with and without subgrade soil improvement in regional roads of Lithuania.
5. Summarize and statistically analyse the data of the experiment, provide the interpretation.
6. Deliver conclusions and recommendations regarding effective pavement structure subgrade soil design with or without improvement.

Research Methods. The research was performed by using Falling Weight Deflectometer to gather road deflections data every 25 meters in the 500 meters section of each selected road. Further analysis was performed by evaluating the deflection bowl and deflection bowl indexes such as surface and base curvature indexes, tensile strain at the bottom of asphalt bound layer, normalized bowl area and subgrade strength index. Deflection data was also used for the calculation of the bearing capacity and the generation of the bearing capacity plots.

1. LITERATURE REVIEW ON ASPHALT PAVEMENT STRUCTURE BEARING CAPACITY VARIATION DEPENDENCY ON SEASON

1.1. Road Structure Subgrade Design and Performance

The major country economics level factor is considered to be logistics. One of the many logistics branches which generate a lot of money is trucks. But the smooth transition of goods could not be achieved without the great quality of the road system. A clear example could be taken from the Republic of Poland. This country is one of the few in the European Union whose road quality level is constantly rising through the years. According to World Economic Forum, from 2010 till 2016, the quality of the roads in Poland grew up from 2,23 to 4,00 points. Meanwhile, the number of lorries that are registered in Poland from 2010 till 2016 grew up from 2,47 to 5,86 million. According to this data, there is no doubt that countries have to invest money in road quality improvement because all this money will pay off in the future.

On the other hand, a major part of the money that is being invested in the road sector falls for road maintenance works. "Kelių priežiūros ir plėtros programos finansavimo lėšų naudojimo 2021 metų sąmata" is an annual fund allocation for Lithuanian roads law. According to this law, in 2021 the Ministry of Transport and Communications of the Republic of Lithuania allocates 531 612 thousand euros for road maintenance and development. 251 298 thousand euros of the total fund are allocated for the national importance roads network development and maintenance works. Also, 76 000 thousand euros are allocated to the company "Kelių priežiūra" which carries out maintenance work for the roads of national importance. It makes 61,57% of the annual money allocation for the Lithuanian road system and it is a very large amount of money. However, compared to the Republic of Poland, the Republic of Lithuania's roads quality index from 2010 till 2016 dropped from 5,27 to 4,90.

Firstly, to achieve the higher road quality index, less money has to be spent on road repair works. To achieve that, the exposure time of the road without any repair works has to be extended. The way to do that is to design and build road layers that meet the expected lifetime requirements which are set by national regulations. For example, "Lithuanian Rules for the Design of Road Standard Pavement Structures KPT SDK 19" set the road subgrade layer's expected lifetime to 100 years. However, it is common that the roads do not live up to the expectations and damages, such as alligator cracking, appear. It usually shows that there is a poorly designed or built drainage system and the road pavement subgrade soils are wet. To repair this damage, it is not enough to simply install a patch on cracked asphalt pavement, the much larger repair works have to be applied that would fix the subgrade layer. Those repairs will cost a lot of money so it means that it is better to invest more money into the design and construction works.

To design a subgrade layer that will withstand its expected lifetime three main factors have to be evaluated: subgrade layer soil type, its frost susceptibility, and groundwater water drainage.

1.1.1. Soil type

The major part of structures is affected by the live-load which comes from various kinds of sources – people, vehicles, objects. Also, all structures have their self-weight which adds up to the live-load. All these loads affect the structure foundation. Despite the type of foundation, eventually, part of the forces are transmitted to the soils. That is why it is crucial to analyze them in detail.

Since there are various kinds of soils on the earth and a large part of them are not able to withstand large forces, geological and geotechnical researches have to be performed. These researches are relatively cheap compared to the consequences of the building disaster due to foundation soil fault. (Kouretzis, 2018) provided a diagram that clearly shows how the soil investigation affects the final cost of the structure (figure 1). The bigger amount of money spent on geological and geotechnical investigations drops the cost of structure (and its failures) significantly.

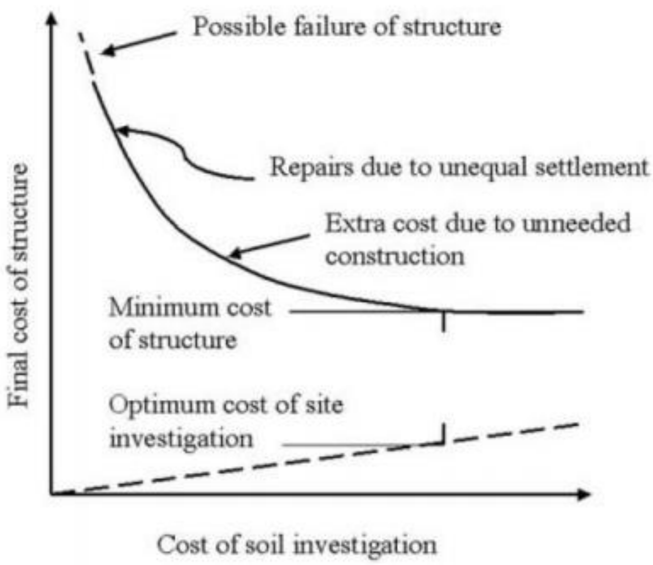


Fig 1. Effect of soil investigation on the final cost of structures

Source: Kouretzis (2018)

According to Lithuanian recommendations for the engineering geological and geotechnical and structure researches of roads R IGGT 15, there are various types of researches that can be performed:

- Previously performed geological and geotechnical researches archival data collection, analysis, and application;
- Aerial photography research and interpretation;
- Drilling the borehole;
- Excavation and collection of the undamaged structure monoliths;

- Field tests;
- Structures and slopes deformation monitoring;
- Hydrogeological research;
- Laboratory research.

One of the most important methods is the drilling of the boreholes. Using this method various geological data could be determined. Drilling of boreholes aims to examine the geological and hydrogeological structure of the selected object. It also evaluates composition, water content, the physical condition of soils. According to this method, preliminary geological strata can be formed. The depth of the groundwater can be measured, soil and water specimens, rock samples could be excavated while drilling the boreholes (Kvaraciejus 2008).

The boreholes are drilled using drilling rigs (figure 2). A drilling rig is a machine that has a powered rotary drilling bit on the end of the drilling rod, which is driven into the ground as it rotates. This system requires lubrication such as air or water to prevent the drilling rod from overheating. Drilling rods, according to ISO 22475-1:2021, could be of various types. But tube corebarrel and hollow stem auger rods are most commonly used by geotechnical companies.

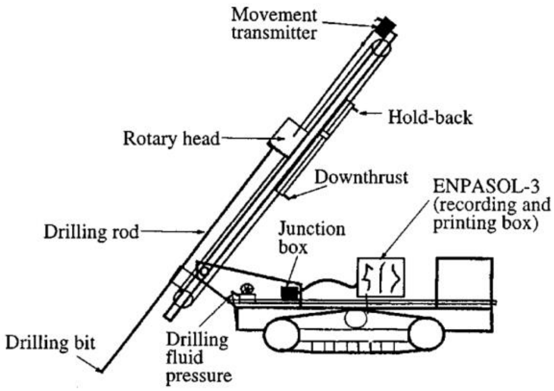


Fig 2. Drilling rig

Source: http://web.a.ebscohost.com/ehost/pdfviewer/pdfviewer?vid=1&sid=046f7ccc-67ed-49eb-b236-11c71a9ac861%40sessionmgr4006

Tube corebarrel is a complex drilling rod consisting of the head assembly, inner tube, stop ring, core lifter spring, and core lifter case. Head assembly indicates landing, provides circulation of drilling fluids to the core bit and latches the inner tube assembly in place (McCoremick 2018). The latch head lets the head assembly cooperate with the outer tube assembly for spinning while keeping the inner tube still. Meanwhile, the inner tube receives the soil core and stores it until it is retrieved. Core lifter spring allows the core sample to move into the inner tube as the bit advances in the formation. While advancing, the core lifter spring slides up against the stop ring (McCoremick 2018). According to ISO 22475-1:2021 guideline value of borehole diameter that is drilled using tube corebarrel is from 100 to 200 mm.

A hollow stem auger is a simple hollow tube (figure 3) with flutes and lands on the side. While penetrating the soil, the hallowed part of the drill rod collects soil for further investigations. Hollow stem auger boring may be used for relatively shallow highway and utility alignment explorations and explorations to define likely shallow bedrock along excavation alignments. Hollow stem auger should not be used when there is significant penetration below the groundwater table or when recovery of undisturbed soil samples is needed (Baxter et al. 2005). According to ISO 22475-1:2021 guideline value of borehole diameter that is drilled using a hollow stem auger is from 100 to 300 mm.

Fig 3. Hollow stem auger

Source: https://www.explorationcoredrilling.com/sale-12859873-hollow-stem-auger-8-1-4-210mm-triple-key-heavy-duty.html

To obtain representative geotechnical data that could be properly evaluated for some specific structure, different minimum requirements for boreholes number and their depth are set. (Kouretzis, 2018) describes minimum number of borings and a minimum depth of borings for retaining walls, culverts, bridge approach embankments over soft ground, and road structure cuts and embankments. For the retaining walls, two parallel borings have to be drilled every 30 to 60 m. The depth of them has to be a minimum of two times wall height or a minimum of 3 m into the foundation. For the culverts, minimum of two borings have to be drilled and one boring for the bridge approach. For the road structure, according to (Kouretzis, 2018), borings have to be drilled out from 60 m (unstable conditions) to 150 m (stable conditions) with an additional one boring for different landforms. For high cuts and fills, two borings on different sides of selected road section for the drawing of the section view which will show geological strata. The depth of the road borings depends on the type of soil. If the soil consists of stable materials, borings from 3 to 5 m below-cut grade have to be drilled. For the soil of unstable materials, borings have to be drilled till firm materials are reached.

When the boreholes are drilled and the soil samples are gathered, laboratory research has to be performed to determine, whether the natural soil is appropriate for the foundation of the structure.

ISO 14688-1:2018 determines different mineral soil groups according to their particle size ranging from bigger than 630 mm to smaller than 0,002 mm. Of course, not every group of soil could be used for road subgrade construction. Therefore, the road subgrade layer can be constructed out of natural soil or elsewhere excavated soil that meets the soil particle size, particle size distribution, plasticity, frost susceptibility, organic soil additions, soil derivative requirements.

According to LST 1331:2015, soils that have particles bigger than 63 mm can not be used for road subgrade layers. Soils that 95% of mass consists of bigger than 0,063 mm particles are considered to be coarse-grained soil and are classified according to particle size distribution. Soils that are not less than 40% of mass consist of smaller than 0,063 mm particles are considered to be fine-grained soils and are classified according to plasticity. Everything that is left is considered to be multi-grain soils and is classified according to both particle size distribution and plasticity. The soil groups are determined by using sieve sets (figure 4).

Fig 4. Sieve set

Source: http://ithatech.co.ke/En/Product/Test-Sieve.html

Coarse-grained and multi-grain soils, according to ISO 14688-2:2018, could be divided into two main groups: gravel (Gr) and sand (Sa). Soil is considered to be gravel if more than 50% of it consists of particle size that ranges from 2,0 mm to 63 mm, while the soil is considered to be sand if more than 50% of it consists of particle size that ranges from 0,063 mm to 2,0 mm. Meanwhile, in LST 1331:2015, which is the Lithuanian standard, these percentages are increased up to 60%. Also, coarse-grained and multi-grained soils have their separate classifications. Coarse-grained soil is classified as poorly graded, well-graded, and gap graded particle size distribution according to their coefficient of curvature and uniformity coefficient. Multi-grained soil that consists of 5% – 15% of 0,063 mm particles is considered to be lowly silty or lowly clayey soil, and if soil consists of 15% - 40% of 0,063 mm particles is considered to be silty or clayey soil. Fine-grained soils are classified according to liquid limit W_L. If the liquid limit is less than 35% of soil mass, the soil is considered to have low plasticity. If the liquid limit is bigger than 35% but less than 50%, the soil is considered to have average plasticity. If the liquid limit is bigger than 50%, the soil is considered to have high plasticity. Soils according to the quantity of the organic soil additions are divided into organic soils and soils with organic additions. Organic soils can burn and soils with organic additions can not.

Technical properties for road pavement structure subgrade of previously mentioned soils and their properties are described in LST 1331:2015. Well-graded and gap graded gravel, well-graded sand, lowly silty gravel, lowly silty sand are the soils that have the highest shear resistance. On the other hand, high plasticity clay, clay with organic additives have the lowest shear resistance. The highest density can be achieved by compacting well-graded gravel and well-graded sand but it is practically impossible to achieve the required density for a road subgrade layer of high plasticity clay and clay with organic additives. Gravel and sand are the strongest soils if they do not have any other soil additives, therefore, once again, high plasticity clay is the weakest soil that could be used for the subgrade layer. The soil according to LST 1331:2015 which has the best resistance to erosion is poorly graded gravel and on the other hand, low plasticity silt has the worst erosion resistance.

1.1.2. Frost susceptibility

It is now clear that soils play a major role in the structural engineering field. In the previous section, soils were divided and evaluated according to their technical properties such as shear resistance, density, and et cetera. But when it comes to soils weakening during the spring thaw, one technical property has to be excluded and more deeply analyzed which is frost susceptibility.

Roads construction and maintenance work per one kilometre in the cold climate regions are significantly expensive compared to warm climate regions. It is due to the low-temperature negative impact on road structure and mostly subgrade performance. Therefore, roads in cold climate regions have to have additional instalments to prevent their rapid deterioration. This makes them very expensive and low-traffic roads can encounter a lack of funds for their maintenance. This could be clearly seen by taking look at paved and unpaved roads ratio in cold and warm climate countries. According to (Doré & Zubeck, 2009), cold region roads have a higher amount of unpaved roads, compared to warm region roads.

Table 1. Paved and unpaved roads ratio by country

Country	Paved roads, km	Unpaved roads, km	Ratio
Finland (2007)	50 836	27 325	35%
Latvia (2018)	9000	11000	55%
Lithuania (2021)	15 480	5 756	37%
Greece (2009)	117 000	9 360	8%
France (2009)	1 000 000	0	0%

Source: Greece - https://tradingeconomics.com/greece/roads-total-network-km-wb-data.html, https://tradingeconomics.com/greece/roads-paved-percent-of-total-roads-wb-data.html; France - https://ppiaf.org/sites/ppiaf.org/files/documents/toolkits/highwaystoolkit-russian/6/pdf-version/france.pdf, https://tradingeconomics.com/france/roads-paved-percent-of-total-roads-wb-data.html; Lithuania - https://lakd.lrv.lt/lt/veiklos-sritys/lietuvos-keliai/valstybines-reiksmes-keliai; Latvia - https://bnn-news.com/lsr-large-proportion-of-gravel-roads-presents-the-largest-challenge-to-mobility-in-latvia-183237; Finland - Doré & Zubeck (2009).

There can be various types of damages influenced by the cold climate. Probably almost everyone knows that during the freezing-thawing cycle, water that came from rain or snow fills the pavement cracks and then expands while freezing, forming potholes. But not only the road pavement gets damaged from the influence of the freezing temperature. Freezing temperatures can also damage road pavement structure: base, subbase layers and subgrade. Of course, negative temperature alone does not reduce the quality of granular roads structure. In fact, according to (Aursand, 2008), the road base layers bearing capacity during the cold winter period becomes the highest throughout the year. But when negative temperature meets groundwater, frost susceptible soils encounter two major damages: frost heaves and bearing capacity depression during the thaw period.

According to (Chamberlain, 1981), the most accepted definition of frost susceptibility in the world is described in "Highway Research Board Committee on Frost Heave and Frost Action in Soil" which was published in 1955. According to it, frost susceptibility is "soil in which significant ice segregation will occur when the requisite moisture and freezing conditions are present".

Although all soils are considered to be frost susceptible, some of them have very low susceptibility levels and can be neglected. There are a lot of conditions that influence the level of frost susceptibility. However, (Bilodeau et al. 2008) exclude grain size distribution, mineral composition of fines, water content, density, hydraulic conductivity, and capillary as the main factors for it.

Any kind of soil, which has a high amount of fine particles can be easily considered to be frost susceptible. It happens because fine soil easily sucks the groundwater into the surface of the particles. When the frost affects the aggregate, the sucked water starts to freeze. While the frost progresses to penetrate saturated soil particles, ice particles expand and eventually connect by forming ice lenses. According to (Bilodeau et al. 2008), the amount of water that is absorbed by fine aggregate is a function of the mineral composition of the fine particles. Therefore, water freezes at ranging temperatures and influences the soil's level of frost susceptibility.

There are a lot of ways to evaluate aggregate frost susceptibility according to the number of fine particles and gradation characteristics. (Bilodeau et al. 2008) mentions some engineers that came up with their own frost susceptibility determination rules. One of the first rules was defined by Casagrande in 1932. In his work, he specified that if particles finer than 0,002 mm consist of 3% full soil mass and the coefficient of uniformity C_U is higher than 15%, soil can be considered as frost susceptible. (Lemieux, 2001) defined critical frost susceptible soil and aggregate particle sizes which are 0,080, 0,020 and 0,002 mm.

Nowadays, different countries have set their own technical normatives to classify frost susceptible soil. United States Department of Transportation Federal Highway Administration released "Geotechnical Aspects of Pavements" in May 2006 in which frost susceptibility is classified into four groups (F1, F2, F3, F4) based on the amount of particles that get through a 0,075 mm sieve.

According to the Norwegian pavement design handbook N200 2014, frost susceptible soils are classified also into four groups (T1, T2, T3, T4) based on the amount of particles that get through 0,002 mm, 0,020 mm, and 0,200 mm sieves. Meanwhile, “Additional technical conditions of contract and directives for earthworks in road construction ZTV E-StB 09” which is published by the German Road and Transport Research Association defines only three groups of frost susceptible soils (F1, F2, F3) according to particle size distribution and the plastic properties. This division of soils also fits the “Lithuanian Rules for the execution of earthworks and the instalment of the subgrade ĮT ŽS 17”.

While designing road pavement structure subgrade layer and choosing its soils, designers must follow local design rules and regulations. However, different countries could have better-perfected design rules that could lead to more efficient road structures that would be in good shape for a longer time. Table 2 provides the comparison of frost susceptibility groups used in the United States and Germany. The table shows that the German approach of dividing soils into groups is more strict. For example, in Germany, gravelly soils and sands can have less fine particles percentage of the whole mass of soil, compared to the United States, to be in the same frost susceptibility group. Also, the frost susceptibility class in the United States for Clays changes at a 12 % plasticity index. Meanwhile, the frost susceptibility class in Germany for Clays changes at 30 %, which is much higher than in the United States. Therefore, it means that it is better to design pavement structure subgrade layer by using German design rules rather than the United States, even if the project takes place in the United States.

Table 2. Frost susceptibility class by country according to soil parameters

Soil type	United States			Germany		
	Percentage Finer than 0,075 mm by Weight	**Plasticity Index**	**Frost susceptibility class (F1-F4)**	**Percentage Finer than 0,063 mm by Weight**	**Plasticity index**	**Frost susceptibility class (F1-F3)**
Gravelly soils	3 – 10 %	-	F1	< 5 %	-	F1
	10 – 20 %	-	F2	5 – 15 %	-	F2
	> 20 %	-	F3	15 – 40 %	-	F3
Sands	3 – 15 %	-	F2	< 5 %	-	F1
Fine silty sands	> 15 %	-	F3	5 – 15 %	-	F2
Very fine silty sands	> 15 %	-	F4	15 – 40 %	-	F3
Clays	-	> 12 %	F3	-	> 30 %	F2
	-	< 12 %	F4	-	< 30 %	F3
Silts	-	-	F4	-	-	F3
Silts with banded sediments	-	-	F4	-	> 10 %	F2
Clays with banded sediments	-	-	F4	-	< 10 %	F3

Source: United States Department of Transportation Federal Highway Administration released “Geotechnical Aspects of Pavements”; “Additional technical conditions of contract and directives for earthworks in road construction ZTV E-StB 09”

Knowing frost susceptibility of the soil is not enough when designing roads pavement structures. Any previously mentioned soils that are considered to be frost susceptible could be perfectly used for pavement structure subgrade layer and its functionality would not be different from the subgrade which was made out of frost unsusceptible soils, however, the adequate compaction of subgrade and the required thickness of subbase layer has to be ensured.

Road pavement structures in cold regions are frequently designed with a subbase layer. This layer is used to change frost susceptible soil into frost unsusceptible soil under the pavement structure base layer. Therefore, it is crucial to evaluate how thick the subbase layer has to be to avoid any negative impact from the frost to the pavement structure. That is why the minimum thickness of the frost-resistant pavement structure has to be calculated by evaluating the maximum possible frost depth.

Not all cold climate country's road pavement structure design rules indicate to calculate frost-resistant pavement structure by evaluating frost susceptibility of soils. However, the majority of them calculate it by evaluating frost depth. For example, Latvian “Recommendations for the road design. Road pavement structure” does not evaluate soils frost susceptibility parameters. However, the minimum thickness of frost-resistant pavement structure is calculated by evaluating the frost depth, road pavement structure category, the distance between surface and groundwater, subgrade compaction, particle distribution of subgrade soil coefficient, self-weight of the structure, and moisture of the subgrade soil. Poland's "Catalogue of typical constructions. Semi-rigid surfaces" also does not evaluate soils frost susceptibility parameters. However, the minimum thickness of frost-resistant pavement structure is calculated by evaluating frost depth and class of the soil (G1, G2, G3, G4). These classes are determined by evaluating the CBR index of subgrade soil after four days of soaking with water and by the secondary modulus of deformation E_{V2}.

Important to mention that frost depth data has to be measured specifically under the road pavement structure. It happens that frost depth which is measured under road pavement structure and frost depth which is measured in meteorology stations are significantly different. It can be clearly seen in the Lithuanian example. On the left side, figure 5 represents Lithuania's soil frost depth according to meteorology stations' measured data. On the right side, figure 6 represents frost depth according to Road Weather Stations data, which measures soil frost depth directly under the road pavement structure. For example, in Šiauliai city, the natural soil frost depth is measured to be lower than 80 cm while the soil under road pavement structure frost depth is measured to be 160 cm which is twice as much. On the other hand, in the southwest part of Lithuania, next to the border with Poland, natural soil frost depth is measured to be higher than 120 cm, while soil under road pavement structure frost depth is measured to be only around 130 cm.

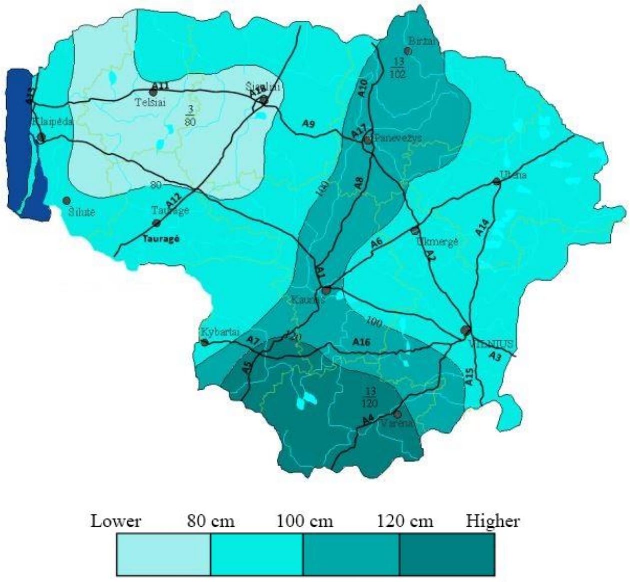


Fig 5. Soil frost depth according to meteorology stations data

Source: Juknevičiūtė-Žilinskienė (2009)

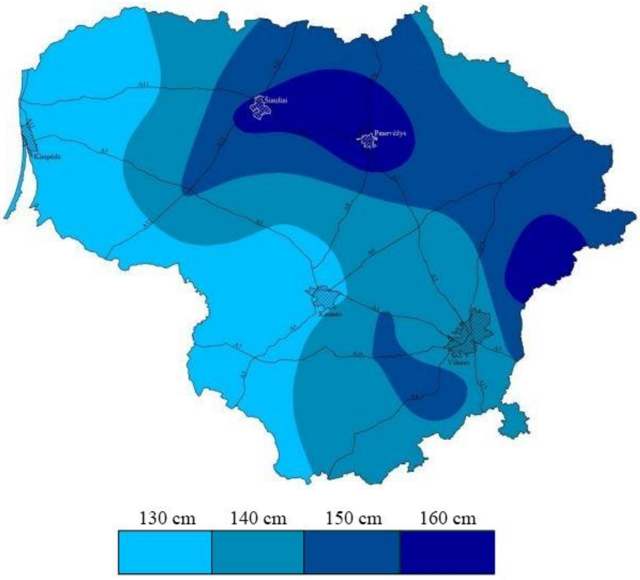


Fig 6. Soil frost depth according to Road Weather Stations data

Source: KPT SDK 19

This frost depth unevenness is caused by several influences. Very basic factors are simply represented in figure 7. One of them is the difference in soils that are affected by frost. The most commonly found natural soil in Lithuania is sand or clay which has many fine particles that fill up the empty spaces between bigger particles. Meanwhile, road pavement structure base and subbase layer are built out of the soil that has fixed particle sizes distribution and the percentage of fine particles is lower compared to natural soil. This feature creates more empty spaces in the soil which allows frost to penetrate the soil more freely. Another frost depth influencing aspect is the snow cover layer over the ground during the winter period which protects the soil from higher penetration of frost. On the contrary, snow is being removed from the surface of the road by snow ploughs to ensure safe driving conditions. This action opens up the road surface layer directly to frost which can freely penetrate the whole pavement structure and underlying soils.

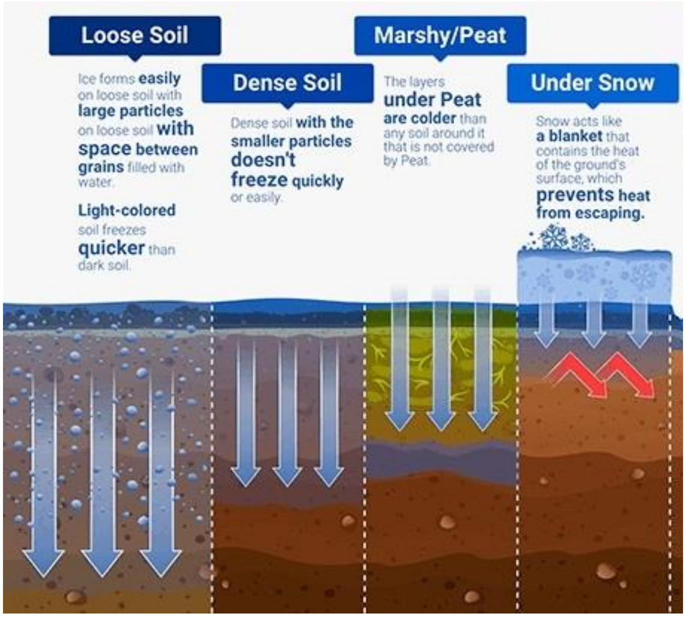


Fig 7. Frost depth dependency on different conditions

Source: https://www.heatxperts.com/en/blog/post/understanding-the-basics-of-frost-depth.html

Cold climate countries have to pay great attention to frost susceptibility and frost depth of the soils that are underlying below road pavement structure. Frost susceptibility of the soil can be evaluated differently through countries and the same type of soil could be determined as low or high frost susceptible. As well as frost depth has to be measured directly under the road pavement structure since depth would be much higher compared to natural soils. These underestimated parameters could lead to major damages in the road pavement structure like frost heave and loss of bearing capacity during the spring thaw. These failures eventually build up the need for a high amount of annual money that has to be allocated to the repair of damaged roads, rather than being allocated to asphalting gravel roads.

1.1.3. Water Drainage

Soils frost susceptibility and frost depth would not have a major negative effect on the road pavement structure if the soil would be completely dry throughout the year. However, there are a lot of water sources that moisturize road pavement structure soils. The negativity of the water particles that enter the soil is that water affected by frost starts to freeze and expand. The expansion breaks down the continuity of natural soil by pushing away soil particles and forming empty voids. This could form frost heaves in the road pavement structure. Also, during the spring thaw, frozen water lenses start to melt and then keep still in the road subgrade layer until late spring or early summer according to (Doré & Zubeck, 2009). This excess moisture decreases the bearing capacity of the structure layers. (Rokade et al. 2012) specified that undrained pavement structures experience 15 times higher damages compared to undrained pavement structures. Therefore, it is highly important to prevent any kind of water from entering road pavement structure aggregate layers. According to (Dawson, 2009), it would be more profitable to spend more money on drainage systems and afterwards have lower maintenance costs rather than vice-versa (figure 8).

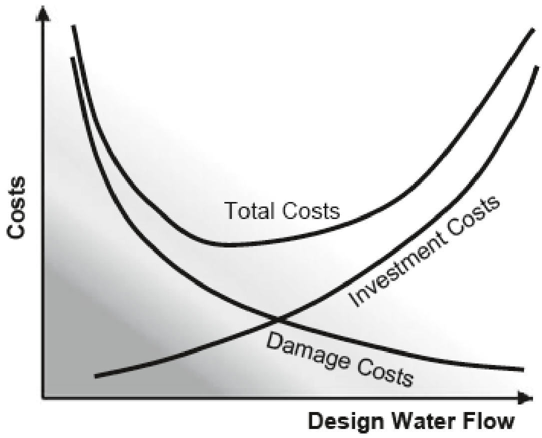


Fig 8. Drainage economics

Source: Dawson (2009)

Before designing water drainages, moisture sources that affect road pavement structure have to be analyzed and understood. The most basic water cycle in road layers is presented in figure 9 which is provided by (Doré & Zubeck, 2009). Capillary rise (1) is the ability of moisture from the groundwater table zone to climb up through the soil and enter the road‘s pavement structure layers. The possible height of water rise mainly depends on grain size properties and void ratio, according to (Lu & Likos, 2004). Lateral moisture transfer (2) usually comes from groundwater whose table is higher than the build road. Water flow that comes to the sides of road pavement structure layers could wash out fine particles from the aggregate mixture and break down the continuity of different size particles. Also, (Doré & Zubeck, 2009) mentions the artesian water flow underneath of road pavement structure. This situation likely reduces road pavement structure layers bearing capacity and stability of embarkment. Also, it can influence the formations of frost heaves if soils are frost susceptible. Frost's action (4) is detailed in the 1.2.3 section.

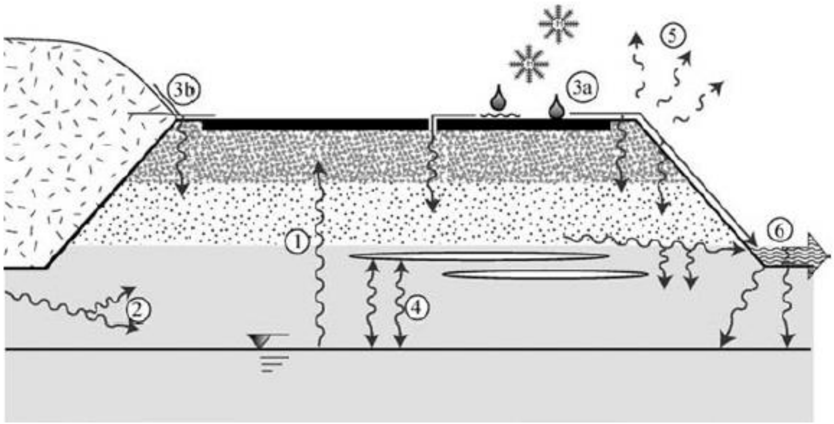


Fig 9. Factors affecting moisture regime in the pavement structure

Source: Doré & Zubeck (2009)

Infiltration from precipitation according to (Doré & Zubeck, 2009) is the main source of moisture in the pavement structure. Water can access pavement structure by leaking through bound layers air voids or cracks and also by absorption through granular parts in pavement structure like shoulders and slopes (3a and 3b in figure 9). (Cooley et al. 2002) noted that the permeability level of different asphalt mixtures disparities significantly and shows it in figure 10 (NMAS stands for biggest grain size in asphalt mixture). Since smaller grain sizes are better in filling up the whole asphalt mixture, it prevents high air voids formation. Therefore, the lower percentage of air voids, the lower velocity of water filtration. However, according to "Additional technical terms of contract and guidelines for the construction of road surfacing from asphalt ZTV Asphalt-StB 07" different asphalt layer has different biggest grain size. For example, the asphalt base layer has 22 or 32 mm biggest particle size while asphalt wearing course has 5, 8, or 11 mm biggest particle size. It means that if the water filtrates through the wearing course, the rest of the layers would let water through more rapidly. According to figure 10, water will filtrate through the base layer around 10 times quicker compared to wearing course.

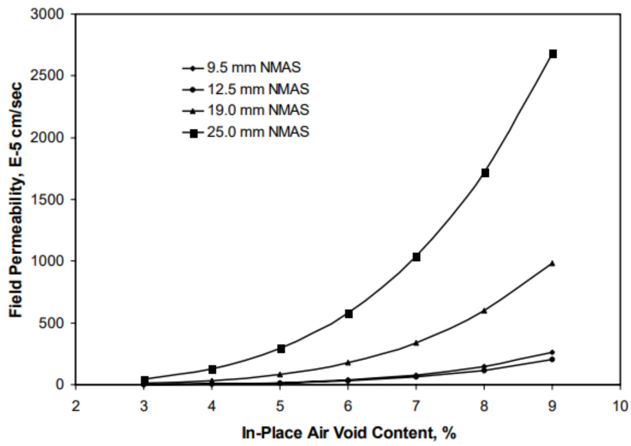


Fig 10. Effect of biggest grain size on permeability

Source: Cooley et al. (2002)

Since there are a lot of abilities for water to enter the pavement structure which could have a negative effect, the high quality of drainage has to be ensured. According to (Doré & Zubeck, 2009), a drainage system usually includes these features: surface drainage, internal pavement drainage, collectors, and evacuation systems.

The surface drainage system's purpose is to eliminate water from any kind of surface. The main method of draining water from the surface is to form grades and slopes on any kind of surface. That is why roads pavement, shoulders, ditches must have a longitudinal grade. Also, the first two of them must have a transverse grade. Road pavement surfaces without any grade could impel faster water penetration into pavement structure layers and also form marshes that create unsafe driving conditions. Ditch without any grade could make water stand which will eventually drain into the soil and could enter into road pavement structure granular layers. To prevent this, surface drainage systems have to be used that could be ditches, gutters, channels, swales, and culverts.

The internal pavement drainage system‘s purpose is to eliminate water that penetrates or could penetrate into pavement structure layers. (Cedergren et al. 1972) noted the high importance of internal pavement drainage and specified that drainage systems have to be installed in the full width of the pavement structure which could be subjected to heavy vehicle load while the pavement structure is affected by the excess amount of water.

The geotextile drainage layer is one of the horizontal drainage solutions. Geotextile is quite new material and is now widely used in road engineering. It delivers a lot of benefits to the pavement structure such as restraining mixing of different course aggregate layers, stabilizing pavement structure, restraining erosion, controlling sediments, and et cetera. An additional part of these geotextile benefits is the performance of the drainage layer. This layer is placed against the aggregate layer, catches the moving water particles, and directs it to the arterial pavement structure drainage system. The effectiveness level of the drainage layer according to (Zornberg et al. 2013) consists of aggregate layer grade, soil plasticity, hydraulic conditions, and geotextile opening size. There could be used any type of geotextile, however, (Zornberg et al. 2013) exclude one with a grooved cross-section that has a very high seepage level. Grooved cross-section geotextile fiber has deep hollows which let water through in a longitudinal direction to the arterial drainage system. Also, this type of geotextile is manufactured from a nylon material which is hydrophilic and hygroscopic.

The installed geotextile drainage layer according to (Zornberg et al. 2013) has multiple advantages in draining water particles that enter pavement structure in one or another way. The first advantage is draining water from the pavement structure that has a high water table. What geotextile does is simply interrupts the capillary rise of water particles and does not let them overflow the drainage layer. All caught water is conveyed to the arterial pavement structure drainage system (figure 11). The second geotextile advantage is the ability to minimize the accumulation of moisture within base course materials. Accumulation of moisture in the pavement structure appears on the contact between two different aggregate layers that have different filtration coefficients. This situation forms capillary barriers and therefore increases moisture around the contact area which forms a temporary barrier for further water flow. However, if the geotextile would be placed in the contact area between two different aggregate layers, moisture would not be able to accumulate and it would be eliminated from the pavement structure. The third advantage is road pavement protection from frost heaves. According to (Blades & Kearney, 2004), due to capillary action, water particles from the groundwater table can uprise from 9 to 27 meters if the surrounding soil is fine-graded such as clay or silt. Raised water could form ice lenses in frost susceptible pavement structures and form frost heaves and also during spring thaw could reduce bearing capacity. However, placing the geotextile beneath the plane of freezing soil could form the barrier for uprisen water and convey it to the arterial pavement structure drainage system. Therefore, the potential damage of frost-heave or bearing capacity depression would be eliminated (figure 12). Another geotextile advantage is the road pavement protection from swelling and shrinkage of expansive subgrades. According to (Zornberg et al. 2013), expansive clays are found in many places around the world, which means that problem of huge pavement heaves during wet seasons is very important. Moisture seeps into unbounded shoulders and eventually reaches the expansive soils while the centre of the road does not receive this high amount of water. This forms differential deformations in the pavement structure and during the dry period forms significant longitudinal asphalt pavement cracks when soil shrinks and settles unevenly. Therefore, placed geotextile could help to remove moisture from the pavement structure as well as balance its unevenness which is the main factor of differential settlements (figure 13).

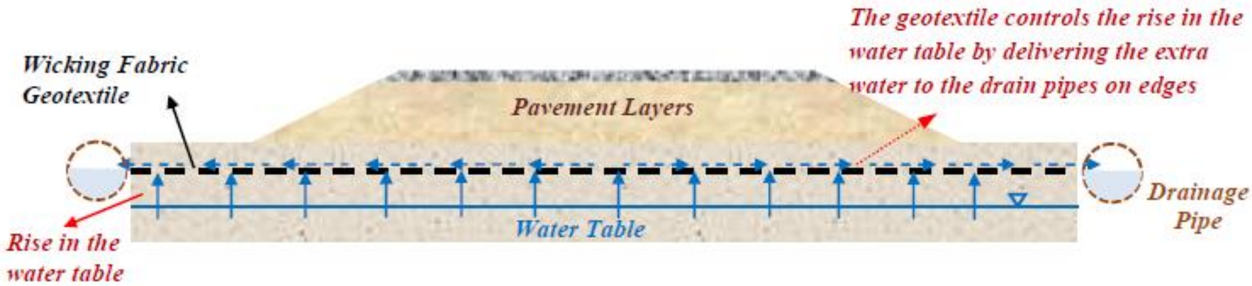


Fig 11. Advantage of the enhanced lateral drainage mechanism in controlling capillary rise from a high water table

Source: Zornberg et al. (2013)

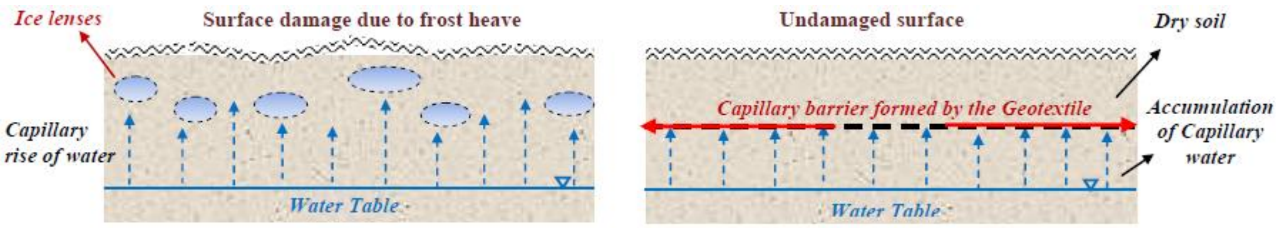


Fig 12. Advantage of the geotextile drainage mechanism in mitigation of damages caused by frost-heave deterioration

Source: Zornberg et al. (2013)

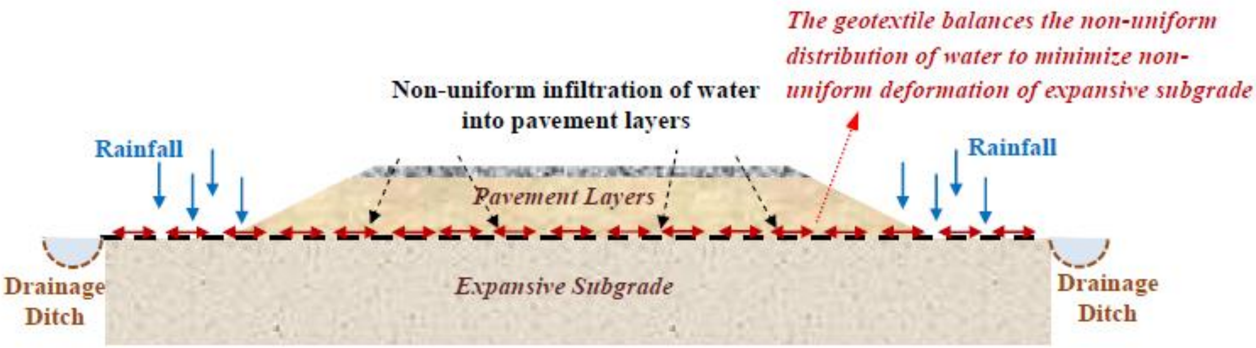


Fig 13. Advantage of the geotextile drainage mechanism in mitigation of damages caused by swelling-shrinkage of expansive subgrades

Source: Zornberg et al. (2013)

All previously mentioned moisture that was caught by geotextile has to be conveyed from pavement structure to arterial drainage systems. One of the most popular internal drainage systems is trench drains. This system usually contains a drain wrapped with geotextile, whether the whole trench is filled up with permeable aggregate or with a pipe surrounded by permeable aggregate. However, according to (Dawson, 2009), aggregate trenches are unpopular these days. Nowadays, trench pipes are a very common instalment, where different kinds of materials for pipes could be used such as perforated or porous concrete, PVC, fibreglass, and et cetera. The main function of these pipes is to have the ability to let in the surrounding water inside and covey it out of the pavement structure or surrounding territory. "Lithuanian Rules for the Design of Road Drainage Systems KPT VNS 16" describes the most basic design rules for drainage trenches. The minimum width of the trenches has to be 0,30 m, the minimum diameter of the drainage pipe has to be 100 mm, and the minimum grade for ensuring the self-cleaning ability has to be 0,30 %. Also, the drainage pipe crown has to be placed lower than the subbase layer of the pavement structure by 20 cm. The purpose of the geotextile which is wrapped around the pipe is to prevent fine aggregate particles from siling up the pipe. However, geotextile has to be permeable enough to ensure easy water particles entrance to the pipe. Well installed drainage has multiple advantages as long-term effectiveness, low-priced construction and maintenance works, the possibility of using the above area for other instalments, for example, pedestrian path.

Since there is a lot of ways for moisture to enter the pavement structure, high-level attention has to be paid to the adequate surface and internal drainage instalment. Surface drainage has to be meet grade requirements and even the asphalt grain sizes are recommended to be lower. And if the surface drainage is not enough, internal drainage equipment such as geotextile and drain trenches has to be used. These instalments would significantly reduce the maintenance works cost and reduce or even eliminate the pavement structure damages from frost-heave and bearing capacity depression during the spring thaw period.

1.2. Spring thaw effect on pavement structure performance

Spring thaw is a common problem for roads that are situated in cold regions that experience seasonal climate mode. As mentioned in the previous subchapter, during spring thaw road pavement structure bearing capacity decreases, therefore the traffic of heavy vehicles generates a high amount of damages. According to (Saarenketo & Aho, 2005), the AASHO research program measured distresses in the pavement structure during different seasons. Research showed that of all pavement structure distresses that appeared throughout the year, 60 % of them appeared during the spring season. (Doré, 1998) observed two test roads and determined that more than 90 % of fatigue cracks formed during partial winter thaw and spring thaw periods. Therefore, during this severe period, different countries try to solve this problem by using different solutions, says (Saarenketo & Aho, 2005). For example, Sweden rates weakly paved or gravel roads into three different classes: BK1, BK2, and BK3. BK1 allows traffic of vehicles that weighs up to 60 tones. BK2 and BK3 allow traffic of vehicles that weighs up to 51,4 tones, however, for BK2 the maximum axle weight can be 10 tones and for BK3 only 8 tones. The other example is Finland which has developed a very complex heavy vehicle traffic management system. Every road is rated in A, B, C, and D classes according to the significance of the heavy vehicle's transportation corridors. Only for classes, B, C, and D restrictions can be made. The level of restrictions is set by evaluating the previous year's road section thaw weakening history and also evaluating the thaw weakening forecast which is being generated every year in autumn. These countries' examples demonstrate the seriousness of the impact of heavy vehicles on the pavement structure during the spring thaw.

The degree of spring thaw severity for pavement structure depends on many factors and can not be the same for different areas of cold climate zone. It depends on the subgrade soil freeze-up, soil frost susceptibility, amount of moisture in the soil, quantity of standing water in subgrade soil that melted from the ice lenses, and heavy vehicles traffic. According to (Saarenketo & Aho, 2005), if any of these factors is absent, the spring thaw would not have a negative influence on the pavement structure. Therefore, the aforementioned factors have to be analyzed separately for the different areas and the expected spring thaw severity has to be determined before building the road. Some of the factors were mentioned in the previous sections and others will be discussed in the further sections.

1.2.1. Spring season climatic conditions throughout the years in Lithuania

Any place on the earth has different climatic conditions that are influenced by geographical position, sun radiation, movement of air masses, the shape of the earth's surface. Therefore, some parts of the earth are affected by four-season climate conditions. Those parts are distinguished as temperate and subarctic climates classification. These climates encounter major weather conditions changes throughout the year which affect not only human activities but also the performance of structures or mechanisms. In this case, roads are not exceptional.

Lithuania enters the temperate climate zone according to the Alisov climate classification and the warm-summer humid continental zone according to the Köppen climate classification, which means that during the winter, temperature decreases below 0℃, and during summer, the average temperature of this zone is around 22℃. Significant precipitation difference throughout the year is imperceptible.

Lithuania is situated on the east coast of the Baltic sea, around 1000 km away from the Atlantic ocean. It enters the east European plains territory. Lithuania's distance from the equator and the north pole is mainly determined by the amount of sunlight irradiance which, according to (Juknevičiūtė-Žilinskienė, 2009), is the most constant factor that influences Lithuania’s climate conditions. Since one square meter of Lithuania’s territory receives 3560 MJ of solar energy, the annual average temperature should be lower, however, additional warmth is brought by air masses. Air masses circulate the atmosphere and bring cyclones from the Atlantic ocean (oceanic climate) and anticyclones from the East European plains (continental climate). (Vaitekūnas & Valančienė, 2004) composed a table (table 3) that presents different types of air masses and from where do they come from, the weather conditions that are brought by them, and the period of the year that these weather conditions last.

Table 3. Properties of air masses forming the climate of Lithuania

Air mass	Comes from	Properties, weather conditions	Duration per year
Arctic-oceanic	Arctic ocean	Cold. During winter brings cold weather, snow. During spring and autumn causes ground frost.	13 %
Arctic-continental	The northeast part of Europe	Dry and cold. Brings a very severe cold. Reaches Lithuanian only during winter.	5 %
Temperate-oceanic	The northeast part of the Atlantic ocean	Warm and wet during winter. It Causes overcast weather, thaw, brings rain and sleet. Cool and wet during summer. Brings a lot of rain, causes storms.	42 %

Air mass	Comes from	Properties, weather conditions	Duration per year
Temperate-continental	East Europe and West Asia	Dry. Brings cold and sunny weather during winter. During summer season brings hot sunny weather without precipitation.	38 %
Tropical-oceanic	The middle of the Atlantic ocean, also the Mediterranean sea.	Warm and wet. Causes rapid warming during winter.	0,5 %
Tropical-continental	North Africa, South West Asia	Hot and dry. During summer season brings very hot weather, during autumn – sunny, pleasant, and warm weather.	1,5 %

Source: Vaitekūnas & Valančienė (2004)

The presented amount of different air masses create unpredictable weather conditions in Lithuania’s territory, and therefore meteorologists quite often mispredict the upcoming week's weather forecast. This is why Lithuanians have a quite popular controversial phrase “winter stumbled road workers unexpectedly”. It is usually said when the road workers do not manage to sprinkle the roads with salt or sand in time, which happens due to incorrectly predicted snowfall or blizzard and creates dangerous driving conditions.

This high annual weather change affects roads and generates severe damages for all pavement structure layers. Asphalt layers are very dependent on the temperature and it is the main disadvantage of them, says (Žiliūtė et al. 2016). According to (Juknevičiūtė-Žilinskienė, 2009), during hot summer days, the asphalt mixture’s bitumen loses its viscosity thus leading to depression of asphalt layer strength. While during cold winter days, the asphalt mixture’s bitumen acquires higher viscosity thus leading to the strengthening of asphalt layers. This forms asphalt layers ruts, corrugations, thermal cracks. Also, with the help of moisture, potholes could be formed.

In terms of unbound layers of pavement structure, the temperature would not make a huge impact on their conditions, however, the connection of temperature, frost depth, and moisture can create severe damages such as frost heave or bearing capacity depression. Fixing these damages costs a higher amount of money compared to asphalt layers damages since asphalt layers must be removed before repairing unbound pavement structure layers. Also, previously mentioned (Saarenketo & Aho, 2005) and (Doré, 1998) reports revealed that a major part of pavement structure damages appeared during the spring thaw period. All in all, KPT SDK 19 sets the expected lifetime for unbound pavement structure layers of a minimum of 50 years and 100 years for the subgrade. Therefore, the climatic conditions of the selected territory have to be carefully analyzed before designing a new road.

Even if the highest amount of damages appears during the spring season, that does not mean that the weather which generates these severe damages comes only from the spring season. As previously mentioned, damages appear while temperature, frost depth, and moisture influence each other. During the autumn season, a high amount of precipitations causes moisture in the pavement structure‘s unbound layers. During winter seasons, cold temperature penetrates through pavement structure and freezes soils. During the spring season, all frozen soils thaw due to warmer temperatures. Therefore Lithuania‘s winter-spring season's temperature and autumn season precipitation will be analyzed relying on Lithuanian Hydrometeorological Service provided data.

The further analyzed temperature data is provided in figures 14 and 15. Data was gathered from the Lithuanian Hydrometeorological Service website which provides measured climatic conditions in weather stations that are located in empty fields. Figures present the average ten days temperature or frost depth of the last four years during the winter and spring seasons and compare them with averages of the 1991-2020 period. Temperatures are only analyzed for winter and spring seasons since only these seasons influence the frost depth and thaw rate.

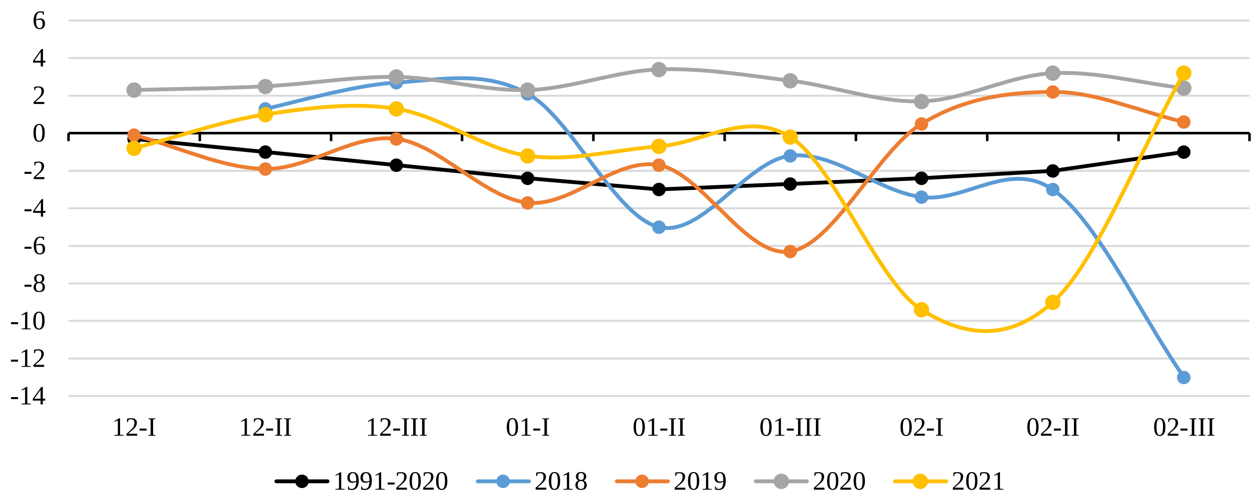


Fig 14. Winter season air temperature change during years 2018 – 2021

Source: designed by author

It is seen that during the winter season, the temperature constantly changes. For example, the year 2019 was very unpredictable, one week's temperature drops, while the other week's vice versa and this cycle continue for 7 weeks straight until temperature drops by a total of -6,2℃. This factor does not let soils freeze constantly and keeps their freezing speed at low rates. On the other hand, during the year 2018 winter temperature drops significantly two times, on the second week of January (by -7,1℃) and on the third week of February (by -10℃). This reflects a high impact on frost depth, which drops to 45 cm in January, and 50 cm in February. The last ten days of February's temperature was 13 times lower compared to the standard climate norm. Surprisingly, the year 2020 winter was a record mild with an average temperature of 2,6 and amplitude of 1,7℃. This also reflected on frost depth which was the lowest compared to other years. All in all, the last three winters were very different compared with the standard climate norm of the years 1990-2020. Only the winter of 2019 was rather close to this norm which could be also interpreted as the climate change warning sign. Anyhow, the average coldest month in Lithuania is January with a temperature of around -3℃. December average temperature is around -1℃ and February – -2℃.

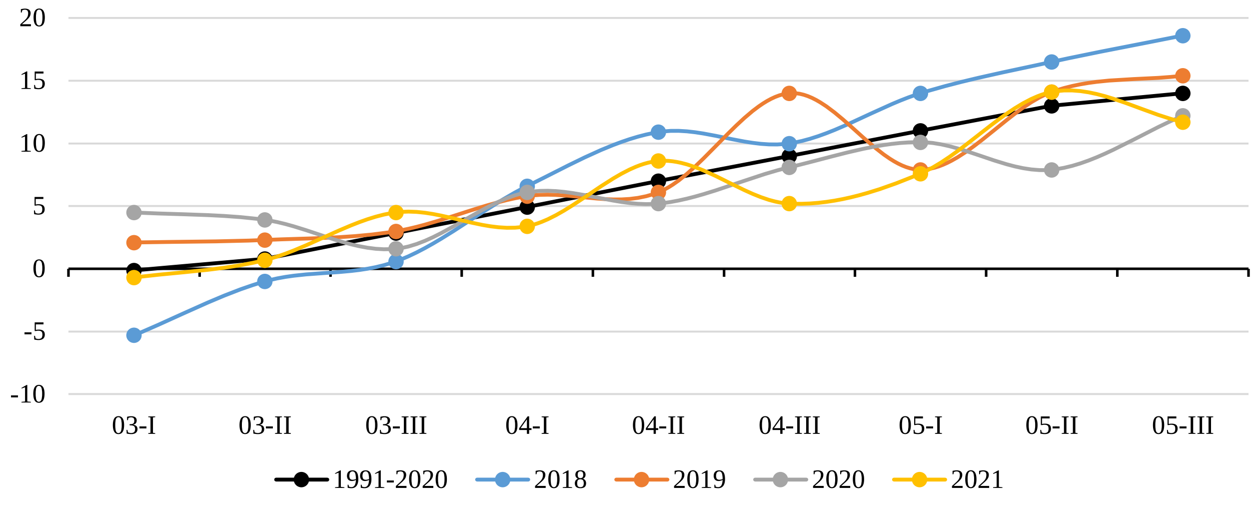


Fig 15. Spring season air temperature change during years 2018 – 2021

Source: designed by author

However, in the last four years, the spring seasons' temperature rose more or less at the same rate as the standard climate norm. The fastest growth pace of springtime temperature was recorded in the year 2018 with an amplitude of 23,9℃. This weather produced a very fast thaw rate and the frost depth disappeared from 65 cm to 0 cm in just four weeks. The slowest growth was recorded in the year 2020. Ironically, the winter of 2020 was very warm while the spring season was cooler than normal. Therefore, frost depth was the lowest compared to other years, however lasted quite long till the end of April. All in all, the average March temperature in Lithuania is around 1,0℃, April – 7,0℃, and May – 13,0℃.

Precipitations analysis is provided in figures 16, 17. Data was gathered from the Lithuanian Hydrometeorological Service website. These figures present the average ten days precipitations of the last four years during the autumn season and compare them with averages of the 1991-2020 period. Precipitations are only analyzed for the autumn season since this season is the one that produces the highest amount of them. Since the volume of precipitations in Lithuania's territory varies significantly, it is chosen to analyze them from two cities data: Gargždai (highest amount of precipitation) and Pakruojis (lowest amount of precipitation). Presented cities' precipitation volume is compared to Lithuania's standard climate norm.

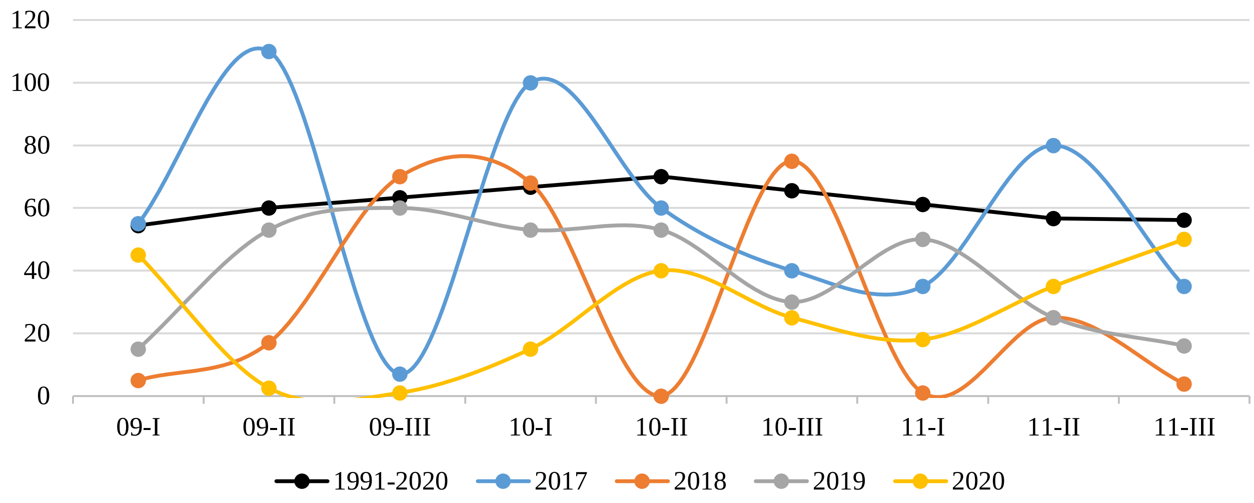


Fig 16. Gargždai city precipitations change during years 2017 – 2020

Source: designed by author

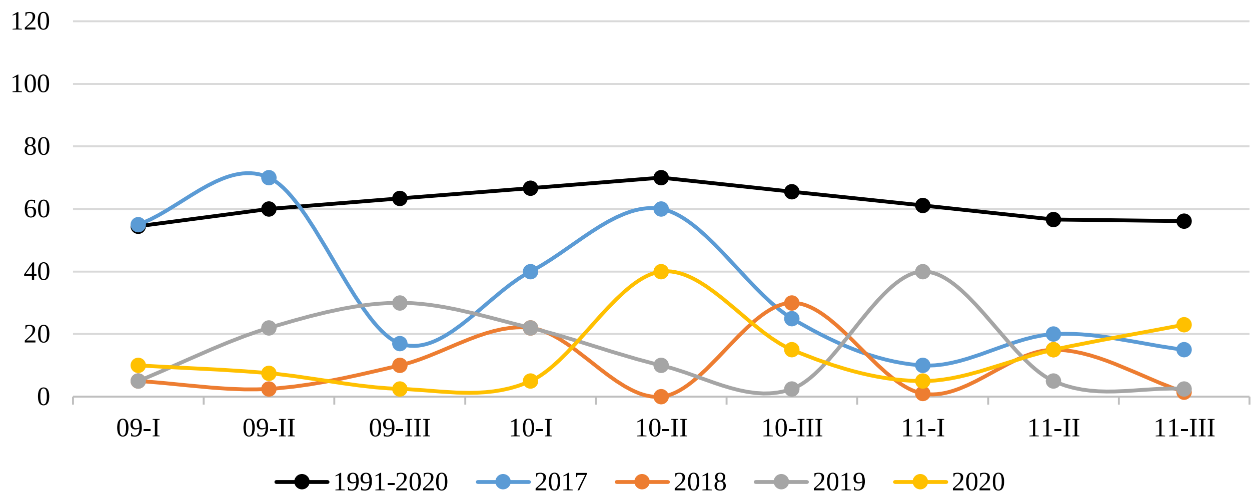


Fig 17. Pakruojis city precipitations change during years 2017 – 2020

Source: designed by author

The presented data for both cities is very inconstant, however, both Gargždai and Pakruojis cities have parallel curves in the figures, only with the different values. Gargždai usually receives higher precipitation volume since this city is 20 km away from the Baltic sea while Pakruojis is 160 km to the east of Gargždai. This is why moving Atlantic ocean cyclones release more precipitations in Gargždai compared to Pakruojis. In the year 2017, cyclones brought the biggest amount of precipitations for both cities compared to other years, 552 mm in Gargždai and 312 mm in Pakruojis. However, the value of precipitations was still lower compared to the standard climate norm of Lithuania (554 mm). The driest year in Gargždai was recorded in 2020 (232 mm), however, the driest year in Pakruojis was recorded during 2018 (87 mm). All in all, the average precipitation volume in Lithuania in September and November is around 60 mm, and in October is around 70 mm.

Analyzed data clearly shows how weather conditions in Lithuania territory are so unpredictable. During one winter, the temperature could be 13 times lower than the standard climate norm and during another winter, the temperature could break the record of the mildest recorded winter ever. All these temperature changes directly influence the frost depth in the soils. The volume of precipitation is highly dependent on the place in Lithuania and the Atlantic ocean cyclones. However, analyzed data could become useless in the future since it was noticed that the Lithuanian climate conditions are already facing climate change problems. Climate conditions' impact on the pavement structure will be analyzed in section 1.2.3.

1.2.2. Thawing rate influence for pavement structure performance

Every year, different climate conditions in the spring season cause different thawing rates, which differently influence pavement structure performance. However, the spring thaw is directly connected with the climate conditions during winter. There would not be any thaw in the spring if the winter did not cause soils to freeze. Also, winter temperatures would not have a high influence on pavement structure performance if there would not be any moisture in the aggregate layers, which comes from the rainy seasons in autumn.

During rainy seasons, pavement structure confronts the high amount of moisture that tries to seep in. The accumulated water in the pavement structure is mainly dependent on the permeability of the soil and the drainage quality in the built road. However, there are a lot of roads that do not have efficient drainage, thus leading to moisture freezing into ice lenses during the winter period. Despite the frost-heave probability, this period is positive when it comes to the bearing capacity of the pavement structure aggregate layers. However, during the spring, ice lenses melt and afterwards create voids in the soil. Therefore, according to (Christopher et al. 2006), moving vehicles creates a high water pressure in the void, which weakens the surrounding soil. Eventually, soil falls from above into the voids and creates damages to the pavement structure.

Previously analyzed climate conditions of Lithuania revealed that temperature in 2018 winter was opposite to temperature in 2020 winter. The average temperature in 2018 was -2,44℃ with the lowest temperature of -13℃, while in the winter of 2020, the average temperature was +2,66℃ with the lowest temperature of +1,7℃. These two winters can be categorized into cold and mild winters since, according to researchers, they have different influences on pavement structure performance during the spring thaw period.

According to (Christopher et al. 2006), spring thaw severity is higher in the southern frost zones since the repetitive mild winter’s freeze-thaw cycle is generating more damage to the pavement structure compared to the zones where frost penetrates deep into the soils but remains the minimum amount of freeze-thaw cycles. According to (Papuc, 2021), during mild winter, more ice lenses are expected to form closer to the pavement surface, thus leading to the high moisture content in the upper layers of pavement structure during the spring thaw. In contrast, (Simonsen & Isacsson, 1999) indicates that during cold winters, the densest ice lenses formation is normally located in deeper layers of the pavement structure and the quantity is usually much higher compared to mild winter. Therefore, severe conditions generally occur later in spring. Locations of ice lenses during mild and cold winters are provided in figure 18. Following these conditions, the 2020 mild winter had to be more damaging to Lithuania's roads compared to the 2018 cold winter.

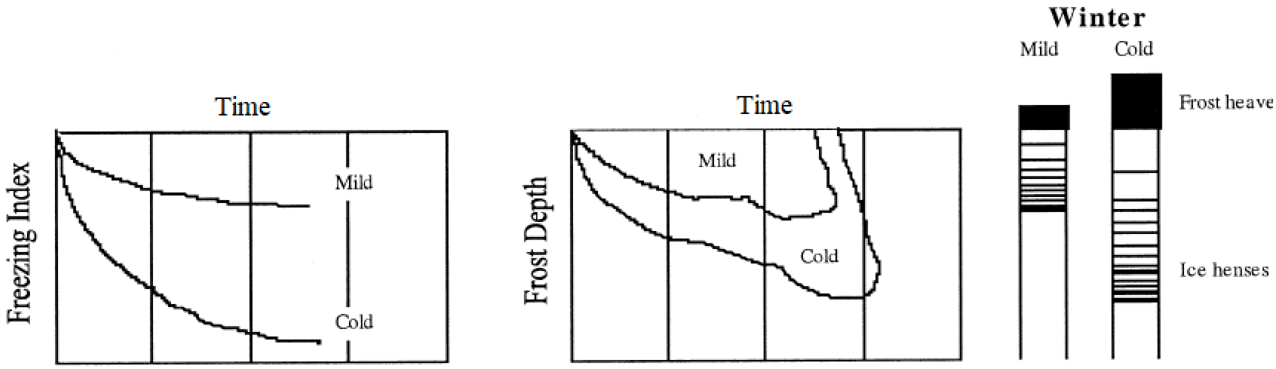


Fig 18. Location of ice lenses during a cold or mild winter

Source: Simonsen & Isacsson (1999)

(Doré & Zubeck, 2009) distinguish two critical periods for thawing weakening. The first period is the partial winter thaw and the early spring thaw that affects pavement structure aggregate layers and the second period is at the end of spring when thaw affects ice-rich subgrade soil.

During the first period, the rising temperature rapidly affects upper aggregate layers of pavement structure and incites the melting of ice lenses. However, lower layers of pavement structure are still frozen, therefore the water can not drain down. Also, the thaw progresses unevenly in the pavement structure due to different conditions on the surface of the road. Thaw progresses faster below the asphalt pavement since it has removed snow cover and the dark colour of the asphalt attracts solar heat. In contrast, road aggregate shoulders and slopes are usually covered in a snow layer which prevents heat transfer to pavement structure layers, thus delaying the progression of thaw. Moreover, melting snow on the shoulders and slopes additionally saturates the aggregate layers of the pavement structure which are already accumulated with a high amount of moisture. These conditions form a bathtub presented in figure 19a and traps water in the pavement structure. According to (Doré & Zubeck, 2009), this period is considered to be a critical part of the thawing process and generates excessive fatigue damages.

During the second period, the progression of thaw reaches ice-rich subgrade soils (figure 19b). The water can still accumulate in the soil above the frozen layer, however excess water in the pavement structure can be drained since the slopes and ditches are now clear. At that point, soil goes under the consolidation process. According to (Simonsen & Isacsson, 1999), if the subgrade soil is frost-susceptible and rich in ice lenses, the settlements will be severe since a high amount of voids are generated during the melting process.

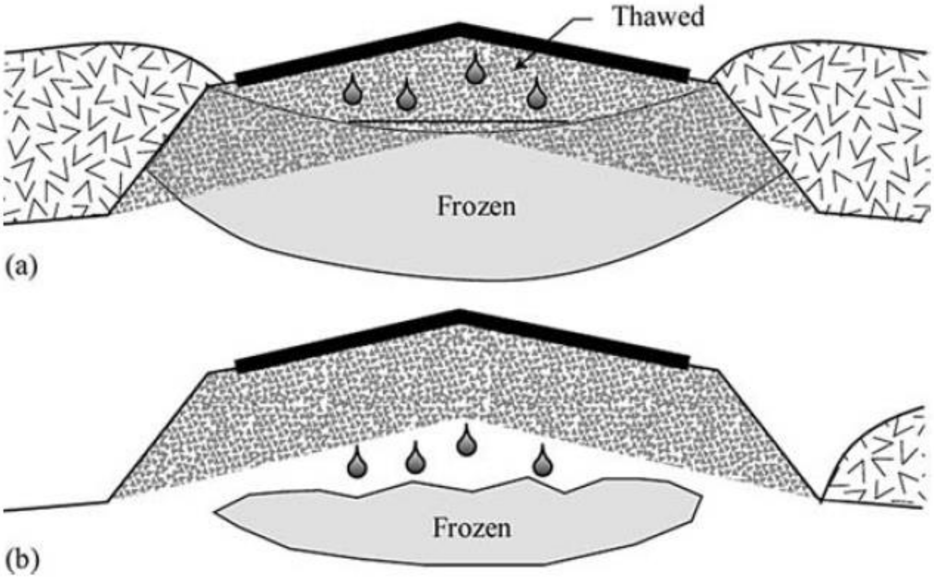


Fig 19. (a) an early stage of pavement thawing forms a bathtub; (b) a late spring thawing process involving frost-susceptible soils

Source: Doré & Zubeck (2009)

According to (Doré & Zubeck, 2009), the rate of thawing is a function of the climatic conditions during spring (heat transmission to the pavement soils) and the thermal response of the material (heat absorption). The heat transmission to the pavement soils can not be controlled, therefore only the thermal response of the material can be modified. However, according to (Doré & Zubeck, 2009), no attempts on reducing thaw weakening on modifying material thermal properties were made by the year 2009.

According to (Simonsen & Isacsson, 1999), rapid thaw influences the quick release of the water and therefore creates critical conditions of a drainage system that can not drain water fast enough, just like in figure 19. (Doré & Zubeck, 2009) add that increasing thaw rate and decreasing drainage capacity will increase the weakened area of the pavement structure and also extent the thawing period. Therefore, the knowledge about the upcoming thawing rate has a major significance in protecting roads, since the rapid thaw rate creates high pore water pressure which leads to the settlements of the pavement structure. (Doré, 2004) provides figure 20 which presents the relationship between thaw rate and the permanent deformation of the pavement subjected to loading during thawing. It can be seen that the rate of 3 mm/day of thawed ice lenses generates three times higher pavement deformation compared to the rate of 2 mm/day.

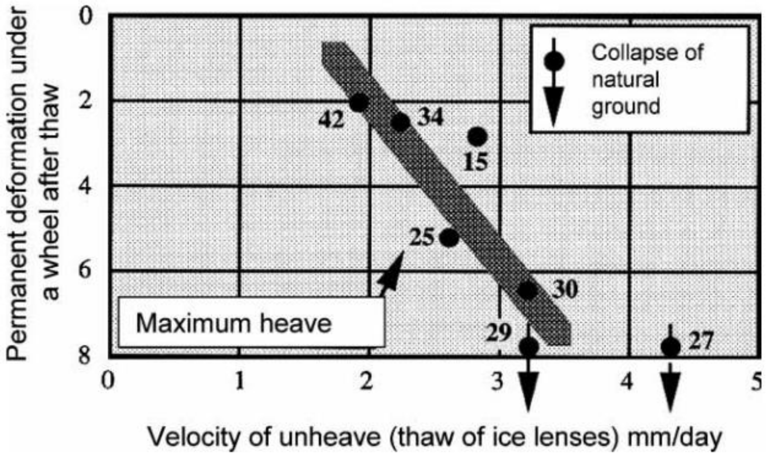


Fig 20. Effect of the thaw rate on pavement damage during thawing

Source: Doré (2004)

In contrast, (Simonsen & Isacsson, 1999) notices that thaw can penetrate not only from the surface to the subgrade layer but also from the subgrade layer to the surface. When the spring air temperatures are more or less moderate with cold nights over a longer time, thawing can mostly occur from below. This type of thaw is beneficial to pavement structure since the thawed soil water drains down into the soils beneath while the upper soil remains frozen. (Salour & Erlingsson, 2012) verified two-direction thawing while performing research on road No. 126 in Sweden and presented it in figure 21.

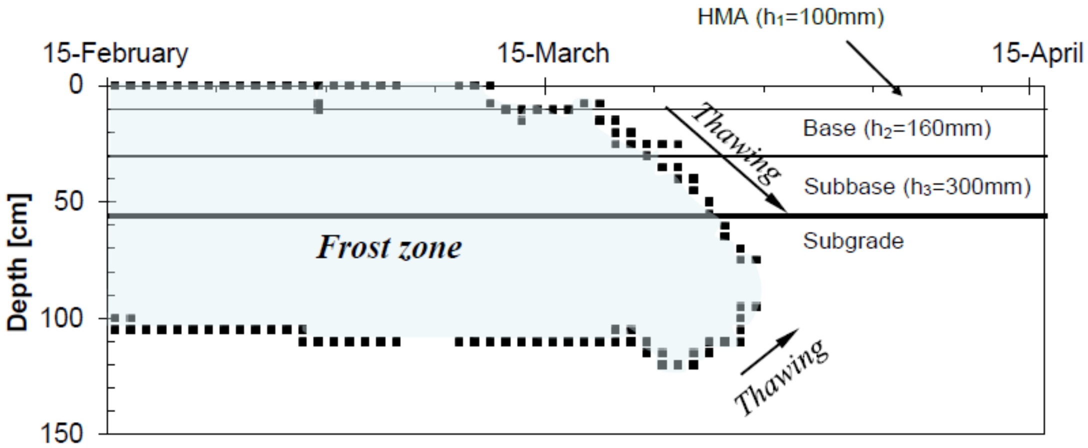


Fig 21. Illustration of pavement structure and frost thaw depths in Torpsbruk on road No. 126, Sweden, 2010

Source: Salour & Erlingsson (2012)

Previously analyzed climate conditions of Lithuania revealed that temperature growth in 2018 spring was more rapid compared to 2020 spring. The average temperature growth in 2018 spring was 2,99℃ per ten days while the 2020 spring average growth was only 0,96℃ per ten days. This means that the 2020 spring should have been less damaging to Lithuania's roads compared to the 2018 spring since the amount of the released water should have been lower.

In summary, the influence of the thaw rate is mainly dependent on the winter and spring air temperatures. During the winter, the biggest density of ice lenses in the pavement structure layer is mainly dependent on the air temperature. If the winter is mild, the ice lenses will form in the upper layers and if the winter is cold, ice lenses will form in the lower layers. Afterwards, during the spring, the rate of temperature change is directly connected with the pore pressure of the water and the settlements of the pavement structure. The rapid temperature changes make the water stuck in the pavement structure layers, therefore decreasing the bearing capacity. While the moderate temperatures keep the pavement structure's upper layers frozen while the thaw is proceeding from the bottom layers of the pavement structure.

1.2.3. Subgrade soil moisture and frost susceptibility impact on pavement structure performance

During the autumn, a huge amount of moisture seeps into the pavement structure aggregate layers. Since the moisture in the pavement structure can cause severe damages, it has to be drained as soon as possible, until the winter comes. During the winter, all moisture that is left freezes into ice lenses. Afterwards, all frozen moisture is being released during the spring thaw period, which, again, reduces the stiffness of the pavement structure. Therefore, the pavement structure damages are dependent on drainage systems and soil frost susceptibility. (Christopher et al. 2006) says that the majority part of different types of damages to the pavement structure can occur from the moisture and the freeze-thaw cycle. Moisture can generate fatigue cracking, rutting, depressions, potholes, and roughness. While freeze-thaw cycle can generate all the same damages as moisture does and additionally could create bumps. Therefore, researchers distinguish two major pavement structure damaging phenomenons that are connected: frost heave and soil thaw.

As previously mentioned in 1.1.2. section, frost susceptibility of soil depends on a few factors, however, the main factor is the number of fine particles. Frost susceptible soils have poor permeability and therefore easily suck in the surrounding water into the surface of its particles. Afterwards, when the accumulated water encounters the frost, it freezes into ice lenses. Frozen water in pavement structure expands around 8-10%, says (Vaitkus et al. 2016). This process produces the frost heave. During the experimental test (Doré, 2004) observed that heave of the pavement structure was only 10 mm high when the frost penetrated only the pavement structure base layers which are frost unsusceptible. However, when the freezing temperatures reached the frost susceptible subgrade soil, the formed heave was up to 150 mm high.

Frost heave would not create such severe damages to pavement structure if it would occur uniformly. However, heave rarely forms uniformly and significant differential movements can appear in the pavement structure due to two main internal mechanisms, according to (Doré & Zubeck, 2009).

The first mechanism is random differential heaving which is influenced by variable conditions of the soil properties along the section of the road. The generated distortions during winter increase pavement roughness. The second mechanism is differential heaving along the transverse axis of the road, which is caused due to variations of pavement geometry and snow accumulation on the pavement sides. Both mechanisms can also bend pavement surface upwards, which could cause the pavement to crack. (Doré et al. 2001) presented the first mechanism in figure 22, which shows how the frost heave can differ in terms of the type of subgrade soil and its frost susceptibility. The sandy subgrade soil dotted line has the lowest heaves since this soil has low frost susceptibility. The glacial tills subgrade soil dashed line shows that it generates around 40 mm high frost heaves due to silty soils which are frost susceptible. The biggest deformations up to 150 mm are generated by lacustrine deposits subgrade soil, which according to (Doré et al. 2001), is a result of alternating soil layers with different frost susceptibility.

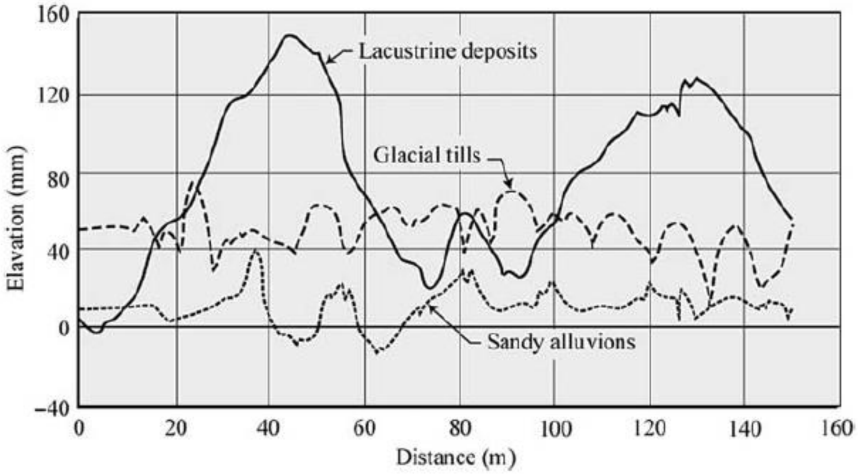


Fig 22. Differential heaving profiles for pavements built in three different geological contexts

Source: Doré et al. (2001)

Another major problem that is caused by differential frost heave is the high tensile stress at the road alignment. According to (Doré & Zubeck, 2009), frost heave is proportional to frost penetration, therefore pavement structure deforms unevenly in the cross-section. As mentioned in section 1.2.2., higher frost penetration is situated over the asphalt pavement due to the removed snow layer. Meanwhile, shoulders and ditches are covered in snow and therefore prevent the extraction of the heat from the sides of the road. This creates a bending moment and increases tensile stress at the road alignment, which leads to the pavement cracking along the centerline as shown in figure 23.

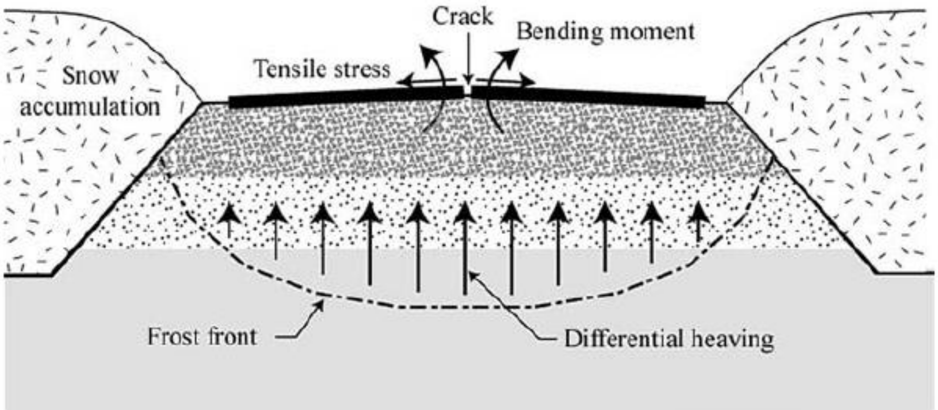


Fig 23. Stresses and cracking inducted by transverse differential heaving

Source: Doré & Zubeck (2009)

However, ice lenses formation has one beneficial side for the pavement structure, which is the increase of aggregate layers stiffness. According to (Papuc, 2021), the resilient modulus of frozen granular layers can reach 20-120 times higher values compared to unfrozen conditions due to air voids replacement with ice lenses. Unfortunately, stiffness benefit losses its importance since, during the spring thaw, all ice lenses are being released, and therefore, accumulated high moisture content severely decreases pavement structure bearing capacity. (Doré & Zubeck, 2009) gathered data from different researches and concluded that loss of bearing capacity during spring thaw ranges from 20 % to 60 % due to frost susceptibility of soils. These major decreases in bearing capacity generate severe deflections to the pavement structure, which, according to (Papuc, 2021), are the biggest throughout the year. It can be seen in figure 24. The peak of deflections is considered to be at the end of the spring thaw when the highest amount of moisture is accumulated in the pavement structure. Later, deflections decrease gradually since the excess moisture in the pavement structure is being drained out. This stage is called the spring recovery period and according to (Salour & Erlingsson, 2012) could last from two weeks for the subbase layer to nearly one month for the subgrade.

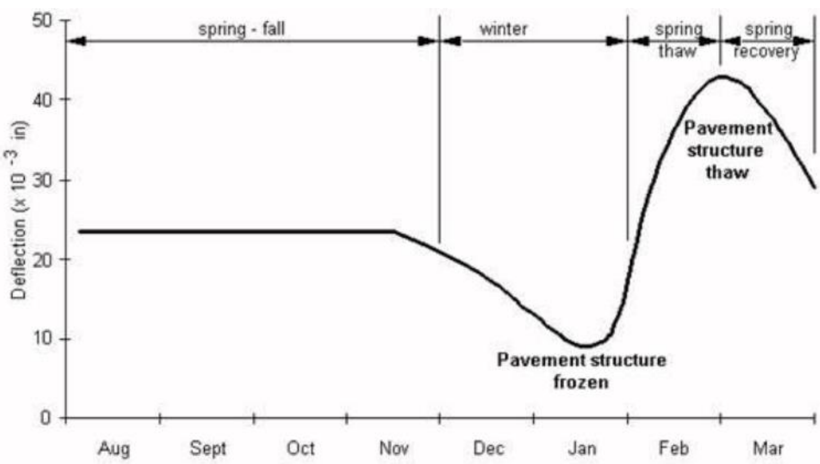


Fig 24. Deflection dependence on the month

Source: Papuc (2021)

One of the major factors of deflections during spring thawing is the settlement of pavement structure caused by thawing. (Simonsen & Isacsson, 1999) notes that settlements derive from the whole soil's volume decrease during the season phase shift, weight of thawing soil, and external loads. The volume of settlements in thawing soil is dependent on the amount of ice produced during winter, soil density, pore water pressure, and soil compressibility. (Tsytovich et al. 1965) provided figure 25 which shows standard results of consolidation test during soil thawing, where (e) stands for void ratio and (P) for external pressure. Phase a-b corresponds to the frozen state of soil and indicates an increase in its compressibility while the external load increases. Phase b-c represents the thawing state and indicates the subsidence of the soil. Phase c-d corresponds to the consolidation of the soil after thawing. The figure also notes that thawing under different external loads does not necessarily produce the same amount of settlements for the same soil (a-b'-c'-d'). The consolidation test shows that maximum settlements in the pavement structure occur during the thawing period rather than subsequent consolidation.

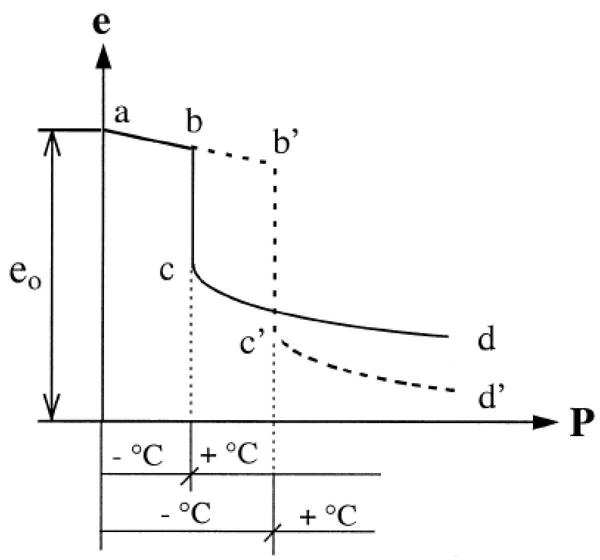


Fig 25. Relationship between change in the void ratio of frozen soils in the process of thawing and change of external pressure

Source: Tsytovich et al. (1965)

However, not only the settlements are caused by the spring thaw. As mentioned in the previous section, it is common that during the early spring thaw period, thawed water is trapped between the asphalt layers and frozen soils, since the water can not drain out of the pavement structure. This excess water content, according to (Salour & Erlingsson, 2012), reduces aggregate layers' structural stiffness and diminishes bearing capacity. In addition to depression of shear strength in soil, the excess amount of pore water pressure can be generated due to heavy vehicles traffic, resulting in a decrease in soil particles internal friction forces. Additionally, a pump of fine course soil into coarse-grained soils can occur thus leading to degradation of pavement material and loss of support. Under all these conditions, permanent deformations are assured. (Simonsen & Isacsson, 1999) says these conditions are especially critical for thin bituminous layers. The depressed layer under the surface results in the bending of the bituminous layer thus generating large tensile strains at the bottom of this layer. Additionally, heavy vehicle tyre contact with the surface generates pressure which is immediately transferred to pore water pressure. In this condition, if the transverse drainage is restricted, high pore water pressure makes the base layer unstable and therefore causes asphalt wearing coarse to break (figure 26).

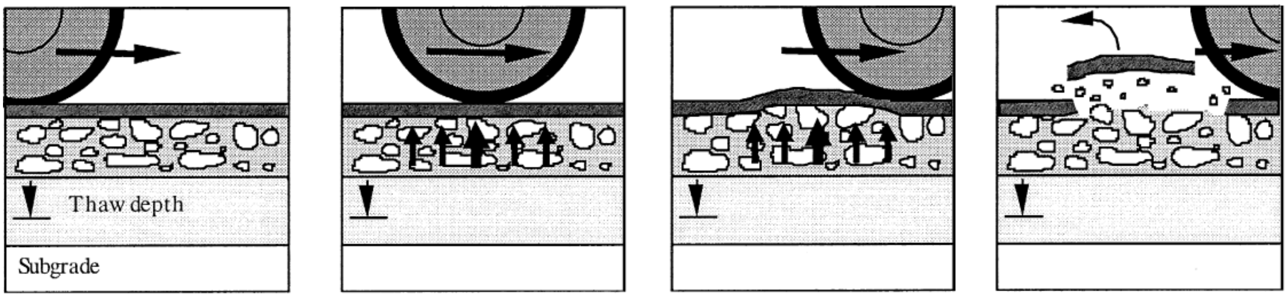


Fig 26. Damage in the road structure during the early spring thaw period

Source: Simonsen & Isacsson (1999)

In summary, the biggest pavement structure damages are generated during the winter frost heave period or spring thaw period. These damages are mainly influenced by excess water content in granular pavement structure materials and their frost susceptibility. As a consequence of frost heave, asphalt pavement bends both longitudinally and transversely by creating an uneven driving surface. Differential heaving could generate such severe stresses that could crack asphalt pavement through the alignment. As a consequence of thawing, pavement structure could be damaged by granular layers settlements due to voids created by melted ice. Also, because of the standing water between bituminous pavement and frozen aggregate layers, base layers of the pavement structure loses bearing capacity and therefore could break the asphalt wearing course.

1.3. Pavement structure subgrade soils improvements

All road pavement structures according to Lithuanian regulations are designed on the same deformation modulus of subgrade which is 45 MPa, with the provision that the deformation modulus of subgrade does not decrease lower than 45 MPa at any time of the year or design lifetime. However, previously analysed data revealed that the strength of subgrade, which is made of frost susceptible soils, during the spring thaw period decreases dramatically thus leading to severe pavement structure damages. Therefore, in the year 2019, the Lithuanian road administration released a new pavement structure design normative “Lithuanian Rules for the Design of Road Standard Pavement Structures

KPT SDK 19”. These rules indicate the requirement to improve pavement structure frost susceptible subgrade soils by applying stabilizing materials.

Since the regulation of soil stabilization is currently only three years old, there is no statistical research on how this regulation improves the quality of Lithuanian roads. However, it is expected that this solution to the problem will significantly decrease the probability of subgrade bearing capacity loss regardless of winter roughness or spring thaw rapidness. Also, it is expected to reduce deflections to the pavement structure which are caused not only by the spring thaw but by the frost heave also.

1.3.1. Methods and material types used for subgrade soil improvements

KPT SDK 19 distinguishes three main situations when different methods of soil improvements have to be used according to the design load of pavement structure and subgrade soil’s frost susceptibility level. When the design load is determined to be higher than 1,0 mln. and the subgrade is designed of frost susceptible soils (F2, F3), stabilization of the subgrade soils has to be applied. If the design load is determined to be lower than 1,0 mln. and the subgrade is designed of low or moderate frost susceptible soils (F2), any of these three actions have to be applied, whether it is soil improvement, soil replacement, or an additional structural layer instalment. If the design load is determined to be lower than 1,0 mln. and the subgrade is designed of very frost susceptible soils (F3), either the qualified improvement of the subgrade soil has to be applied, or the soil has to be replaced. Stabilization, improvement, and qualified improvement works are performed by applying soil stabilization binders into the pavement structure subgrade. The available types of materials, their properties, and their application are specified in “Lithuanian Methodological Instructions for the Improvements and Stabilization of Soils MN GPSR 12”.

Since there are different methods of soil improvements, they all have different purposes. Soil stabilization (SS) enhances soils‘ resistance to traffic loads and climate impact. Therefore, soils acquire long-term bearing capacity and frost resistance. Due to technical reasons, according to MN GPSR 12, the minimum thickness of the stabilized subgrade layer has to be 0,15 m. Soil improvement (SI) enhances soils’ technological and compaction properties while facilitating road construction works. Additionally, increased soils’ bearing capacity and reduced susceptibility to weather conditions can be achieved. Due to technical reasons, MN GPSR 12 recommends a minimum thickness of 0,20 m for the improved subgrade layer. Soil qualified improvement (SQI) is the soil improvement (SI) but with higher requirements on certain soil technical properties, for example, bearing capacity or frost resistance, thus leading to reduced deformations of subgrade. Therefore, according to MN GPSR 12, highly frost susceptible soils can gain technical qualities of the low or moderate frost susceptible soils. Also, due to technical reasons, the minimum thickness of the qualified improved subgrade layer has to be 0,20 m.

All these different types of soil improvements, according to Lithuanian regulations, can be performed by using these four main binder materials: quicklime, hydrated lime, cement, and hydraulic road binders. All these binders have to be selected according to the type of subgrade soil and its current technical properties. For the treatment of fine-grain soils quicklime or hydrated lime are used. Quicklime is produced by milling air lime while hydrated lime is produced by extinguishing air lime with water. Also, quicklime can be used for the subgrade soil with an excess amount of water, thus reaching the optimal amount of water defined by Proctor. For performing different types of soil improvements, different amount of quicklime or hydrated lime has to be used. These amounts are provided in table 4. Meanwhile, cement or hydraulic road binders are used for coarse-grain and multi-grain soils. Both of these binders are hydraulic however, a hydraulic road binder is a binder that is particularly adapted for roads, railways, or airports aggregate layers. This binder is produced in factories and, according to EN 13282-2, its main constituents could be portland cement clinker, granulated blastfurnace slag, pozzolanic materials, fly ash, burnt shale, or limestone. The hardening process of hydraulic road binders is similar to the hardening process of cement but usually takes longer. However, if it is decided to use a cement binder for soil modification, the 32,5 R strength class is used for normal soil conditions. Nonetheless, for special conditions (bad weather, risk of exposure to freezing) the higher strength of cement has to be used. The amount of cement or hydraulic road binder for performing different types of soil improvements is provided in table 4. However, if there is a need to use different kinds of binders (sludge ash, fly ash, secondary materials which come from the steel or coal industry, and et cetera) and their suitability is proven, they can also be used.

Table 4. Binder content for a different type of soil and a different type of their modification

Subgrade modification type		**Binder content as a percentage by mass**			
	Binder / Soil type	Quicklime	Hydrated lime	Cement	Hydraulic road binder
Soil stabilization (SS)	Course-grain	-	-	3-7 %	3-7%
	Multi-grain	-	-	4-12%	4-12%
	Fine-grain	4-6 %	4-8 %	-	-
Soil improvement (SI)	Course-grain	-	-	3-6 %	3-6 %
	Multi-grain	-	-	3-6 %	3-6 %
	Fine-grain	2-4 %	2-5 %	-	-
Soil qualified improvement (SQI)	Course-grain	-	-	-	-
	Multi-grain	3 %	3 %	-	-
	Fine-grain	3 %	3 %	-	-

Source: MN GPSR 12

MN GPSR 12 defines two methods of soil improvements: mixed-in-place and mixed-in-plant. Although the mixed-in-place method is easier and more economically beneficial, the mixed-in-plant method is more useful when the local conditions of the road are complicated, for example, performing road surface widening works or there is a large number of engineering networks in the subgrade. The mixed-in-place method is performed by a milling machine that drives on the prepared subgrade layer and mixes in a previously spread binder and water. The mixed-in-plant method is performed by mixing soil, binder, and water in the plant. The basic steps of soil improvement works are spread of binder, mixing, grading, compaction, maturation.

The spreading of the binder process is performed only for the mixed-in-place method (figure 27). This work can only be performed using machines specially made for this purpose. The amount of spread binder has to be checked by using control sheets. When soils have high plasticity and excess moisture content, the binder can be spread over several times. However, the spread binder can not be left and the mixing has to be performed as soon as possible.

Fig 27. Binder spreading works performed with a special machine

Source: http://www.conatsersiteservicestx.com/files/subgrade_stabilization.asp

The mixing process is performed both by mixed-in-place and mixed-in-plant methods. During the mixed-in-place method for SS and SQI, the milling machine has to mix soils for as long as the uniform colour and uniform content of water is achieved in the whole thickness of the stabilized subgrade layer. However, during the mixed-in-place method for SI, soils can be mixed with different kinds of machines as long as soil and binder are mixed properly. During the mixed-in-plant method, soils can be mixed with binders by using both periodic operation plants or continuous operation plants. However, the most suitable are mobile mixing plants. The mixed soil can be transported to the site with an open-body dump truck or with a closed-body dump truck if the water loss is crucial. The mixed soil in the site has to be laid with a paver machine.

After the subgrade soil ir mixed with the binder, the grading process has to be performed to prepare the layer for the compaction. However, if the SS was performed, the grading process is allowable only for exceptional reasons since the uniform thickness of the layer can not be achieved. Grading works are performed by graders. When the subgrade is graded, compaction works are performed by the standard soil compaction requirements.

Finally, maturation (covering) works are performed. Maturation protects subgrade layers which were stabilized by hydraulic binders from drying up. Stabilized layers have to be kept moist for at least three days, for example, finely sprayed with water. As an alternative, the moistured layer can be covered with a bituminous emulsion film. For the soils which were modified with limes, maturation works usually are not performed.

1.3.2. Mechanical properties of pavement structure with improved or stabilized subgrade soils

Road engineers constantly face poor quality soils during construction works. The excavation and soil replacement works generate a significant amount of costs. However, these works can be avoided by performing soil improvement. This performance has significant technological, environmental and economical benefits, according to (Mosa et al. 2017). Therefore, the soil improvement topic is very popular in the road engineering field these days. Researchers are constantly performing experiments with various types of binders and trying to find the best material which increases the technological properties of soils while requiring as low investments as possible. However, nowadays, the most popular binders are lime or cement.

Quicklime and hydrated lime which are described in MN GPSR 12 has a different type of reaction with the soil. Quicklime which is being mixed into the subgrade layer reacts with the water particles in the soil and therefore releases heat. Soils are being dried since the moisture is involved in the chemical reaction for hydrating quicklime thus leading to reduction of its content. While hydrated lime is being mixed into a subgrade layer, its calcium ions transfer to the surface of soil particles and replace water and other ions. Therefore, the soil becomes friable and granular which encourages a more efficient companion.

(Little et al. 2000) notices that soil improvement using lime advances some important mechanical properties in soils including strength, resilient properties, resistance to fracture, fatigue, permanent deformation, deterioration due to soil moisture, reduce swelling. (Kestler, 2009) adds that lime also reduces soil density, decreases plasticity, improves workability, and reduces volume-change characteristics.

(Bell, 1989) performed research on how lime acts precisely on clay soils. He noticed that lime rapidly reacts with clay reducing the plasticity and converting even heavy clays into friable soil instantly after the mixing. Moreover, lime instantly transforms clay into firm water-resistant soil with higher strength, increased permeability and resistance to erosion. Figure 28 provided by (Bell, 1989) represents how different amounts of lime additive affects the plasticity index of the soil which is dependent on moisture content. Lime slightly decreases the required content of moisture for clay to reach the liquid state, however, significantly increases the required content of moisture to reach the plastic limit. Even 2,0 % of added lime can increase plastic limit around 40 %, therefore subgrade soil can withstand higher water content which is being released during the spring thaw. The effectiveness of added lime content, according to (Bell, 1989), increases till it reaches 4,0 %. Afterwards, the higher amount of lime does not have a major influence on the plasticity index of clay. Also, only 2,0 % of lime addition generates a significant impact on clayey soils linear shrinkage by reducing it from 14,0 % to around 6,0 %. Further increase of lime content in the soil continuously reduces linear shrinkage, however, the decrease of shrinkage level slows down on around 6,0 % of lime content in the soil.

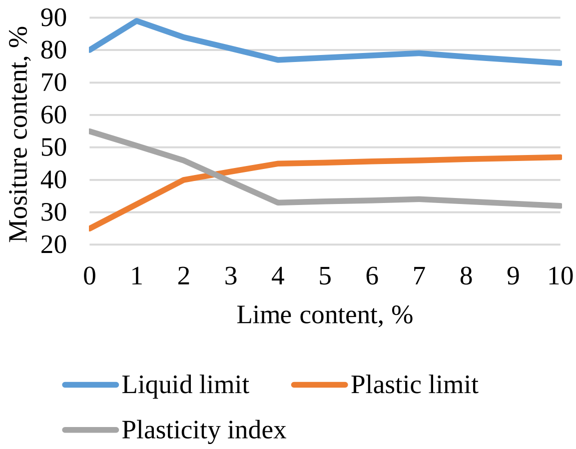


Fig 28. Liquid limit, plastic limit, and plasticity index dependency on lime and moisture contents

Source: Bell (1989)

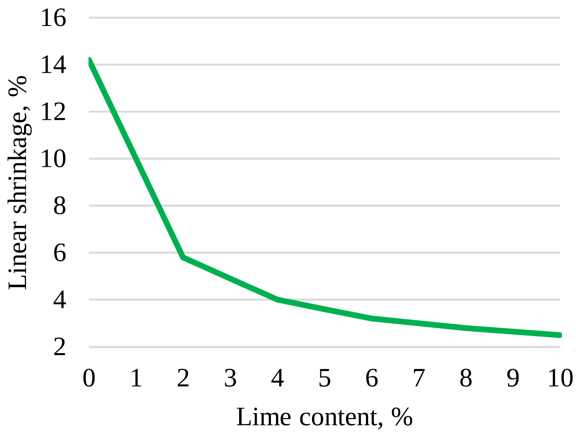


Fig 29. Influence of the addition of lime on the shrinkage

Source: Bell (1989)

Also, according to (Bell, 1989), clay improved with lime flattens the compaction curve. The higher quality of compaction is achieved not by dry density specification but by controlling moisture content. Therefore, achieved lower plasticity index forms better conditions to ensure the specified percentage of the density due to the possibility of a wider range of moisture content. Additionally, the optimum moisture content is increased thus permitting soils in wetter conditions than the original to be compacted sufficiently. During the experiment, compaction tests were performed on three different types of clayey soils which were treated with lime binders and on one untreated clayey soil. The experiment showed that all three improved soils underwent an increase of optimum moisture content from 2,0 % to 11,0 % and a decrease in maximum dry density from 0,02 Mg/m^3 to 0,06 Mg/m^3.

(Robnett & Thompson, 1976) analyzed how hydrated lime affects two soil types during the freeze-thaw cycle. One specimen has a high silt content and the other has high clay content. Both specimens were treated with 5,0 % of hydrated lime binder and the result showed that resilient behaviour was minimized or eliminated. The experiment showed that even after ten freeze-thaw cycles, the resilient behaviour does not appear significantly affected. The resilient modulus of both untreated silt and clay ranged from 20 to 41 MPa after one freeze-thaw cycle. However, when soils were treated with lime, the resilient modulus increased significantly and ranged from 96 to 138 MPa after ten freeze-thaw cycles. Therefore, this experiment emphasizes the importance of lime treatment on the subgrade soil which faces the biggest threatening of deformations during the spring-thaw cycles.

(Primusz et al. 2008) notes in figure 30 that the modulus of elasticity increases in the lime treated soil by hourly accuracy. The test was performed in the experimental road section from Pk 4+50 to Pk 7+80 where untreated subgrade soil's modulus of elasticity ranged only from 9,0 to around 12,5 MPa. However, instantly after the mixing of the soil with the binder, the modulus elasticity ranged from 21,0 to 51,0 MPa and kept constantly rising till 120 hours after the treatment, while eventually ranging from around 41,0 to around 72,5 MPa.

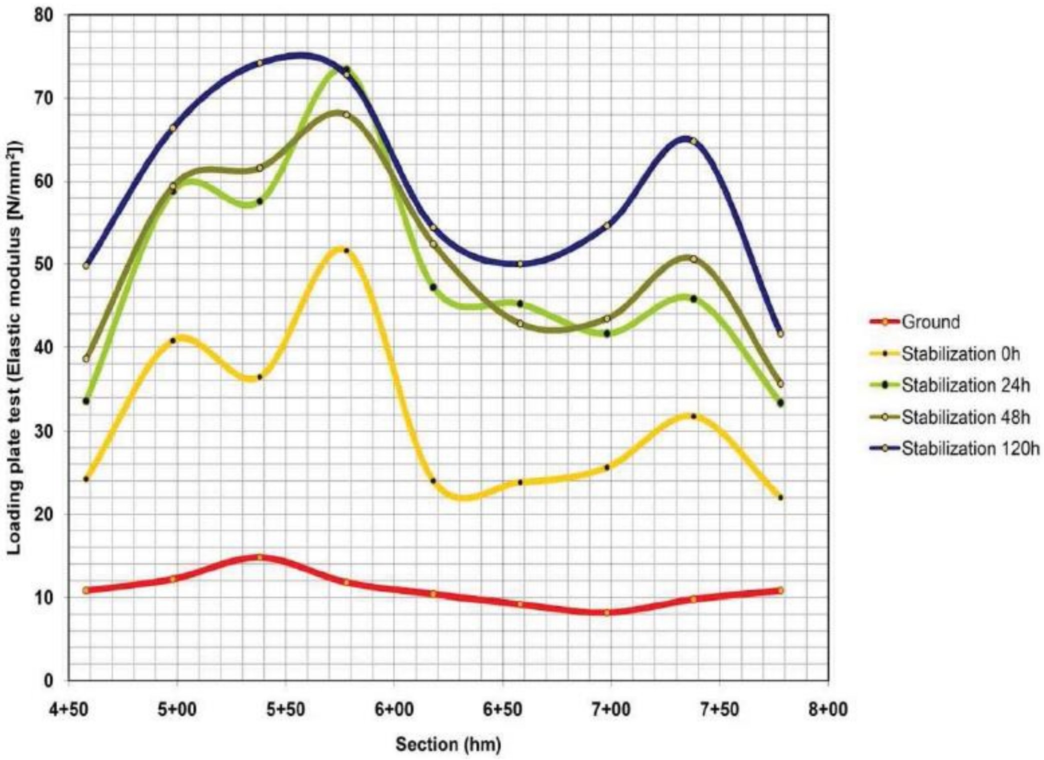


Fig 30. The modulus of elasticity changes as a function of time

Source: Primusz et al. (2008)

However, if the cement binder was chosen to perform subgrade soil treatment, according to (Kestler, 2009) it will increase soil's strength, decrease compressibility, reduce the swell probability, and increase durability. While mixing soil with cement, the imputed water hydrates cement and generates reactions that create a matrix between soil particles and therefore, soil gains strength. In general, the mechanical effect of cement is similar to the lime binder, however, cement has pozzolanic materials that influence rapid hardening and therefore create a solid, bound, impermeable layer.

(Nazari et al. 2021) describe how cement content in the silty clay soil with sand affects its strength and axial strains. The untreated soil axial strains change almost linearly with the increasing compressive stress. The peak of the recorded compressive stress was around 550 kPa with the 4,5 % of axial strains. The increasing cement content constantly increases the strength and decreases axial strain. For example, 3,0 % of added cement increases the strength of soil to around 625 kPa and decreases axial strain to around 3,6 %. 9,0 % of added cement increases the strength to around 700 kPa and decreases axial strain to around 2,7 %. (Nazari et al. 2021) also performed the one-dimensional consolidation test. It revealed that increasing cement content has improved the compression and swelling indexes significantly. The compression index decreased in a range from 70,0 to 83,0 % with the addition of cement from 1,5 to 9,0 %.

Meanwhile, (Parsons et al. 2004) performed the unconfined compression strength test on different types of soils. The experiment presented that strength at the optimum moisture content for clay soils without any additives was around 0,50 MPa and with cement additive strength increased in a range from 1,40 to 2,90 MPa. While the silt soils strength without any additives was around the same 0,50 MPa, however, the strength after the stabilization with cement increased dramatically in the range from 3,50 to 5,50 MPa. (Parsons et al. 2004) also performed the swell potential test which showed, that clay soils swell potential decreased to the minimum values. However, for the silt soils which are affected by cement, the swell potential was completely eliminated.

(Bhattacharja et al. 2003) analyzed shrinkage limit which determines the dimensional balance as the moisture level in the specimen is changed. It is defined as the percentage moisture content at which no further reduction in volume takes place as the specimen loses moisture. Therefore, the best scenario would be that if the shrinkage limit would be higher than optimum moisture content since the further accumulation of moisture beyond optimum moisture content would protect soils from swelling and the later decrease of moisture will not cause soil to shrink and settle. The effect of cement stabilization on shrinkage limit is provided in figure 31. The shrinkage limit of untreated soil was determined around 10 for all specimens. Afterwards, when the cement stabilization was performed, the shrinkage limit increased around three times and outgrew the optimum moisture content. In all cases, the higher additive content was applied, the higher shrinkage index was gained. Comparing cement and lime binders effectiveness, eight out of eleven specimens have reached a higher shrinkage limit with cement binder compared to the lime binder, which summarizes that cement-treated soils are dimensionally more stable over the wider moisture range compared to the lime treated soils.

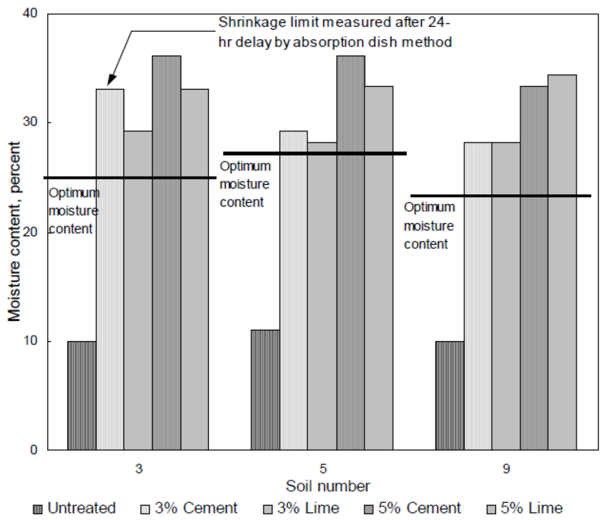


Fig 31. Shrinkage limit of unimproved and improved soils with cement or lime binders

Source: Bhattacharja et al. (2003)

To finalize, the analysis of lime and cement treatment performance on the Lithuanian road subgrade soils will be carried out. These subgrade soil treatments were performed following MN GPSR 12. (Gurskis et al. 2015) complied with an analysis on reconstructed national road No. 136. They performed lime or cement treatment on the road subgrade soils, which were sandy or clayey and afterwards measured deformation modulus by two attempts E_{V1}, E_{V2} and defined their ratio. Four situations were analyzed: sandy soil with lime treatment, sandy soil with cement treatment, clayey soil with lime treatment, and clayey soil with cement treatment. Lime treatment on any type of soil was successful and the required deformation modulus of $E_{V2} \geq 45$ MPa and the ratio of $E_{V1} / E_{V2} \leq 2{,}5$ was achieved. However, the ratio for clayey soil was lower than the ratio for sandy soil which means that higher compaction was achieved in clayey soils. This meets the MN GPSR 12 defined regulation to use lime binder for the fine-grain soils. The same as the lime treatment, the cement treatment on both sandy and clayey soils also reached the required deformation modulus and their ratio. However, the ratio of deformation modulus between clayey and sandy soils was almost equal, which means that the achieved compaction was more or less the same. It is necessary to mention that these deformation modulus values were measured directly on the subgrade structure during the construction phase.

1.4. Conclusions

1. Subgrade soil type, its frost susceptibility, and water drainage are the main factors to achieve the required expected lifetime of the subgrade and whole pavement structure. The frost susceptibility of soil is exactly dependent on the amount of fine particles in it and its plasticity index. A higher amount of fine particles and a lower plasticity index makes soil more frost susceptible. It is important that the subgrade made out of frost susceptible soils can perform similarly good as the

subgrade made out of frost unsusceptible soils, however, the adequate compaction of subgrade soil and the minimum thickness of the subbase layer has to be ensured.

2. To minimise the frost influence on the frost susceptible soil, the subbase layer is being installed. Therefore, to determine the needed thickness of the subbase layer, the frost depth has to be measured directly under the pavement structure since it usually is higher compared to the frost depth in the surrounding territory, usually under the snow. Additionally, water enters pavement structure layers and reaches frost susceptible soils in many ways such as capillary rise, lateral moisture transfer in the soil, and precipitation, thus, effective water drainage has to be ensured. Surface drainage is developed by installing slopes on the surfaces, while internal drainage is installed by using additional equipment. Researchers state that the most effective types of internal drainage systems are geotextile drainage and drain trenches.
3. Researchers note that pavement structure is being highly deteriorated during mild winter when the densest quantity of ice lenses forms in upper pavement structure layers and during the rapid spring thaw since drainage can not work properly due to excess moisture content.
4. The connection of frost susceptible soils and moisture generates two major deteriorations to the pavement structure. One is frost heave, which can heave pavement up to 150 mm or can also generate pavement cracking along the road alignment. The second is spring thaw which generates pavement structure settlements and also reduces internal friction between soil particles due to frost susceptible soils and poor drainage quality. It can reduce pavement structure bearing capacity up to 60 %.
5. KPT SDK 19 distinguishes three different types of pavement structure subgrade improvement which are applied according to the design load and soil frost susceptibility: soil stabilization (SS), soil improvement (SI), and qualified soil improvement (SQI). Moreover, MN GPSR 12 guides four main binder types which have to be chosen according to a different type of subgrade soil. Quicklime and hydrated lime treatment are used for fine-grained soils while cement and hydraulic road binders are used for multi-grained and coarse-grained soils.
6. Researchers analyzed the effect of those binders and stated that lime treatment applied to fine-grained soils increases plasticity limit, reduces linear shrinkage, flattens compaction curve, while cement treatment applied for multi-grained and coarse-grained soils reduces axial stresses and increases soil strength, shrinkage limit and improves compression and swelling indexes.

2. EXPERIMENTAL INVESTIGATION OF PAVEMENT STRUCTURE BEARING CAPACITY IN REGIONAL ROADS SECTORS

2.1. The subject of experiment and methodology

Pavement structure subgrade bearing capacity, according to previously analyzed literature, constantly changes and decreases significantly during the spring thaw period. However, it is expected that deformation modulus does not decrease lower than the required $E_{V2} \geq 45$ MPa which is determined by Lithuanian design rules. Design rules also state that if the deformation modulus can not be reached to be 45 MPa even by using drainage, the subgrade improvement works must be applied. (Gurskis et al. 2015) performed subgrade soil improvement with lime and cement and successfully reached the required deformation modulus. However, they have measured it directly on the subgrade soil during the construction works and no further investigations were made when the whole pavement structure was constructed or later, during the spring thaw period. Therefore, the purpose of this research is to evaluate how pavement structure works during the spring thaw compared to the dry period in currently operating roads. How the pavement structure and deformations are dependent on climate conditions and the subgrade soil improvement type.

To evaluate the subgrade's bearing capacity and deflections on already built pavement structure deflection test has to be performed. The most widely used device in Europe is the falling weight deflectometer (FWD). It is depicted in figure 32 and is usually attached to the vehicle like a trailer. This device consists of two main components. First is a mechanical loading system which is composed of the falling weight and the loading plate. This system has to represent a heavy vehicle wheel dynamic load of 5 t and contact pressure of 707 kPa. The second component is the measurement system consisting of sensors and a data collection system.

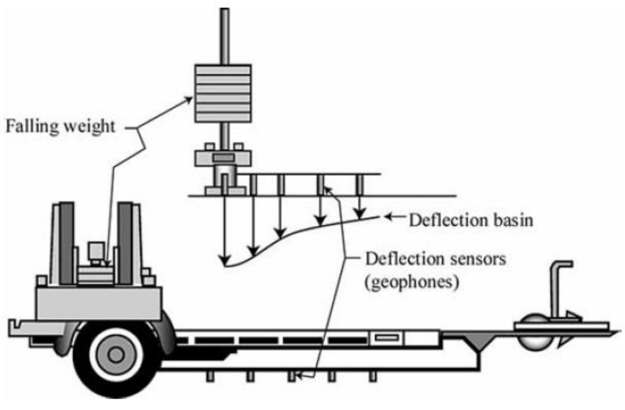


Fig 32. Falling weight deflectometer (FWD)

Source: Doré & Zubeck (2009)

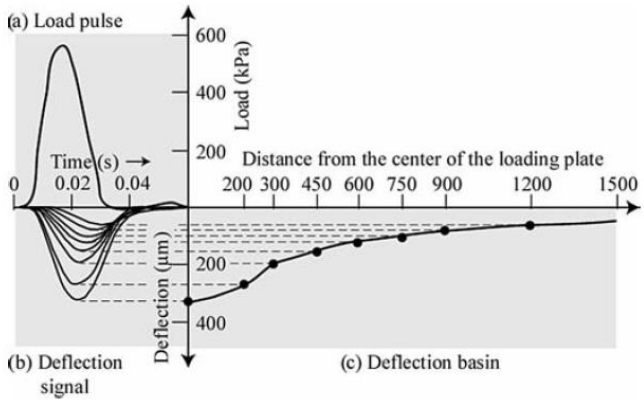


Fig 33. FWD loading and related pavement response

Source: Doré & Zubeck (2009)

The FWD operating principle is detailed in COST 336. This device generates the load pulse (figure 33 (a)) by dropping weight on the spring system which is mounted on the loading plate. The load pulse operating on pavement structure generates a “wavefront“ of recoverable deflections and spreads from the load centre. The highest vertical deflection is measured in the centre of the loading plate and the “wavefront” deflections are measured with several geophones which are placed at increasing distance from the loading plate. Figure 33 (b) represents the measured deflections by the geophones. Measured deflections that are caused by the applied impulse load indicates pavement structure strength. After the measurements, only the maximum deflection of each sensor is considered and used to reproduce the deflection bowl (basin) which is presented in figure 33 (c).

The measuring procedure has to meet the requirements of COST 336. Arrived at the test site, firstly the air, pavement, and surface temperatures have to be measured since the temperature is influencing deflections of the pavement structure. Therefore, after the measurements, these deflections will be normalized to reference temperature. To measure the temperature of the pavement, a hole has to be drilled at 0,30 m from the pavement edge and the hole has to be filled with glycerol. Following temperature measurements, the traffic lane to be measured has to be selected. If it is a two-lane road, measurements can be performed on only one traffic lane. If it is a multi-lane road, measurements have to be performed on the heavest loaded lane. Afterwards, the measurement alignment has to be selected whether measurements will be performed between wheel path or on the nearside of wheel path. If it is desired to measure data of original unaffected pavement, the measurements have to be performed between wheel paths. Also, this part of the road is not affected by rutting thus loading plate contacts uniformly with the surface. However, if it is desired to measure data of affected pavement by traffic load, the measurements have to be performed next to the wheel path or directly on it. When the alignment is set, test point spacing has to be determined with the personal needs, however, longitudinal spacing should not be more than 100 m. Also, the number of weight drops per one test point is selected according to the standard number of drops that are performed in the current country. After completing these steps, the test using FWD can be performed.

After the data is gathered and a deflection bowl is generated, it still can not be used for further investigations since the data was measured in variable temperatures and loads. Therefore data has to be normalized to reference conditions. Temperatures have to be normalized according to the relevant country normalization methodology. In 2010 (Motiejūnas et al. 2010) established new temperature normalization formula (1) for Lithuanian roads since the road-building materials were changing due to traffic loads and climatic factors. Additionally, the FWD measurements have to be normalized to the reference load (formula 2) if this has not been achieved.

$$k_T = 10^{-0,000221} * h_{asf}^{1,0229*(T-20)} \quad (1)$$

where:

- k_T – temperature correction factor;
- h_{asf} – asphalt layer thickness, cm;
- T – mean temperature of pavement layers measured during research, ℃.

$$w_i = w_{m,i} \frac{F_d}{F_m} \quad (2)$$

where:

- w_i – normalized deflection at i deflection sensor, mm;
- $w_{m,i}$ – measured deflection at i deflection sensor, mm;
- F_d – load impulse during measurements, kN;
- F_m – normalized load impulse, kN.

When the data measured by FWD is normalized and the deflection bowl is arranged, according to (Doré & Zubeck, 2009), the first level of analysis can be performed by using deflection bowl indexes. These indexes represent the mechanical performance of the pavement structure and are provided in table 5 and figure 34. The further generated experimental data will be evaluated by using these parameters. These parameters will be evaluated in different aspects to see how does the spring thaw, different soil frost susceptibility levels, different binders affect the mechanical performance of the pavement structure.

Table 5. Deflection bowl indexes that are used in research

Deflection bowl index	Calculation formula	Unit	Description
Centre deflection or the maximum deflection (d_0 or d_{max})		µm	Maximum recorded deflection which most of the time is in the centre of the applied load. Represents the general response of the pavement structure subjected to the applied load.
Non-central deflection d_r		µm	Response of the pavement structure layer at equivalent depth r which is subjected to the applied load.
Surface curvature index (SCI)	$SCI = d_0 - d_{200}$ (2)	µm	The curvature of an inner portion of the deflection bowl. Represents the stiffness of the top layers of the pavement structure (0 – 200 mm).
Base curvature index (BCI)	$BCI = d_{600} - d_{900}$ (3)	µm	The curvature of an outer portion of the deflection bowl. Represents the stiffness of the bottom layers of the pavement structure or the top part of subgrade soil (600 – 900 mm).
The radius of curvature of the centre of the bowl (R)	$R = \frac{(d_0 - d_{200})^2 + a^2}{2(d_0 - d_{200})} \backsimeq \frac{a^2}{2(d_0 - d_{200})}$ (4)	mm	Where d_{200} is the deflection (mm) measured at the sensor located just outside the loading plate and a is a radius of the loading plate (mm).
Tensile strain at the bottom of asphalt bound layer (ε_t)	$\varepsilon_t = \frac{h_1}{2R}$ (5)	10^{-6}	Where h_1 is the thickness of the asphalt bound layer (mm).
	$A = A_{norm} * d_0$ (6)	mm	

Deflection bowl index	Calculation formula	Unit	Description
Bowl area (A) and normalized bowl area (A_{norm})	$A_{norm} = 6(1 + 2\frac{d_{200}}{d_0} + +2\frac{d_{600}}{d_0} + \frac{d_{900}}{d_0})$ (7)	mm	Considered as a good indicator of pavement structure mechanical performance during the spring thaw.
Subgrade strength index (SSI)	$SSI = \frac{d_{600t}}{d_{600s}}$ (8)	-	Where d_{600t} is the deflection measured at the offset of 600 mm during the spring thaw and d_{600s} is the deflection measured at the same sensor after thaw recovery. SSI is considered a good indicator of pavement structure bearing capacity loss during the spring period.

Source: Doré & Zubeck (2009)

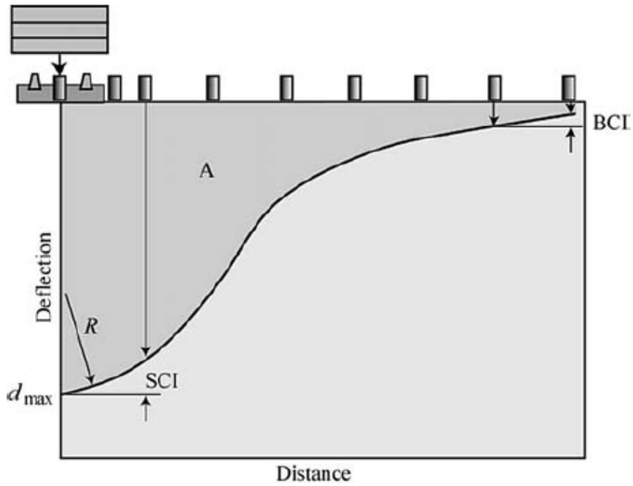


Fig 34. Deflection bowl indexes that are commonly used by the road engineers

Source: Doré & Zubeck (2009)

Also, by having the deflection data, the stiffness modulus of every measured depth of the pavement structure can be derived. According to COST 336, a great approach for calculating this derivative is by using the surface modulus. "The surface modulus at equivalent depth r approximates the stiffness modulus of a layer equivalent to the combination of the actual pavement layers situated below the equivalent depth $h_e = r$". Therefore, stiffness modulus at the centre of the loading plate and at the distance r from the centre can be calculated by using 9 and 10 formulas.

$$E_0 = \frac{2(1 - v^2) * \sigma_0 * a}{w_0} \quad (9)$$

$$E_i = \frac{(1 - v^2) * \sigma_0 * a^2}{r * w_i} \quad (10)$$

where:

- v – Poisson‘s ratio;
- σ_0 – normalized contact pressure under the loading plate (MPa);
- a – radius of the loading plate, mm;
- r – distance from the sensor to the loading centre, mm;
- w_0 – deflection at the central sensor, mm;
- w_i – deflection at the sensor distance r from the loading centre, mm;

The best way to analyze and understand the spring thaw influence on the pavement structure performance is to compare bearing capacities during dry and spring thaw periods. Therefore, FWD tests were performed in the first 10 days of April (spring thaw period) and the second 10 days of September (dry autumn period). Also, to compare different roads parameters as best as possible, their parameters has to be closely relatable. Therefore, tests were defined to be performed on Regional roads only which was newly built since 2019. The selected roads are No. 1125, No. 2006, No. 2008, No. 3118, No. 3131, No. 3425, and No. 5120. Their calculated design load reaches only up to 0,18 mln. ESAL’s. They are built out of one or two coarse asphalt layers. The thickness of the pavement structure is from 0,55 to 0,66 m. The subgrade is made out of different soils with different frost susceptibility levels. Some road’s subgrades are unimproved, for some improvement (SI) was applied, and one of the road’s subgrades has stabilization (SS) performed. However, no qualified improvement (SQI) was performed on selected roads. Though, all main binders that are specified in MN GPSR 12 were used: lime, cement and hydraulic road binders. Also, all roads fall into different frost depth zones. All selected road’s detailed parameters are provided in table 6. The frost depth values in the table are selected according to the average frost depth values measured in the pavement structures according to figure 6.

As mentioned in subchapter 2.1., before operating the FWD test, a preparation procedure must be performed according to COST 336. Therefore, air, pavement and surface temperatures were measured. The FWD tests were selected to be performed on the one traffic lane in the direction of increasing mileage since all regional roads in Lithuania are two-lane roads. The measuring alignment was taken between wheel paths since the necessary data has to be gathered from the original unaffected pavement structure (figure 35). The test was performed every 25 meters for 500 meters of the road section which makes a total of 21 tests points made per one road. Three drops of five tones weight were performed, however, only the third drop data is going to be analyzed in further investigations. The sensors of the FWD are arranged in the following order from the centre of load:

0, 200, 300, 450, 600, 900, 1200, 1500, 1800, and 2100 mm. Measured deflections during the spring thaw are provided in table 7 and during the dry period are provided in table 9. Bearing capacities calculated with formulas 8 and 9 for spring thaw are provided in table 8 and for the dry period are provided in table 10.

2.2. Pavement structure bearing capacity measurement during different seasons

Table 6. Selected Lithuanian Regional roads and their parameters

Road No.	Section of measurements, km		Design load ESAL's, mln.	Subgrade soil improvement type	Subgrade soil improvement binder, content, and layer thickness	Subgrade soil type and frost susceptibility class*	Subgrade depth, cm	Depth of groundwater table, m	Frost depth, m	Pavement structure layers (thickness)
	From	To								
1125	0,025	0,360	≤ 0,10	-	-	**Sand F1** or silty sand F3	65	-	1,40	AC 16 PD (10 cm) SPS 0/32 (20 cm) AŠAS (35 cm)
	2,530	3,030				**Gravel F2** or low plasticity clay F3	55	> 1,30		AC 16 PD (10 cm) SPS 0/32 (20 cm) AŠAS (25 cm)
2006	9,000	9,500	0,18	Stabilization (SS)	Lime	**Low plasticity clay F3**	55	-	1,40	AC 11 VN (4 cm) AC 22 PN (8 cm) SPS 0/45 (20 cm) AŠAS (23 cm)
2008	15,000	15,500	0,17	Improvement (SI)	Lime, < 4 %, 30 cm	**Lowly silty sand** or clay with organic additives, F2	65	-	1,40	AC 11 VN (4 cm) AC 22 PN (8 cm) SPS 0/45 (20 cm) AŠAS (33 cm)
3118	1,300	1,800	0,09	Improvement (SI)	Cement, 8 %, 30 cm	**Low plasticity clay** or silt with organic additives, F3	65	-	1,50	AC 16 PD (10 cm) SPS 0/45 (20 cm) AŠAS (35 cm)
3131	0,030	0,530	0,01	Improvement (SI)	Lime, 5 %, 30 cm	Sand F1 or **low plasticity clay F3**	65	-	1,60	AC 16 PD (6 cm) SPS 0/45 (20 cm) AŠAS (39 cm)
3425	3,610	4,110	0,04	Improvement (SI)	Hydraulic road binders, 30 cm	Low plasticity clay F3, **silty sand F3** or clay with organic additives F2	66	-	1,40	AC 16 PD (6 cm) SPS 0/45 (25 cm) ŠNS (35 cm)
5120	3,140	3,640	0,09	-	-	Low plasticity clay or **silty sand, F3**	65	> 3,40	1,30	AC 16 PD (10 cm) SPS 0/32 (15 cm) AŠAS (40 cm)

where: AC 16 PD – asphalt base-pavement course; AC 11 VN – asphalt wearing course; AC 22 PN – asphalt base course; SPS 0/32 or SPS 0/45 – crushed aggregate base layer and its fraction; AŠAS – frost resistant subbase layer; ŠNS – frost unsusceptible subbase layer. * - soil typewritten in bold refers to the soil which makes up the bigger part of the measured road section.

Source: designed by author

Fig 35. FWD test in the Regional road No. 1125

Source: pictures taken by author

2.2.1. Pavement structure bearing capacity during the spring thaw

Table 7. Deflection measurements during the spring thaw

Road No.	Section, km		Date	Avg. section pavement temp., ℃	Avg. section surface temp., ℃	Avg. section air temp., ℃	Normalized load, kN	Normalized pressure, kPa	Avg. section deflection normalized to load and temperature, µm									
	From	To							0	200	300	450	600	900	1200	1500	1800	2100
1125	0,025	0,360	21-04-06	16,1	14,2	7,3	50	707	346	281	239	183	142	91	66	51	39	32
	2,530	3,030		13,1	13,4	6,9			389	318	270	209	164	109	80	62	49	41
2006	9,000	9,500	21-04-07	7,4	7,9	2,8			313	272	244	201	165	111	76	54	38	30
2008	15,000	15,500		13,2	12,3	6,8			264	223	195	156	125	81	57	42	32	26
3118	1,300	1,800	21-04-08	7,0	5,3	2,6			359	308	271	219	179	120	86	67	52	47
3131	0,030	0,530		6,6	5,6	2,4			443	343	275	198	151	96	70	55	43	37
3425	3,610	4,110		7,5	9,2	3,0			456	346	274	195	145	91	65	49	38	32
5120	3,140	3,640	21-04-02	11,9	15,1	9,4			374	312	269	211	167	108	77	58	44	38

Source: designed by author

Table 8. Calculated bearing capacity during the spring thaw

Road No.	Section, km		Date	Avg. section pavement temp.,℃	Avg. section surface temp.,℃	Avg. section air temp.,℃	Normalized load, kN	Normalized pressure, kPa	Avg. section bearing capacity normalized to load and temperature, MPa									
	From	To							0	200	300	450	600	900	1200	1500	1800	2100
1125	0,025	0,360	21-04-06	16,1	14,2	7,3			543	251	198	172	166	173	181	189	203	212
	2,530	3,030		13,1	13,4	6,9			484	222	175	151	144	146	150	154	164	170
2006	9,000	9,500	21-04-07	7,4	7,9	2,8			607	263	196	159	146	146	161	183	213	230
2008	15,000	15,500		13,2	12,3	6,8			708	315	240	200	188	193	208	225	251	258
3118	1,300	1,800	21-04-08	7,0	5,3	2,6	50	707	522	228	173	143	131	130	135	140	149	143
3131	0,030	0,530		6,6	5,6	2,4			422	205	170	158	156	163	166	170	183	180
3425	3,610	4,110		7,5	9,2	3,0			414	205	173	163	165	175	183	194	209	213
5120	3,140	3,640	21-04-02	11,9	15,1	9,4			504	227	176	149	142	146	153	161	177	177

Source: designed by author

2.2.2. Pavement structure bearing capacity during the dry period

Table 9. Deflection measurements during the dry period

Road No.	Section, km		Date	Avg. section pavement temp., ℃	Avg. section surface temp., ℃	Avg. section air temp., ℃	Normalized load, kN	Normalized pressure, kPa	Avg. section deflection normalized to load and temperature, µm									
	From	To							0	200	300	450	600	900	1200	1500	1800	2100
1125	0,025	0,360	21-09-13	24,3	26,4	19,6	50	707	348	254	203	147	113	75	56	43	35	29
	2,530	3,030		24,3	26,4	19,8			370	269	216	159	126	87	67	52	43	35
2006	9,000	9,500	21-09-17	12,9	11,4	10,8			271	225	196	156	126	81	55	39	30	23
2008	15,000	15,500		14,7	11,6	11,0			251	204	176	137	108	69	48	36	28	23
3118	1,300	1,800		13,7	11,7	11,6			333	273	235	185	148	97	71	55	45	39
3131	0,030	0,530		12,8	11,4	11,9			382	278	218	154	116	77	58	45	36	31
3425	3,610	4,110		12,4	12,1	11,1			405	297	233	165	123	77	55	42	32	27
5120	3,140	3,640	21-09-13	24,1	26,1	20,4			385	294	240	178	138	89	65	50	40	33

Source: designed by author

Table 10. Calculated bearing capacity during the spring thaw

Road No.	Section, km		Date	Avg. section pavement temp.,℃	Avg. section surface temp.,℃	Avg. section air temp.,℃	Normalized load, kN	Normalized pressure, kPa	Avg. section bearing capacity normalized to load and temperature, MPa									
	From	To							0	200	300	450	600	900	1200	1500	1800	2100
1125	0,025	0,360	21-09-13	24,3	26,4	19,6	50	707	544	281	237	219	215	217	219	227	232	243
	2,530	3,030		24,3	26,4	19,8			506	262	218	198	189	184	183	188	189	200
2006	9,000	9,500	21-09-17	12,9	11,4	10,8			703	320	247	208	196	205	228	257	284	309
2008	15,000	15,500		14,7	11,6	11,0			745	344	267	229	217	229	248	270	289	301
3118	1,300	1,800		13,7	11,7	11,6			563	258	200	169	159	161	166	170	172	171
3131	0,030	0,530		12,8	11,4	11,9			491	253	216	204	203	204	203	207	215	219
3425	3,610	4,110		12,4	12,1	11,1			463	238	202	192	194	207	214	227	243	250
5120	3,140	3,640	21-09-13	24,1	26,1	20,4			492	242	198	178	172	177	181	189	194	201

Source: designed by author

2.3. Statistical analysis of experimental investigation data

The FWD test was performed every 25 meters for 500 meters which generates a high amount of data. Therefore, to summarize the measurements, the data were averaged and presented in 7, 8, 9, and 10 tables. The pavement structure measurements performed during spring thaw and dry periods did not show any abnormal values thus allowing to analyze pavement structure performance without any unnecessary data interruptions.

Each pavement structure reacted differently during the spring thaw. The highest average bearing capacities ($E_{0,surf}$) and lowest average deflections of the surfaces were measured on the two-course asphalt roads: 607 MPa and 313 μm on road No. 2006 and 708 MPa and 264 μm on road No. 2008. On contrary, the lowest average bearing capacities ($E_{0,surf}$) and highest average deflections of the surfaces were measured on the thinnest one-course asphalt roads: 422 MPa and 443 μm on road No. 3131 and 412 MPa and 456 μm on road No. 3425. This means that surface bearing capacity ($E_{0,surf}$) values are mainly influenced by the asphalt layers thickness.

However, the number of asphalt courses or their thickness does not directly impact the bearing capacity ($E_{600,sub}$) of the subgrade. According to table 11, the biggest average bearing capacity ($E_{600,sub}$) and lowest average deflections of the subgrade was measured in two-coarse asphalt road No. 2008: 189 MPa and 118 μm. However, road No. 2006, which is also a two-course asphalt road, has significantly inferior measured values: 150 MPa and 177 μm. Even the subgrades of both roads No. 3131 and No. 3425 that has the thinnest asphalt layers, have bigger average bearing capacities ($E_{600,sub}$) and lower average deflections compared to road No. 2006: 157 MPa and 142 μm on road No. 3131 and 166 MPa and 136 μm on road No. 3425.

Table 11. Pavement structure subgrade average deflections and bearing capacities ($E_{600,sub}$) during the spring thaw period

Road No.	Section, km		Pavement structure subgrade				
	From	To	Depth, cm	Average section deflections, μm	Standard Deviation	Average section bearing capacity ($E_{600,sub}$), MPa	Standard deviation
1125	0,025	0,360	65	134	18,55	168	22,36
	2,530	3,030	55	180	22,48	146	20,09
2006	9,000	9,500	55	177	32,35	150	26,58
2008	15,000	15,500	65	118	11,02	189	18,83
3118	1,300	1,800	65	169	11,67	131	8,94
3131	0,030	0,530	65	142	11,90	157	13,13
3425	3,610	4,110	66	134	21,65	167	26,79
5120	3,140	3,640	65	157	19,01	143	20,92

Source: designed by author

The biggest recorded average bearing capacity ($E_{600,sub}$) during the spring thaw, according to figure 36, was in road No. 2008 and the lowest in road No. 3118. Road No. 2008 subgrade was built 65 cm deep out of the F2 class soil which was improved (SI) 30 cm in depth with < 4 % lime binders. The road No. 3118 subgrade was also built 65 cm deep, however, the soil varies between F2 and F3 classes. Also, the soil was improved (SI) 30 cm in-depth but with < 8 % cement binders.

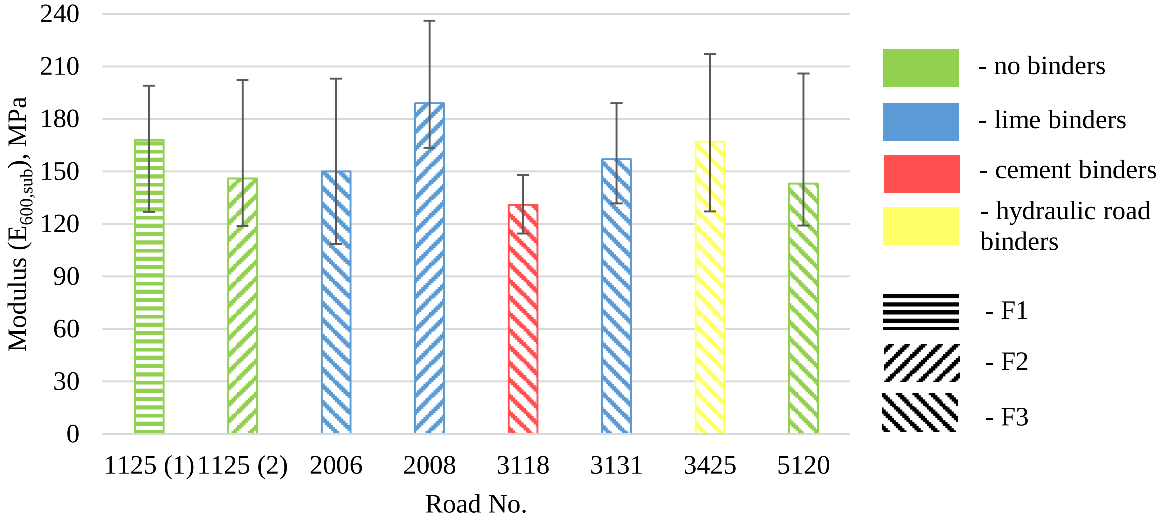


Fig 36. Pavement structure subgrade bearing capacity ($E_{600,sub}$) during the spring thaw period

Source: designed by author

As it can be seen in figure 36, the bearing capacities ($E_{600,sub}$) of subgrades during the spring thaw without soil improvements (except the first section of road No. 1125) are slightly lower compared to subgrades which are improved with lime or hydraulic road binders. Still, the bearing capacities ($E_{600,sub}$) of subgrades with lime binders differ and are dependent on some other factors since roads No. 2008 and No. 3131 subgrade bearing capacity ($E_{600,sub}$) differs by 17 %.

Also, the bearing capacity ($E_{600,sub}$) of the subgrade constantly varies every 25 meters and the average value does not represent the distribution of all measured values. Only road No. 3118 has little data deviation but road No. 2006 has a very high one. For example, the average bearing capacity ($E_{600,sub}$) of the subgrade of road No. 2006 is 150 MPa, however, the highest measured value was 203 MPa while the lowest value was 108 MPa, which, moreover, is the lowest recorded subgrade bearing capacity ($E_{600,sub}$) value in all of the roads. The absolute highest subgrade bearing capacity ($E_{600,sub}$) during the spring thaw was measured in road No. 2008 of striking 236 MPa. Also, what can be seen in figure 36 is that road's No. 5120 subgrade average bearing capacity ($E_{600,sub}$) of 143 MPa is significantly closer to the measured minimum value compared to the maximum value. This means that by default, bearing capacity ($E_{600,sub}$) is more or less constant in the whole section of the road and keeps close to the minimum values. However, at some points, bearing capacity ($E_{600,sub}$) peaks to the maximum value, which creates an image of an unpredictable subgrade. Therefore, the variation of the least constant (No. 5120) and the most constant subgrades (No. 3118) are provided in figures 37 and 38.

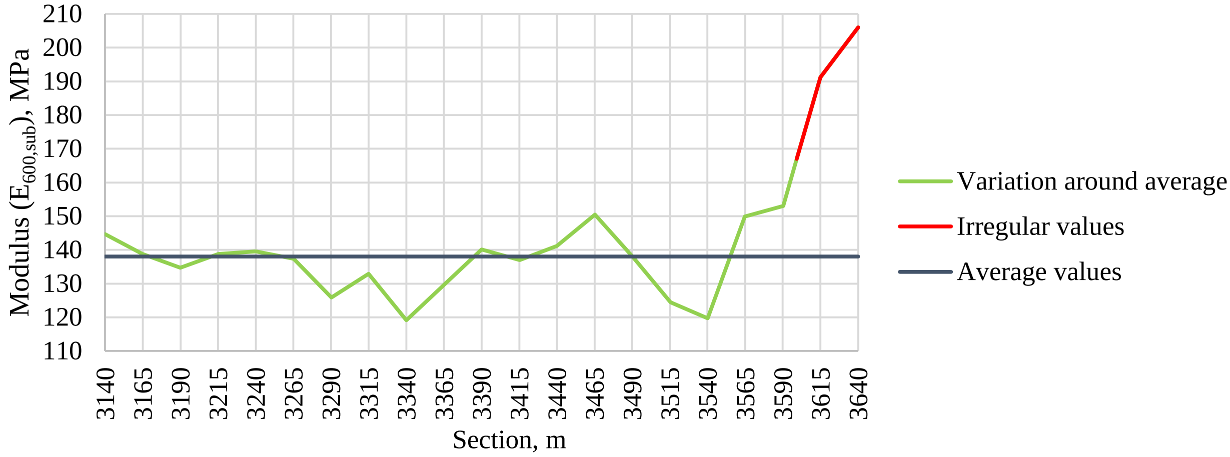


Fig 37. Subgrade's bearing capacity ($E_{600,sub}$) variation during the spring thaw on road No. 5120

Source: designed by author

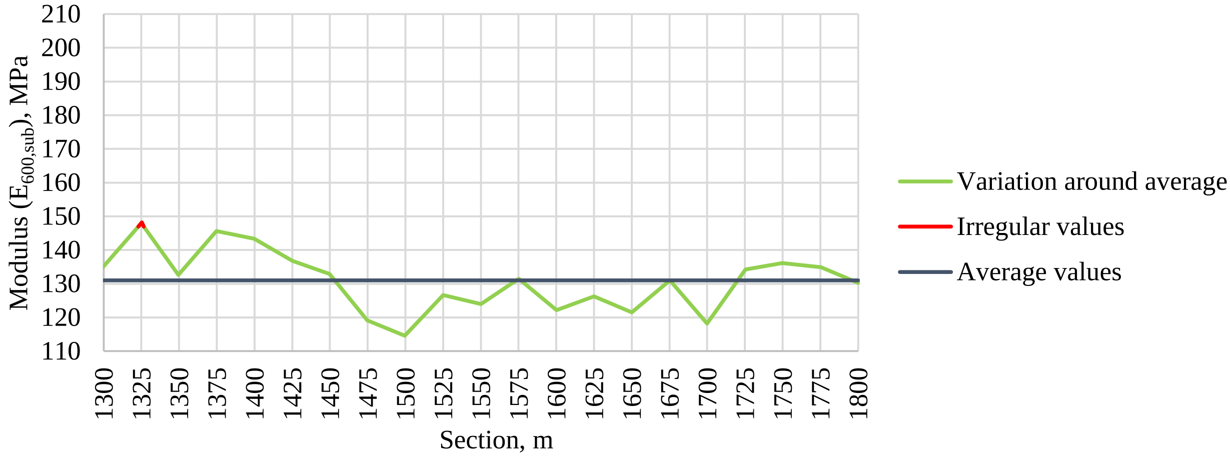
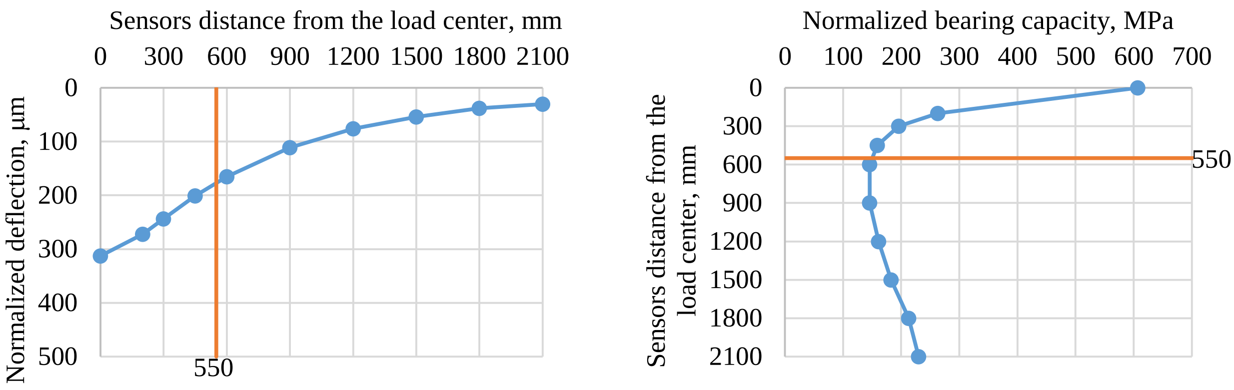


Fig 38. Subgrade's bearing capacity ($E_{600,sub}$) variation during the spring thaw on road No. 3118

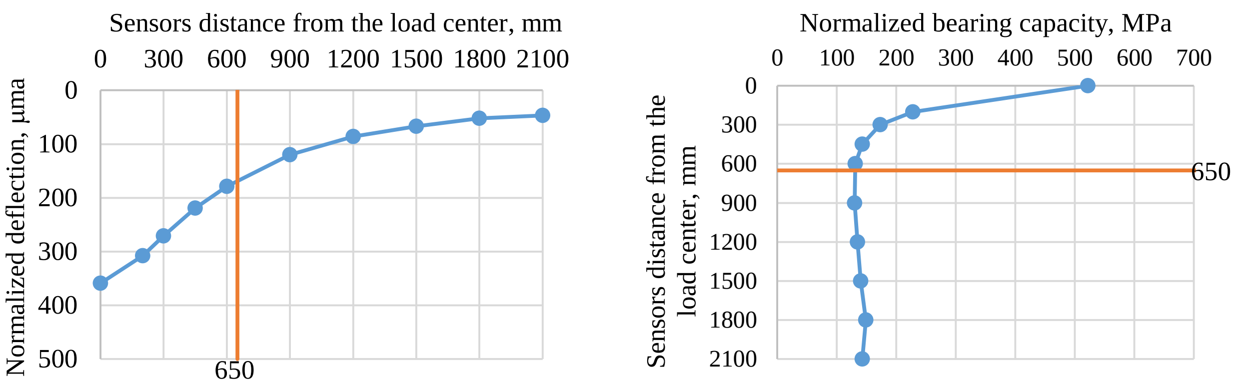
Source: designed by author

The FWD test was performed to measure soils deflections and bearing capacities up to a maximum of 2100 mm depth. These measurements are presented in deflection bowls and bearing capacity plots (figure 39). The orange line in the figure represents the depth of the subgrade. All measured roads data during the spring thaw period represented different bearing capacity plots configurations. Bearing capacity plots show that the weakest part of 2100 mm deep soil most of the time was exactly at the pavement structure subgrade. Some roads bearing capacity starts to increase after reaching the subgrade, meanwhile, some roads bearing capacity keeps similar values after reaching the subgrade. This trend represents the depth of the freeze/thaw effect in the soil and means that the highest amount of moisture is situated particularly in the pavement structure layers or subgrade. The subgrade part was measured as the weakest part in all roads except No. 3425. This road had the weakest part in the subbase layer which means that these roads have poor drainage quality. For example, the bearing capacity on road No. 3425 was measured to be lower in 450 mm deep (subbase layer) than in 600 mm deep soil (subgrade).

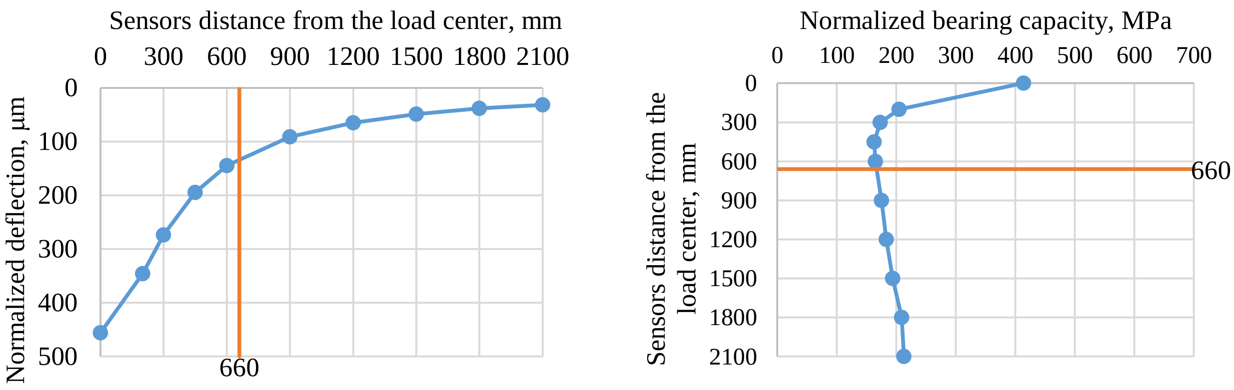
a) Road No. 2006 with lime binders



b) Road No. 3118 with cement binders



c) Road No. 3425 with hydraulic road binders



d) Road No. 5120 without binders

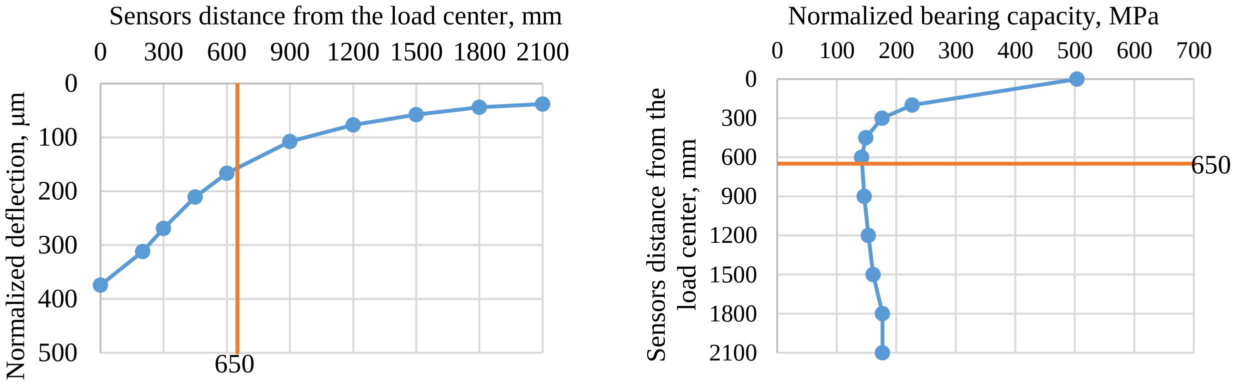
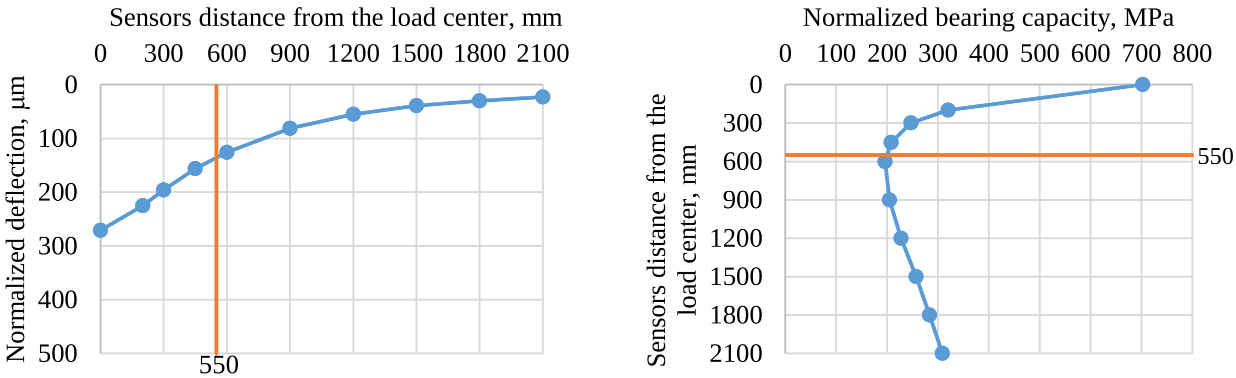


Fig 39. Road deflection bowls (left) and bearing capacities plots (right) during the spring thaw

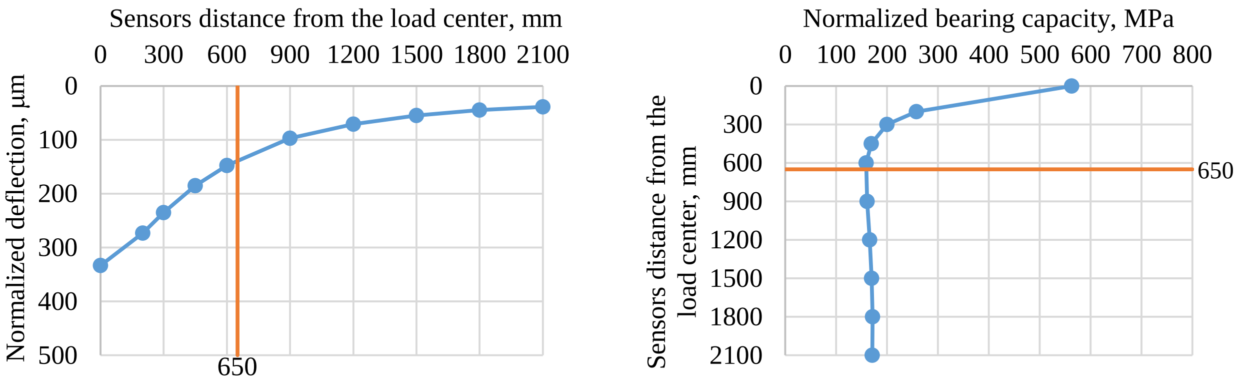
Source: designed by author

During the dry period, a major part of roads bearing capacity plots has a similar configuration where the weakest part of all 2100 mm is at subgrade (figure 40). Subgrade was the weakest part of measured soils in almost all roads. Meanwhile, the subbase layer was the weakest part in road No. 3425 just like during the spring thaw period. Also, road No. 1125 (2) was exceptional during the dry period. Its bearing capacity values kept decreasing below subgrade up until 900 mm soil.

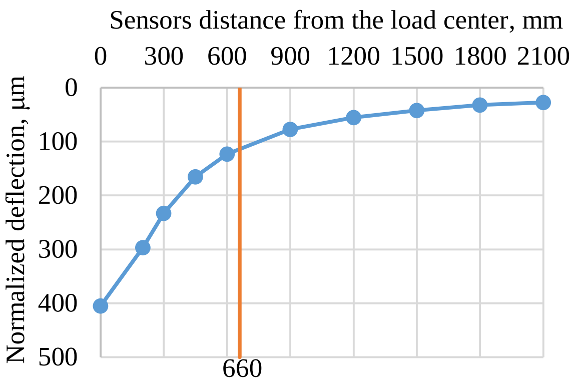
a) Road No. 2006 with lime binders

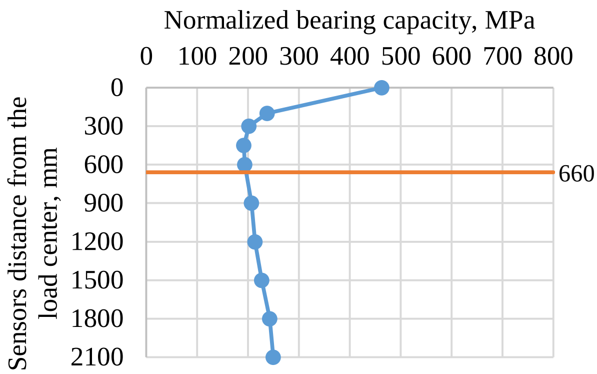


b) Road No. 3118 with cement binders

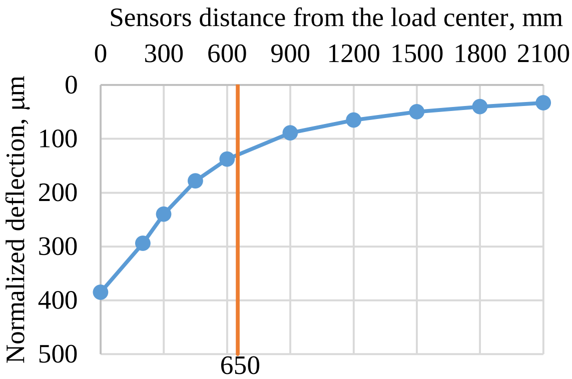


c) Road No. 3425 with hydraulic road binders





d) Road No. 5120 without binders



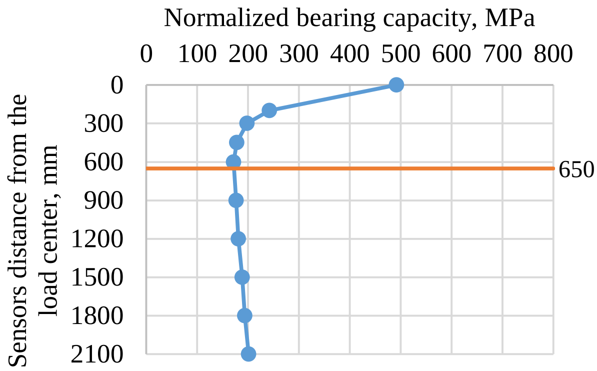


Fig 40. Road deflection bowls (left) and bearing capacities plots (right) during the dry period

Source: designed by author

The average bearing capacity ($E_{600,sub}$) and average deflections of the subgrade, according to table 12, varies from 159 to 219 MPa and from 102 to 139 µm respectively during the dry period. The biggest recorded average bearing capacity ($E_{600,sub}$), according to figure 41, was in road No. 2008 and the lowest in road No. 3118. This allocation was the same as during the spring thaw. Road No. 2008 performed the best since it has the best quality level which is determined by F2 subgrade soil, improvement with lime and the thickest asphalt layer. During the dry period, subgrades without any treatment performed not worse than other subgrades that have lime, cement or hydraulic road binders treatment. For example, the bearing capacity ($E_{600,sub}$) of the subgrade of road No. 1125 (first section) is only 4 MPa lower compared to the strongest subgrade which is treated with the lime binder.

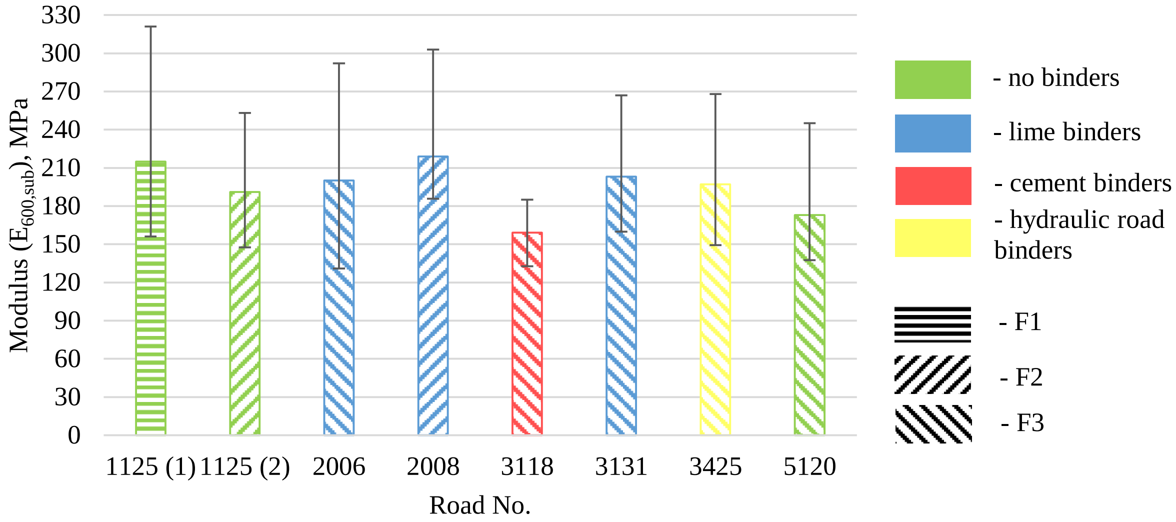


Fig 41. Pavement structure subgrade bearing capacities ($E_{600,sub}$) during the dry period

Source: designed by author

Table 12. Pavement structure subgrade average deflections and bearing capacities ($E_{600,sub}$) during the dry period

Road No.	Section, km		Pavement structure subgrade				
	From	To	Depth, cm	Average section deflections, µm	Standard deviation	Average section bearing capacity ($E_{600,sub}$), MPa	Standard deviation
1125	0,025	0,360	65	107	22,38	215	48,56
	2,530	3,030	55	138	19,57	191	27,49
2006	9,000	9,500	55	136	31,89	200	46,37
2008	15,000	15,500	65	102	10,65	219	26,43
3118	1,300	1,800	65	139	13,22	159	14,93
3131	0,030	0,530	65	110	12,75	203	23,80
3425	3,610	4,110	66	113	16,97	197	30,23
5120	3,140	3,640	65	130	18,20	173	27,77

Source: designed by author

The standard deviation of dry period subgrade average bearing capacities ($E_{600,sub}$) is significantly higher compared to the spring thaw period. For example, the subgrade‘s of road No. 2006 average bearing capacity ($E_{600,sub}$) is 200 MPa, however, the highest measured value was 292 MPa while the lowest value was 131 MPa, which, moreover, is the lowest recorded subgrade bearing capacity ($E_{600,sub}$) value in all of the roads. Bearing capacity values should be additionally analyzed in the third chapter by comparing them to the reference value which fulfils the deformation modulus of 45 MPa. The absolute highest subgrade bearing capacity ($E_{600,sub}$) during the dry period was measured in road No. 1125 (first section) of striking 321 MPa. On the other hand, subgrade bearing capacities ($E_{600,sub}$) in road No. 3118 are least dispersed of all roads and, surprisingly, both minimum and maximum values are spaced from the average value equally by the same 26 MPa. The same trend was noted also during the spring thaw period, therefore it can be stated that this road‘s subgrade is installed to be most constant and reliable. There is no uniqueness in this road, thus it allows to assume that these constant values are generated by cement binders. However, it was the only road, which was improved by using cement binders. Also, what can be seen in figure 41 is that road's No. 2008 subgrade average bearing capacity ($E_{600,sub}$) of 219 MPa is significantly closer to the measured minimum value compared to the maximum value. This means that by default, bearing capacity ($E_{600,sub}$) is more or less constant in the whole section of the road and keeps close to the minimum values. However, at some points, bearing capacity ($E_{600,sub}$) peaks to the maximum value, which creates an image of an unpredictable subgrade. Therefore, the variation of the least constant (No. 2008) and the most constant subgrades (No. 3118) are provided in figures 42 and 43.

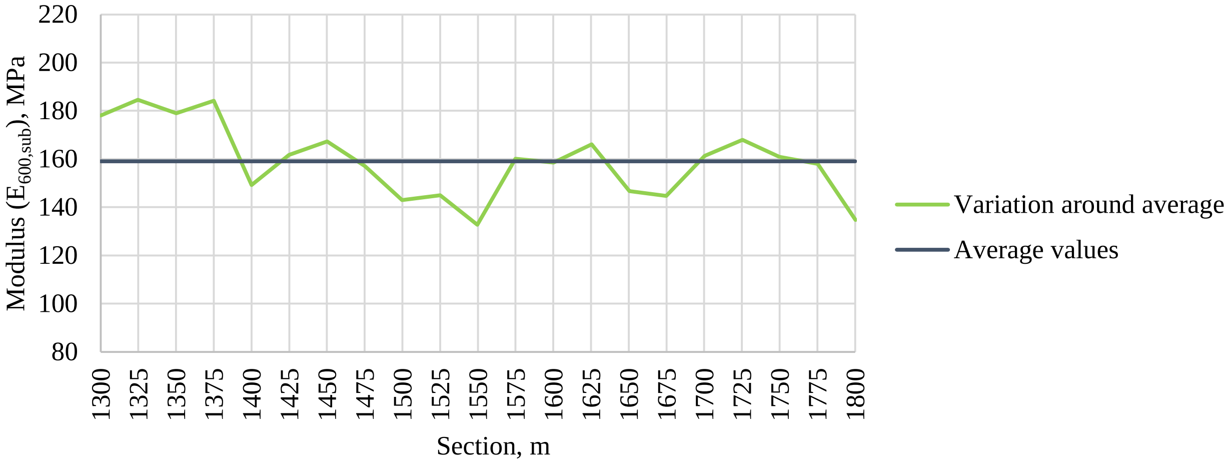


Fig 42. Subgrade's bearing capacity ($E_{600,sub}$) variation during the dry period on road No. 3118

Source: designed by author

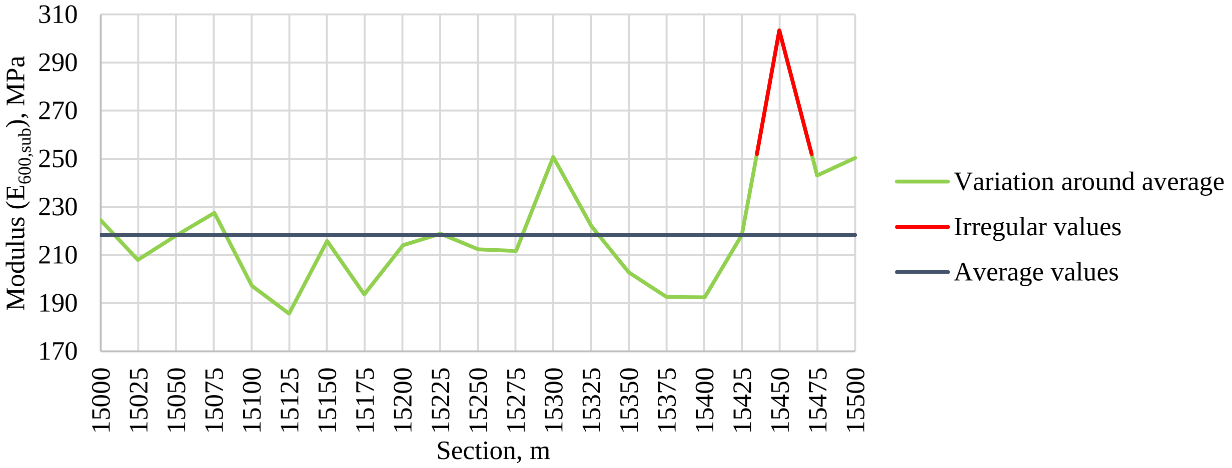


Fig 43. Subgrade's bearing capacity ($E_{600,sub}$) variation during the dry period on road No. 2008

Source: designed by author

2.4. Conclusions

1. Pavement structure performance was measured during the spring thaw and dry period by the falling weight deflectometer on Lithuanian regional roads that were built later than 2018. Measurements were performed every 25 meters on one traffic lane, between wheel paths by dropping weight which generates a load of 50 kN and pressure of 707 kPa. Measured deflections were normalized to the reference temperature and load. Bearing capacity was calculated from measured deflections.
2. Selected different regional roads have design loads that reach up to 0,18 mln. ESAL‘s. The subgrade is made out of different soil types with different frost susceptibility levels. Subgrades were unimproved, improved and stabilized by using lime, cement or hydraulic road binders. Selected roads are situated in the 1,30 – 1,60 m frost depth zones.
3. The bearing capacity ($E_{0,surf}$) on the surface of all roads during the dry period were from 491 to 745 MPa and during the spring thaw period were from 414 to 708 MPa. The bearing capacity ($E_{600,sub}$) on the subgrade of all roads during the dry period were from 173 to 219 MPa and during the spring thaw period were from 131 to 189 MPa.
4. The bearing capacity ($E_{0,surf}$) of the pavement structure‘s surface is mainly dependent on asphalt layer thickness where bearing capacity ($E_{0,surf}$) on road No. 2008 (0,12 m thick) was recorded to be 745 MPa during the dry period and on road No. 3131 (0,06 m thick) was recorded to be 463 MPa during the dry period.
5. Results of measurements during the spring thaw presented that subgrade strength is not a key factor for bearing capacity ($E_{0,surf}$) of the whole asphalt pavement structure. Road No. 2006 with two asphalt layers with a thickness of 0,12 m had a surface bearing capacity ($E_{0,surf}$) of 703 MPa and its subgrade bearing capacity ($E_{600,sub}$) of 150 MPa. However, the subgrade value is lower compared to the road‘s No. 3131 subgrade bearing capacity ($E_{600,sub}$) of 157 MPa, while this road has one asphalt layer with a thickness of only 6 cm which surface bearing capacity ($E_{0,surf}$) was recorded to be only 463 MPa.
6. The highest average subgrade bearing capacity ($E_{600,sub}$) was recorded both during the spring thaw (189 MPa) and dry period (219 MPa) on road No. 2008 with lime improved subgrade which is made off F2 frost susceptibility class soils. While the lowest average subgrade bearing capacity ($E_{600,sub}$) was measured both during spring thaw (131 MPa) and dry period (159 MPa) on road No. 3118 which is improved with cement binders (on F3 class soils). However, specifically, this road‘s subgrade was recorded to be the most stable since the deviation of bearing capacities ($E_{600,sub}$) were the smallest due to applied cement binders. Bearing capacity values should be

additionally analyzed in the third chapter by comparing them to the reference value which fulfils the deformation modulus of 45 MPa.

7. Data analysis showed that both subgrades that were improved or unimproved presented a similar performance tendency in terms of the subgrades modulus ($E_{600,sub}$) values. The modulus ($E_{600,sub}$) values decrease dramatically during the spring thaw period on both improved and unimproved subgrades representatively 18,84% and 20,92%.
8. The bearing capacity of the same road pavement structure constantly changes and is never uniform. The most variable modulus ($E_{600,sub}$) values of the subgrade throughout the year was measured on road No. 2006 which is improved with lime binders and is made of F3 class soils. The values varied between 108 – 203 MPa during spring thaw (standard deviation – 26,58) and 131 – 292 MPa during the dry period (standard deviation – 46,37). The most stable subgrade was recorded to be on road No. 3118 which is improved with cement binders and is made of F3 class soils. The values varied between 115 – 148 MPa during spring thaw (standard deviation – 8,94) and 133 – 185 MPa during the dry period (standard deviation – 14,93).
9. Generated bearing capacity plots revealed that most of the time during both spring thaw and dry period bearing capacity was measured to be lowest around the pavement structure subgrade. Only road No. 3425 and No. 1125 (2) was exceptional. During the spring thaw and dry period, road No. 3425 had the weakest part of 2100 mm deep measurements at the subbase layer (450 mm deep). Meanwhile, road No. 1125 (2) bearing capacity kept decreasing during the dry period up until 1200 mm deep soil.

3.EVALUATION OF ASPHALT BEARING CAPACITY DEPENDENCY ON SUBGRADE CHARACTERISTICS

3.1. Evaluation and interpretation of research data

Every road pavement structure performance is different and is influenced by many different factors. Therefore, it is hard to assign only one structural parameter which is responsible for the different tendencies of pavement structure performance. Figure 44 and figure 45 present all roads bearing capacity plots during dry autumn and spring thaw periods respectively. It is easy to see that during autumn the best road is No. 2008 since the bearing capacity has the biggest values at every measured depth. Road No. 1125 (1) also performs well and almost reaches the same bearing capacity ($E_{600,sub}$) values near subgrade (600 mm deep) as road No. 2008 does. Surprisingly, no improvement was performed for its subgrade. Apparently, these high values were influenced mostly by frost unsusceptible (F1) subgrade soil. The great influence of F1 class subgrade soil on the whole pavement structure performance can be seen by comparing it to the performance of road No. 2006. Road No. 2006 has a stabilized (SS) subgrade with lime binders, however, the subgrade soils are very frost susceptible (F3). At the surface of the pavement structure, the road performs well with a relatively high bearing capacity ($E_{0,surf}$) of 703 MPa due to the thick asphalt layer (0,12 m). However, near subgrade, bearing capacity ($E_{600,sub}$) drops down significantly to 196 MPa. Meanwhile, road No. 1125 (1) has a 0,10 m thick asphalt layer, therefore, bearing capacity ($E_{0,surf}$) at the surface is only 554 MPa, however, the bearing capacity ($E_{600,sub}$) at the subgrade drops down to 203 MPa which is still higher than road's No. 2006. The F3 class soil impact on subgrade bearing capacity ($E_{600,sub}$) can be also seen on roads No. 3118 and No. 5120 since their bearing capacity values are the lowest compared to other roads. The only road which bearing capacity keeps decreasing after reaching subgrade is No. 1125 (2). This is influenced by shallow subgrade, F2 class subgrade soils and high groundwater table.

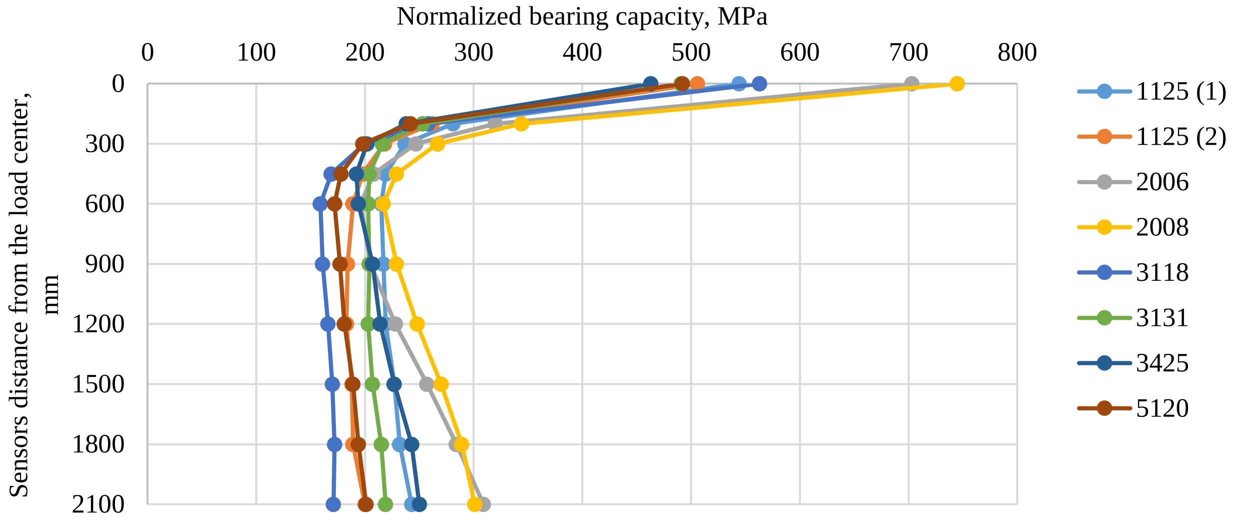


Fig 44. Average values of stiffness modulus distribution at each depths of pavement structure during the dry autumn period

Source: designed by author

During the spring thaw period, the overall best road was recorded to be No. 2008 since it has a 0,12 m thick asphalt layer, subgrade was installed relatively deep (0,65 m) out of F2 class soils and the frost depth was relatively shallow (1,40 m). Surprisingly, all other roads bearing capacity values during spring thaw come close to the same value of 175 MPa at 300 mm deep layer despite different influencing factors. However, apart from road No. 2008, the best performing bottom parts of pavement structure were on roads No. 1125 (1) and No. 3425. Road No. 1125 (1) subgrade performs well since it is installed out of F1 class soils. On the other hand, the worst performing subgrades are on roads No. 2006, No. 3118, and No. 5120 since these subgrades are installed on F3 class soils. Also, roads No. 1125 (2) and No. 5120 has noticeable performance similarity during the spring thaw since both of them bearing capacity values are almost the same. These values are similar due to unimproved subgrade soil.

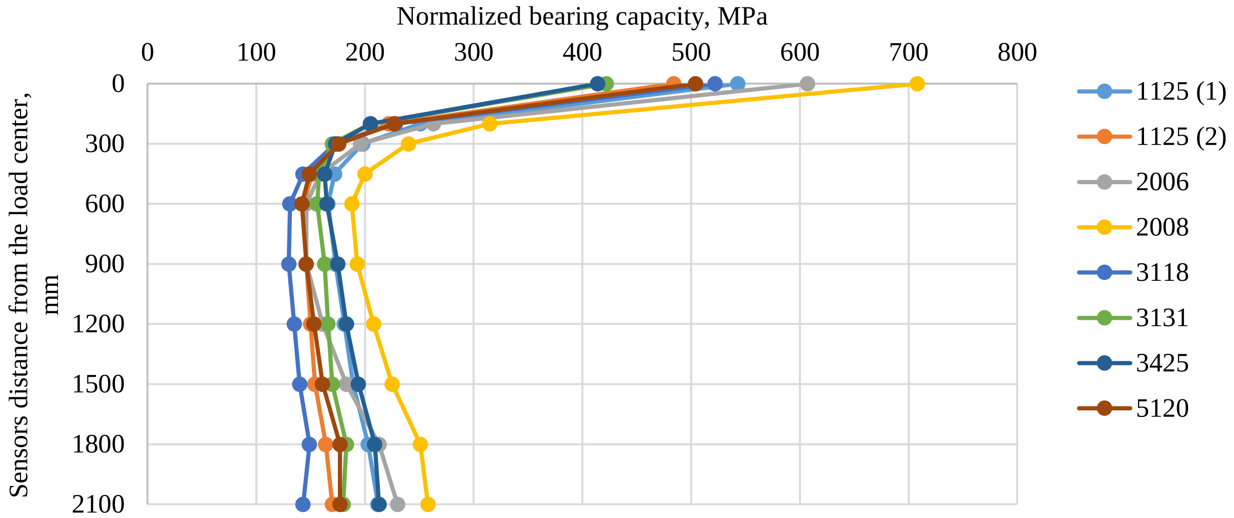


Fig 45. Average values of stiffness modulus distribution at each depths of pavement structure during the spring thaw period

Source: designed by author

For a better understanding of how different characteristics influence pavement structure performance, deflection bowl indexes have to be calculated according to formulas provided in table 5. Average values of surface curvature index (SCI), base curvature index (BCI), the radius of curvature (R), tensile strain at the bottom of asphalt layer (ε_t), bowl area (A), and subgrade strength index (SSI) during both spring thaw and dry autumn periods are provided in table 13.

Table 13. Average pavement structure deflection bowl indexes during the spring thaw and dry autumn periods

Road No.	**Spring**					**Autumn**					**SSI**
	SCI, µm	**BCI, µm**	**R, mm**	**ε, 10^{-6}**	**A, mm**	**SCI, µm**	**BCI, µm**	**R, mm**	**ε, 10^{-6}**	**A, mm**	
1125 (1)	64,48	50,82	0,705	283,87	7,710	94,04	38,45	0,481	415,47	6,946	1,278
1125 (2)	70,49	55,56	0,647	308,96	8,772	101,04	38,64	0,447	447,22	7,492	1,320
2006	40,98	54,27	1,119	214,51	7,788	46,50	44,31	0,977	245,59	6,324	1,321
2008	41,22	43,35	1,098	218,61	6,251	46,78	39,47	0,966	248,43	5,671	1,158
3118	51,22	59,03	0,887	225,41	8,708	60,36	50,68	0,023	266,37	7,628	1,217
3131	100,20	54,97	0,451	266,21	9,162	104,04	39,25	0,434	276,35	7,493	1,299
3425	109,55	54,04	0,413	290,29	9,170	108,31	46,02	0,417	287,79	7,922	1,185
5120	62,34	58,56	0,727	275,20	8,637	90,85	48,65	0,500	400,03	8,026	1,213

Source: designed by author

The most straightforward method to evaluate pavement structure subgrade performance during the spring thaw and dry autumn seasons and the effect of subgrade improvement and binder type is to analyze SSI values that are provided in figure 46. However, while performing deeper analysis, this figure becomes irrelevant. For example, the best subgrade to withstand the seasonal changes without a significant increase of deflections was recorded on road No. 2008 with an SSI of 1,16. Meanwhile, the poorest subgrade was recorded to be road‘s No. 2006 with an SSI of 1,32. It is hard to distinguish the main factor which influences this big difference. Road's No. 2006 subgrade is shallower by 0,10 m and is installed out of F3 frost susceptibility class soils. However, the subgrade soil improvement type on road No. 2006 is stabilization (SS) which is better in enhancing performance properties rather than soil improvement (SI) which is applied to road No. 2008. Therefore, the margin should have not been such big. Another example is that subgrade without any improvements (road No. 5120) performs as good as improved (SI) subgrade with cement binders (road No. 3118) with the SSI values of 1,21 and 1,22 respectively. Although the main purpose of improvement is to enhance the subgrade performance. Therefore, all roads have to be analyzed and compared in deeper layers to understand the real seasonal and soil improvement effect on pavement structure performance.

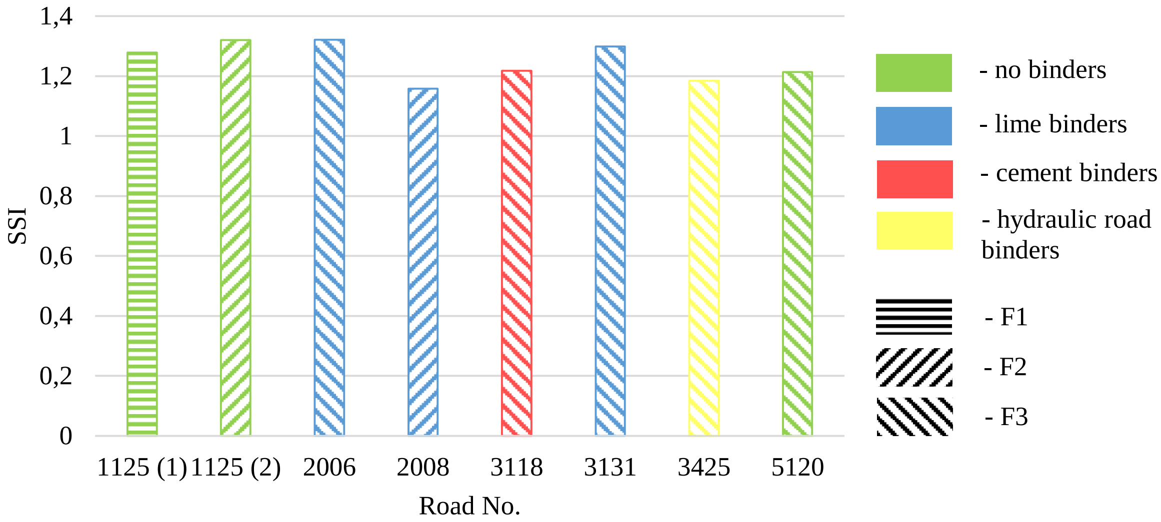


Fig 46. Pavement structure subgrade strength index (SSI)

Source: designed by author

3.2. Asphalt pavement structure bearing capacity variation dependency on season

The performed experiment confirmed that pavement structure subgrade performance significantly changes during a different season on all analyzed roads. Figure 47 presents different road average subgrade bearing capacity ($E_{600,sub}$) values during spring thaw and dry autumn periods. The smallest change in bearing capacity ($E_{600,sub}$) between different seasons of 28 MPa was recorded on road No. 3118. However, particularly this road was recorded to have the lowest bearing capacity ($E_{600,sub}$) both during spring thaw (131 MPa) and dry autumn (159 MPa) periods. On the other hand, the biggest change in bearing capacity ($E_{600,sub}$) between different seasons of 50 MPa was recorded on road No. 2006. Meanwhile, road's No. 2008 subgrade performance was recorded to be the best compared to others with the highest bearing capacity ($E_{600,sub}$) values and a relatively small change of it during different seasons (30 MPa). The average change of bearing capacity ($E_{600,sub}$) on all measured roads was around 38 MPa.

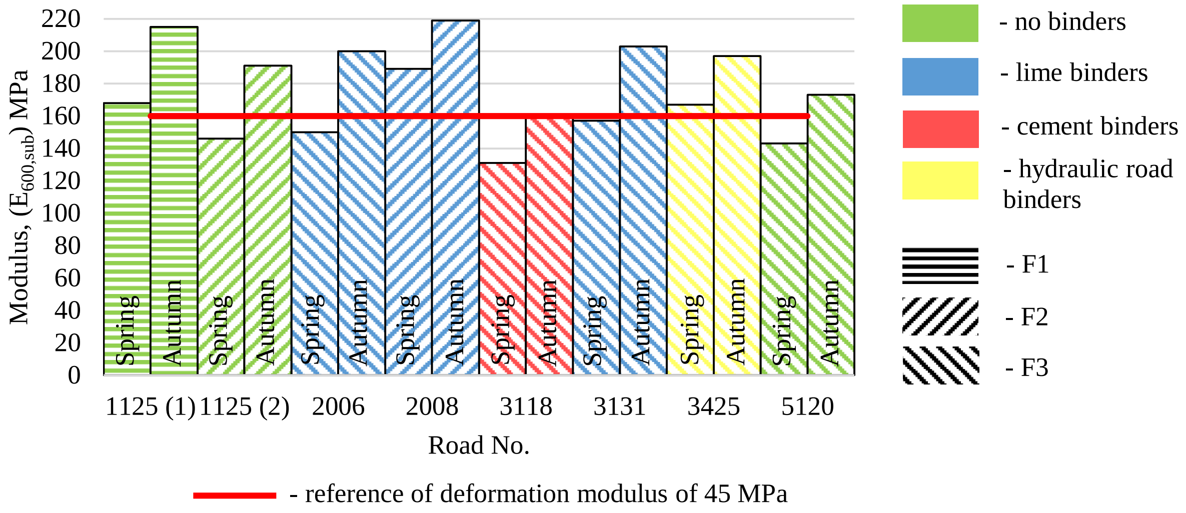


Fig 47. Pavement structure subgrade bearing capacities ($E_{600,sub}$) during the spring thaw and dry autumn periods

Source: designed by author

KPT SDK 19 states the minimum deformation modulus of 45 MPa for the subgrade. Unfortunately, researchers still have not managed to find a way to measure the deformation modulus for the subgrade on a fully built road and therefore it is not possible to determine whether the analyzed roads subgrade deformation modulus decrease lower than 45 MPa. However, there is an indirect way of checking whether the deformation modulus specification is being breached. Scientists of Vilnius Gediminas Technical University Faculty of Environmental Engineering Road Research Institute performed investigations on reconstructed roads of national significance (research topic – "Development of the Software Package for the Design Model and Application of the Asphalt Pavement Structure"). An investigation determined that the measured bearing capacity of not less than 160 MPa on the Regional road subgrade guarantees that the deformation modulus of the subgrade is not less than 45 MPa. Therefore, figure 47 presents that roads No. 1125 (2), No. 2006, No. 3118, No. 3131, and No. 5120 subgrades breach the KPT SDK 19 regulation during the spring thaw period. Unfortunately, the road's No. 3118 subgrade bearing capacity is already lower than permissible during the dry autumn period. This analysis points out that the objective stated by KPT SDK 19 of reducing the possibility of the decrease of subgrade's deformation modulus below 45 MPa is unfortunate.

To evaluate how does season change influence the pavement structure performance, the best (No. 2008) and the worst (No. 3118) roads are compared. The bearing capacity plot (figure 48) presents that both roads pavement structure layers perform similarly since plots have the same configuration where bearing capacity decreases dramatically at the first layers of the pavement structure and slows down in lower layers. However, below subgrade, a clear difference in performance can be seen since both roads have different plot configurations. The weakest part of the measured pavement structure of road No. 2008 was recorded at the subbase layer (600 mm deep) with 188 MPa during spring and 217 MPa during autumn. After this point, the bearing capacity starts to increase. Meanwhile, the weakest part on road No. 3118 was measured at the subbase layer (600 mm deep) during the autumn period of 159 MPa and at the subgrade (900 mm deep) during the spring period of 130 MPa. Afterwards, the bearing capacity starts to increase but at a very low pace and eventually starts to decrease again from the depth of 1800 mm. All these bearing capacity plots trends are mainly dependent on subgrade soil type and not on seasonal variation since road No. 2008 was built on F2 class soils and road No. 3118 on F3 class soils. There are only two things that change in bearing capacity plots due to the seasonal variations. The first one is the parallel decrease of bearing capacity during the spring thaw period without any unusual graph change. The second one is the noticeable increase of bearing capacity in the specific depth which was not affected by the frost.

Figure 49 presents the surface curvature index (SCI) and the base curvature index (BCI) for roads No. 2008 and No. 3118 calculated in table 13. The best performing road No. 2008 also has a higher stiffness level since both SCI and BCI values are lower compared to road No. 3118. However, the surface and the base part of pavement structure layers perform differently during different seasons. Both roads reached higher stiffness levels at the surface of the pavement structure during the spring thaw period compared to the dry autumn period since SCI values were lower during spring measurements. Road No. 2008 deflection during dry period increases to 6,00 μm and road No. 3118 deflection increases up to 9,00 μm. It is assumed that stiffness increased at the surface of the pavement structure due to decreased subgrade performance since it is affected by the spring thaw. Subgrade performance decrease is indicated by BCI values which increase during the spring thaw period. It determines that bottom layers stiffness is higher during the dry autumn period. Road No. 2008 deflection during dry period decreases by 4,00 μm and road No. 3118 decreases by 8,00 μm. Stiffness decreased during the spring thaw due to higher moisture content in the pavement structure subgrade which decreases soil particles friction which is dependent on soil frost susceptibility. Once again, analysis shows that spring thaw has influenced the change of pavement structure performance, however, the change is symmetrical to all roads and the BCI and SCI values are more dependent on subgrade soil.

Figures 48 and 49 presents that road No. 2008 which is made out of 0,12 m asphalt layer, 0,20 m base layer, 0,33 m subbase layer and which subgrade is made from F2 class soils and additionally improved with lime binders demonstrated the lowest surface deflection and also the highest $E_{0,surf}$ and $E_{600,sub}$ modulus.

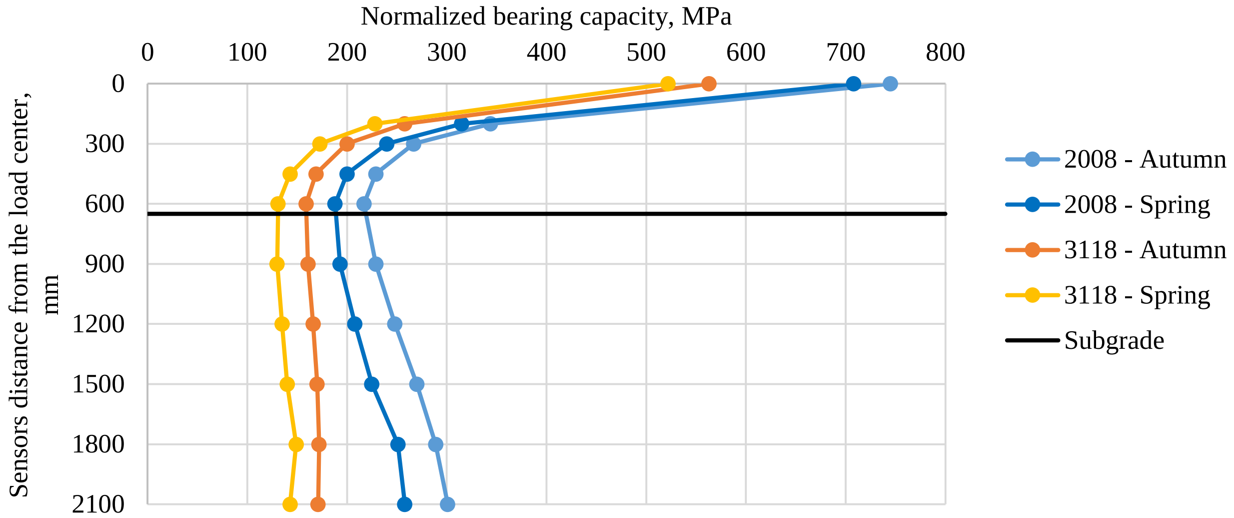


Fig 48. Bearing capacity plots of roads No. 2008 and No. 3118 during the spring thaw and dry autumn periods

Source: designed by author

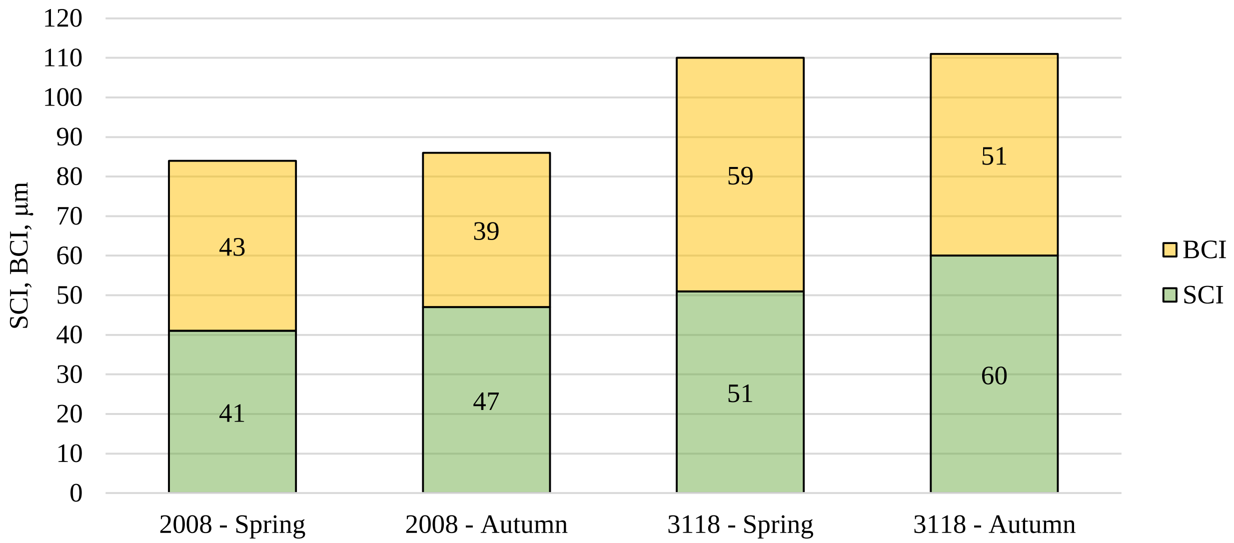


Fig 49. The average SCI and BCI of roads No. 2008 and No. 3118 during the spring thaw and dry autumn periods

Source: designed by author

The normalized bowl area presents pavement structure overall deflections up to 2100 mm in depth. It is a very good indicator of pavement structure performance during different seasons. Figure 50 presents that road No. 2008 is the best performing road compared to others by receiving the lowest amount of deflections during both spring thaw and dry autumn periods. Even during the spring thaw period, the increased area of 6,25 mm^2 is still lower compared to other roads bowl areas during the dry autumn period. Meanwhile, the poorest pavement structure performance was recorded on road No. 3425 during the spring thaw period. The measured area was 9,17 mm^2. However, the most unstable road with the highest area differences during the spring thaw and dry autumn periods was recorded to be road No. 3131. The difference between areas was calculated to be 2,16 mm^2. This high difference can be influenced by multiple factors. One of them can be the highest frost depth since no other roads are in the 1,60 m deep frost zone according to table 6. Another reason can be the highest difference of autumn and spring deflections in different pavement structure layers. Almost all roads have the biggest difference of deflections during different seasons in the 300 mm deep pavement structure layer. The average difference is 38,60 µm. However, the biggest deflection difference on road No. 3131 was recorded already on top of the pavement structure of 61,00 µm and the difference 300 mm deep in the pavement structure layers was recorded to be 57,00 µm. These very poor conditions are influenced by a very thin asphalt layer of 0,06 m and a base layer of 0,20 m. The base layer should have been thicker to compensate thin asphalt layer as in road No. 3118 which also has a 0,06 m thick asphalt layer, however, the base layer is 0,25 m thick. This compensation reflects in figure 50 since the difference in average area is moderate compared to all other roads.

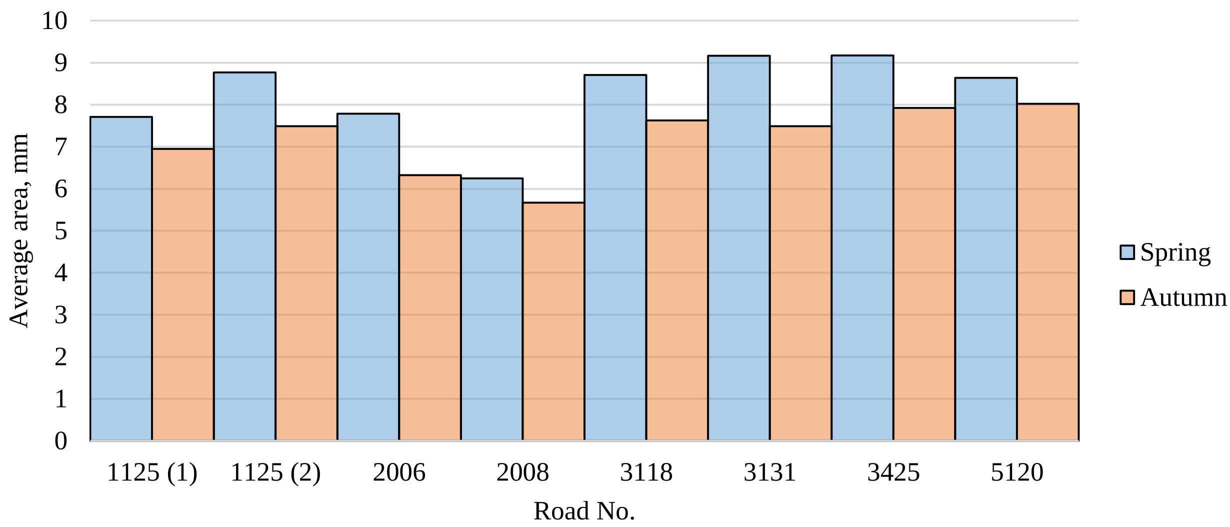


Fig 50. The average normalized bowl area during spring thaw and dry autumn periods

Source: designed by author

3.3. Asphalt pavement structure bearing capacity variation dependency on subgrade

The experiment data analysis presented an obvious pavement structure performance depression during the spring thaw period. However, the subgrade soil improvement influence on the pavement structure performance does not appear so significantly. The average subgrade bearing capacity ($E_{600,sub}$), which is presented in figure 47, does not appear to be directly connected with the improvement type and its binder materials, since subgrades without any improvement (roads No. 1125 and No. 5120) perform better than cement improved subgrade of road No. 3118. Therefore, further analysis has to be performed by additionally evaluating the whole pavement structure performance and subgrade soil type.

The most significant subgrade improvement influence can be seen in figure 51 which presents a high impact on the surface of the pavement structure. Roads that subgrade does not have any type of improvement, a tensile strain of the bottom part of the asphalt layer change significantly during the thaw and dry seasons. Meanwhile, on the subgrade of the road which is improved or stabilized, values change minimally during different seasons. Tensile strain changes on average by 131,56 10^{-6} on roads No. 1125 and No. 5120. While on roads No. 2006, No. 2008, No. 3118, No. 3131, and No. 3425 tensile strain changes on average by 21,90 10^{-6}. Such a huge change is influenced by the performance of the subgrade which can be observed via BCI values in figure 52. Road No. 1125 (1) can be taken as an example. During the autumn period, the subgrade is not affected by frost or extent moisture content, therefore the subgrade is relatively stiff with a BCI of 38 μm. Since the pavement structure has a strong subgrade, its layers can not transmit big deflections to the subgrade coming from FWD. Therefore the highest deflections appear at the surface of the pavement structure with the SCI of 94 μm. Meanwhile, during the spring thaw period, the subgrade is being affected by excess moisture content, therefore its stiffness decreases dramatically and the BCI reaches 51 μm. Since the subgrade does not act as a strong pavement structure foundation and can deform more easily, the surface of the pavement structure does not have to accumulate such high deflection and can transmit them to the subgrade more freely. Therefore, the surface of the pavement structure during the spring thaw period becomes stiffer compared to the dry autumn period where the SCI is 64 μm. To reduce the seasonal impact on the stiffness of the surface of the pavement structure, the subgrade has to be improved or stabilized.

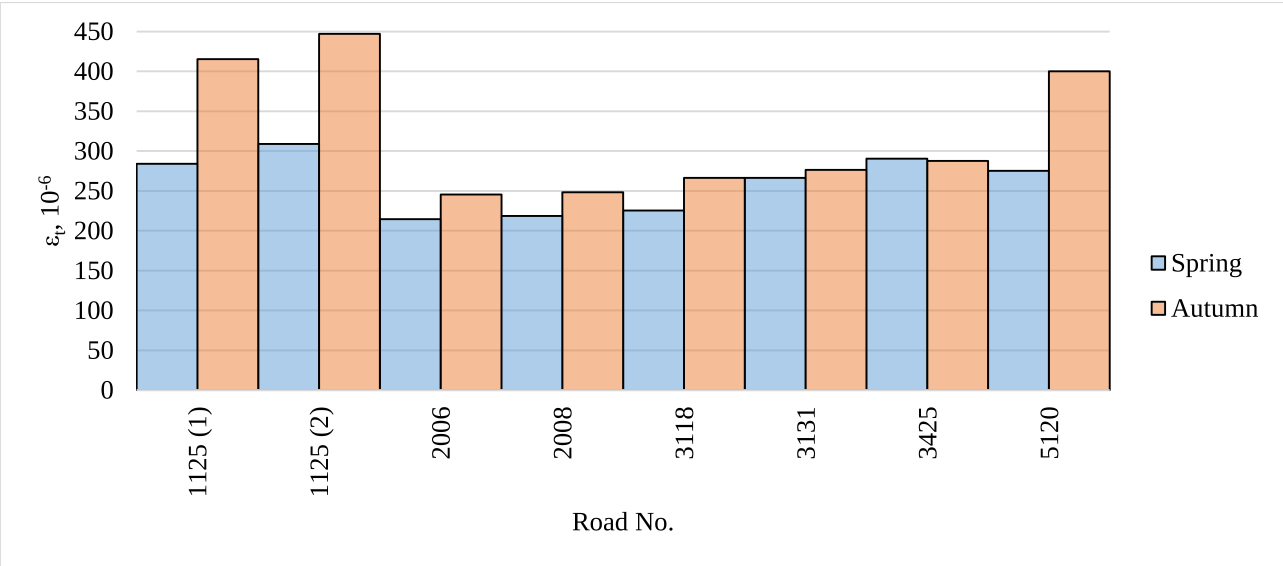


Fig 51. Tensile strain ε_t of the bottom part of the asphalt layer

Source: designed by author

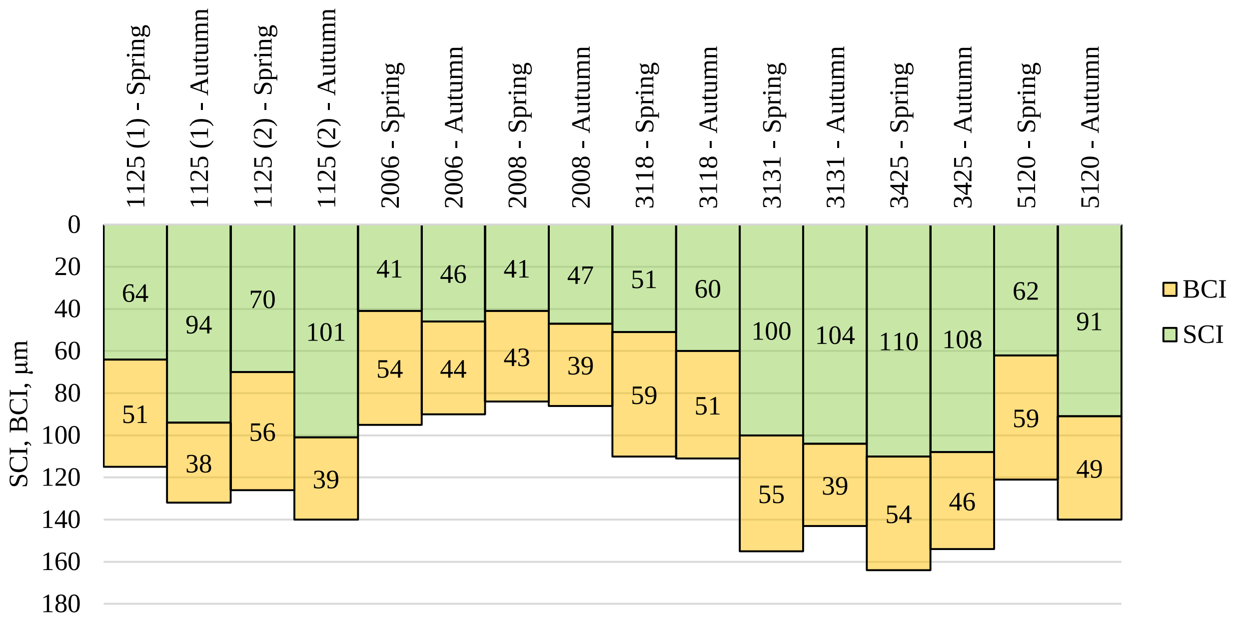


Fig 52. Surface curvature index (SCI) and base curvature index (BCI)

Source: designed by author

However, if it was chosen not to improve or stabilize subgrade, other activities have to be applied to reduce BCI as much as possible. After table 6 and figure 52 analysis, it can be stated that BCI values are mainly dependent on subgrade soil type and the groundwater depth. Road No. 1125 (1) has the lowest BCI value of 51 µm during spring and 38 µm during autumn among other roads in which subgrade is not improved. These relatively good values are achieved since the subgrade is mainly made from the F1 class soils (sand) and there is no groundwater found. The worse BCI value was measured on road No. 1125 (2) since its subgrade was made mainly from F2 class soils (gravel), plus, the groundwater was achieved at 1,30 m deep. However, the worst situation is recorded on road No. 5120 with the highest BCI values of 59 µm during spring and 49 µm during autumn. Although the groundwater was found only somewhere 3,40 m deep, the subgrade of low plasticity clay and silty sand soils have a major impact on performance since they are F3 class soils.

The last observed tendency in figure 52 is related to roads in which subgrades are stabilized or improved. Roads No. 2006, No. 2008, and No. 3118 SCI values are relatively small (from 41 µm to 60 µm) compared to roads No. 3131 and No. 3425 (from 100 µm to 110 µm). This is mainly dependent on the thickness of the asphalt layer. The asphalt layer on roads No. 2006 and No. 2008 is 0,12 m thick and road's No. 3118 is 0,10 m thick. Meanwhile, road's No. 3131 and No. 3425 asphalt layer thickness is only 0,06 m.

A difference in pavement structure performance can be seen when the subgrade is installed out of silty sand soils which are considered to be F3 of frost susceptibility class (figure 53). Silty sand soils that are not improved get significantly affected by moisture during the spring thaw period and therefore bearing capacity decreases in all pavement structure layers. Road‘s No. 1125 (1) bearing capacity ($E_{0,surf}$) at the surface is significantly higher compared to road No. 3425 due to the thicker asphalt layer. However, the bearing capacity in the lower depths decreases faster in road No. 1125 (1) (by 303 MPa during autumn and by 287 MPa during spring) compared to road No. 3425 (by 231 MPa during autumn and 213 MPa during spring). It is the result of the weaker subgrade. Also, another impact of subgrade improvement can be seen on the bearing capacity plot. Road‘s No. 3425 bearing capacity graph during different seasons goes more or less in parallel with the similar decrease of bearing capacity. On the other hand, the road‘s No. 1125 (1) bearing capacity graph is very uneven during different seasons. In the depths from 300 mm to 1200 mm, the graph decreases unusually. It should have more or less repeated the red graph. Meanwhile, during the autumn period, the graph constantly changes its direction. 900 mm deep the bearing capacity increases, 1200 mm deep decreases, 1500 mm deep increases again and so on. Therefore, it can be concluded that subgrade improvement does affect silty sand soils and their effect adjusts pavement structure stability and mechanical properties during the spring thaw period.

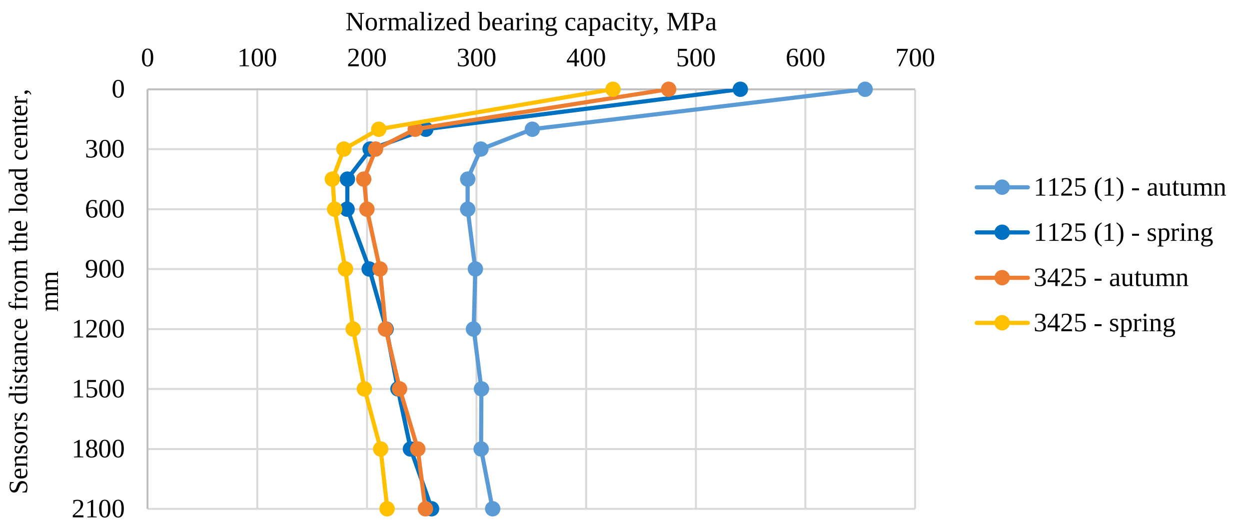


Fig 53. Bearing capacity plots of roads No. 1125 (1) and No. 3425 during the spring thaw and dry autumn periods

Source: designed by author

Section 1.3.1. presented MN GPSR 12 which specified what soil improvement binder has to be used according to the subgrade soil type. Regulations stated that if subgrade is installed out of fine-grained soils, lime binders has to be used. However, two experimental roads breach this regulation since their subgrade was improved by using cement binders or hydraulic road binders even though the subgrade was installed out of low-plasticity clay. Therefore, figure 54 presents the average normalized bearing capacity ($E_{600,sub}$) during spring thaw and dry autumn periods of subgrades which are installed out of low-plasticity clays. The highest performance of 200 MPa during autumn and 150 MPa during spring was achieved by subgrade stabilized with lime binders on road No. 2006. Cement and hydraulic road binders have a quite similar effect on subgrade performance however, it is much lower compared to lime binders. These roads subgrade bearing capacity ($E_{600,sub}$) values are below 160 MPa during autumn and 130 MPa during the spring thaw. Therefore, the MN GPSR 12 regulation is verified. Such high differences can be also influenced by different improvement types since the subgrade of road No. 2006 was stabilized (SS) while two others were improved (SI). However, figure 54 presents that lime binders have one downside compared to cement or hydraulic road binders. Road's No. 2006 subgrade is much more unstable during different seasons since the difference between bearing capacities ($E_{600,sub}$) during dry autumn and spring thaw seasons is 49,76 MPa. Meanwhile, the road's No. 3118 subgrade bearing capacity ($E_{600,sub}$) has the difference of 27,77 MPa and road's No. 3425 of 22,10 MPa.

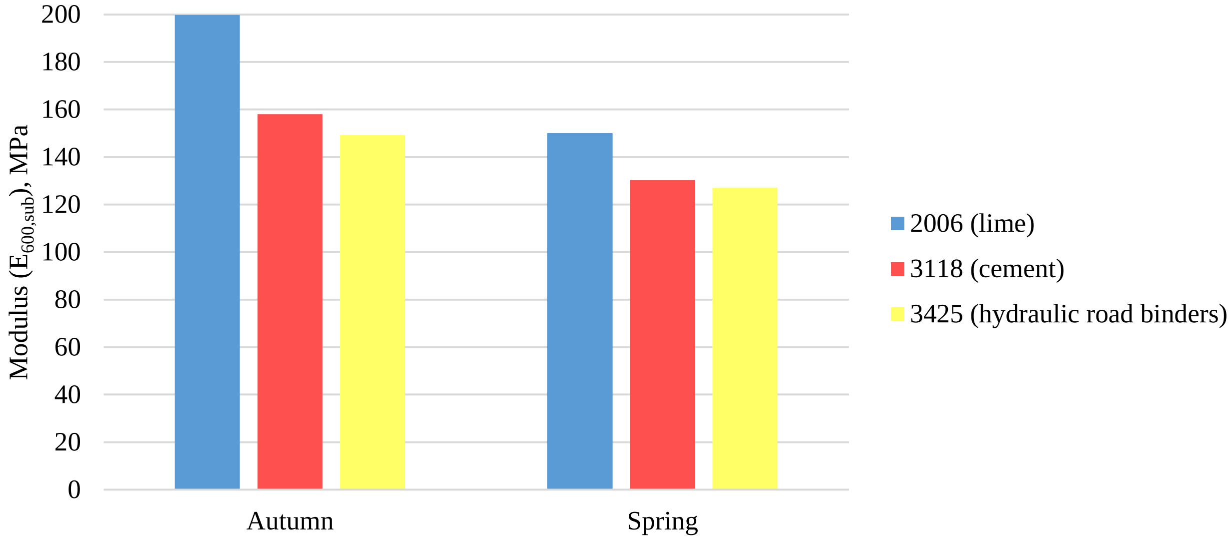


Fig 54. The average normalized bearing capacity ($E_{600,sub}$) during the spring thaw and dry autumn periods of subgrades installed out of low-plasticity clay soils

Source: designed by author

MN GPSR 12 can also be verified by a different approach. This approach reflects on roads in which subgrade is made from silty sand soils. This can be seen in figure 55. Both roads No. 1125 (1) and No. 5120 subgrades were not improved while road's No. 3425 subgrade is improved with hydraulic road binders. At the first sight, it could be thought that hydraulic road binders do not improve subgrade performance on road No. 3425 since its bearing capacity is lower than road's No. 1125 (1) which subgrade is unimproved. However, hydraulic road binders affect pavement structure stability since the difference between different season bearing capacity values on road No. 3425 is only 29 MPa. While on road No. 1125 (1) the difference is 94 MPa. This high difference shows that silty sand soils become very strong when they are dried up. However, when the spring comes, silty sand becomes wet and therefore the bearing capacity decreases down dramatically. This means that hydraulic road binders adjust soil performance dependency on different moisture regimes. Therefore, the MN GPSR 12 regulation can be also verified.

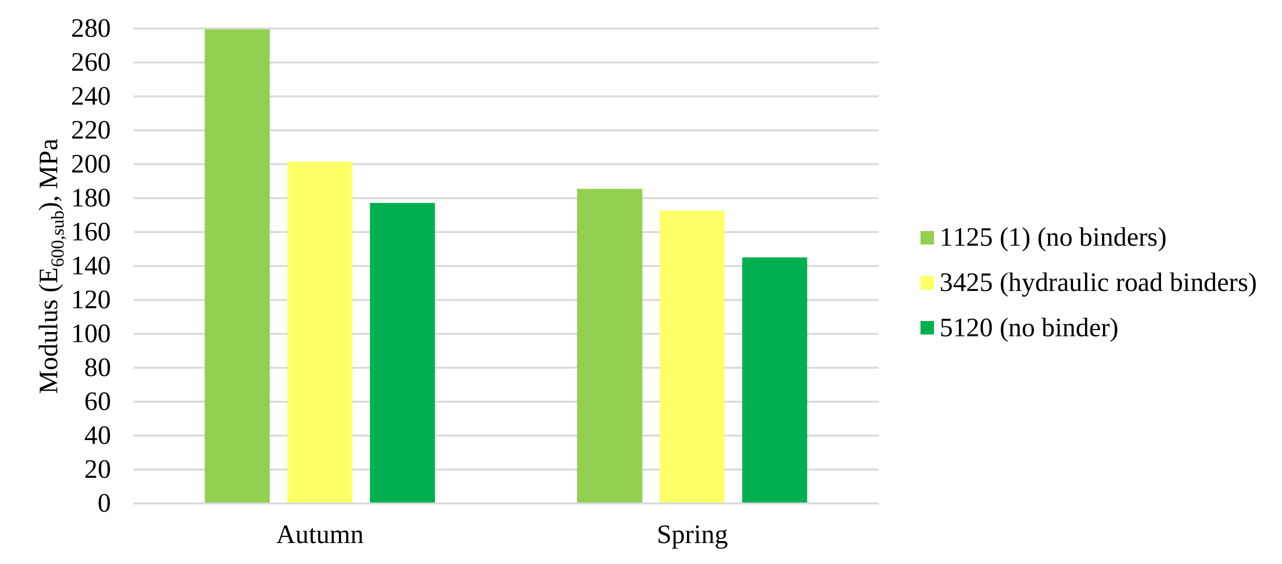


Fig 55. The average normalized bearing capacity ($E_{600,sub}$) during the spring thaw and dry autumn periods of subgrades installed out of silty sand soils

Source: designed by author

3.4. Recommendations for an update of pavement structure design and technical normative regulation

This research showed that the different seasons do make an impact on pavement structure performance. However, it is complicated to determine the greatness of the impact based on different pavement structure parameters. There were only two roads with two-course asphalt pavement structures, only two roads where the groundwater was found. There was only one road with subgrade which was stabilized using cement binders and one road with hydraulic road binders stabilization, and for non of the subgrades the qualified improvement was applied. Additional difficulties were caused by the fact that if some parameters coincide the others do not match. For example, three subgrades were improved with the lime binders, however, these subgrades soil type and their frost susceptibility level were different. Therefore, a straightforward analysis can not be performed. All in all, the future researchers who will analyse the impact of different seasons or soil improvement to the pavement structure bearing capacity ($E_{600,sub}$) should select a bigger amount of experimental roads which will allow them to compare similar road parameters and determine how they influence their performance.

Bearing capacity plots and deflection bowl indexes presented that the pavement structure performance is very dependent on subgrade soil type. Figures 47, 50, and 54 present that the performance of the pavement structure decreases significantly when the subgrade soils are of class F2 and F3, thus subgrade soils are susceptible to frost. Figure 47 additionally presents that subgrade improvement influence is minor compared to the frost susceptibility influence since the KPT SDK

19 regulation of 45 MPa gets breached on the bigger part of analyzed roads during the spring thaw period. Comparing roads without subgrade soil improvement, road No. 1125 (1) has F1 subgrade soil and the performance of this road is the best while road No. 5120 has F3 subgrade soil and therefore the performance is the worst. This trend can be seen both during the spring and autumn periods. Comparing roads with subgrade soil improvement, the most significant difference in performance can be seen during the spring thaw period. Only road No. 2008 has F2 class subgrade soils while the rest of the roads has F3 class subgrade soils and therefore, the difference in the performance changes respectively. Table 5 in LST 1331:2015 assigns different soils into the frost susceptibility classes where soils that are assigned to the F2 class are considered to be low and moderate frost susceptible. It is a very wide range. Since roads of the F3 subgrade soil class performs significantly worse compared to the F2 class soils (figures 44 and 45), it is recommended to repeal the F3 classification and the F2 class should be split into two separate classes of low frost susceptible and moderate frost susceptible soils. All soils that are considered to be F3 class should be replaced with less frost susceptible soils or improved in the future.

The rest of the recommendations come from the breaching of Lithuanian design rules. According to the 75th article of KPT SDK 19, qualified improvement (SQI) or stabilization (SS) has to be performed for the roads which subgrades are built out of F3 class soils. Meanwhile, roads No. 3118, No. 3131, and No. 3425 subgrades are only improved (SI). Therefore, the performance level of those roads should have been higher and the analysis of SQI improvement type could be performed during this research. Another recommendation is referred to the figures 54 and 55. It was proven that not all binder types are suitable for all kinds of subgrade soil. Lime binders performed significantly better on fine-grained soils just as how the second appendix of MN GPSR 12 states. Also, hydraulic road binders noticeably affected the stability of silty sand soils. Therefore, according to rules, lime binders has to be applied on fine-grained soils and cement or hydraulic road binders has to be applied on multi-grained or coarse-grained soils. The last recommendation comes from SCI values in figure 52. The SCI values increase dramatically on roads that are built out of only 0,06 m thick asphalt layer compared to those which are built out of 0,12 m thick asphalt layer. Such a thin asphalt layer creates high deflections at the surface of the pavement structure and therefore can substantially reduce its design lifetime. Therefore, designers must follow the 9th table in KPT SDK 19 rules which indicate that the minimum thickness of the asphalt layer has to be 0,08 m if the design load is lower than 0,05 mln. and 0,12 m if the design load is higher than 0,10 mln.

3.5. Conclusions

1. Pavement structure performance is dependent on numerous factors such as season of the year, subgrade soil type and its frost susceptibility, pavement structure thickness, asphalt layer

thickness, subgrade improvement or stabilization. These factors are presented in bearing capacity plots and the subgrade strength index, however, they do not reflect which of these factors creates the highest influence on the performance.

2. Researchers determined that the measured bearing capacity of not less than 160 MPa on the Regional road subgrade guarantees that the deformation modulus of the subgrade is not less than 45 MPa. The further analysis presented that the deformation modulus of the subgrade still often decreases below 45 MPa during the spring thaw period even if the subgrade was improved. It means that the KPT SDK 19 objective of reducing the subgrade‘s deformation modulus decrease possibility below 45 MPa is not reached.
3. The spring thaw period does have a major impact on all measured road‘s pavement structure strength, however, the impact is different on every road. The spring thaw period evenly reduces the performance of pavement structure layers and subgrade, however, the greatness of performance loss is mainly influenced by the changes of hydrothermal conditions in the subgrade area. The average loss of bearing capacity ($E_{600,sub}$) on the subgrade during spring thaw was recorded to be 38 MPa. The biggest deflections in almost all measured roads were recorded to be 300 mm deep in the pavement structure layers. The average difference in the bowl area during different seasons was recorded to be 38,60 μm. The biggest spring thaw influence on subgrade performance was recorded to be in road No. 2006 and the biggest spring thaw influence on the whole road structure (2100 mm deep) was recorded to be in road No. 3131.
4. Subgrade soil improvement or stabilization reduces the seasonal impact on the pavement structure performance by reducing the difference of the stiffness at the surface of the pavement structure during spring thaw and dry autumn periods. The average difference of tensile strain at the bottom part of the asphalt layer on roads without soil improvements is 131,56 10^{-6} while on roads with improvement or stabilization it only reaches 21,90 10^{-6}. Such high difference is mainly dependent on the stiffness of subgrade which decreases dramatically during spring thaw and increases during the dry period.
5. The comparison of improved and unimproved frost susceptible soils subgrade performance has proven that improvement increases pavement structure bearing capacity uniformly and reduces the negative impact on performance influenced by the spring thaw. The unimproved silty sand subgrade on road No. 1125 (1) reduces the bearing capacity ($E_{0,surf}$) of the whole pavement structure during spring thaw by 287 MPa and improved silty sand subgrade on road No. 3425 reduces the bearing capacity ($E_{0,surf}$) of the surface of the pavement structure by 213 MPa.
6. It was proven that the right type of improvement binder has to be used on corresponding soils as recommended by MN GPSR 12. Comparison of roads in which subgrade is made out of low-plasticity clay soils presented that lime binders have a bigger bearing capacity ($E_{600,sub}$) increase

over the cement or hydraulic road binders. It is worth mentioning that there was only one research road improved with cement binders and only one improved with hydraulic road binders. During autumn, the bearing capacity ($E_{600,sub}$) of road‘s No. 2006 subgrade of low-plasticity clay soils was bigger more than 40 MPa, and during spring thaw was bigger around 20 MPa compared to other roads subgrades of low-plasticity clay soils. A comparison of roads in which subgrade is made out of silty sand soils presented that hydraulic road binders do affect the performance of the subgrade. Road‘s No. 1125 (1) unimproved subgrade is very unstable and changes by 94 MPa during different seasons while road‘s No. 3425 improved subgrade with hydraulic road binders made subgrade very stable since its bearing capacity changed by only 29 MPa during different seasons.

CONCLUSIONS

1. Subgrade soil mechanic characteristics, its frost susceptibility, and water drainage are the main factors to achieve the required expected lifetime of the subgrade and whole pavement structure. The combination of frost susceptible soils and moisture generates two major deteriorations to the pavement structure: winter frost heave and spring thaw. Therefore, it is important to achieve a good performance of the frost susceptible soils by installing subbase, drainage or performing subgrade improvement.
2. Researchers note that pavement structure is being highly deteriorated during mild winter when the densest quantity of ice lenses forms in upper pavement structure layers and during the rapid spring thaw due to excess moisture content in the drainage. To reduce the negative impact of these effects on the subgrade and prevent the decrease of subgrade modulus, soil replacement or treatment should be applied. For soil treatment purposes quicklime, hydrated lime, cement, and hydraulic road binders are usually applied. Researchers determined that lime treatment increases plasticity limit, reduces linear shrinkage, flattens compaction curve, while cement treatment reduces axial stresses and increases soil strength, shrinkage limit and improves compression and swelling indexes.
3. The author experimental research in 7 different roads sections and two seasons presented that the bearing capacity of the whole pavement structure is mainly dependent on asphalt layer thickness and thickness of the whole pavement structure. The bearing capacity of measured pavement structure, expressed with $E_{0,surf}$ modulus, varied from 463 MPa to 745 MPa in the dry autumn period and from 414 MPa to 708 MPa in the spring thaw period. It should be taken into account that both for the autumn and spring periods highest $E_{0,surf}$ modulus values were achieved in No. 2008 road pavement structure with a composition of 65 cm in total and 12 cm thickness of total asphalt layers and subgrade of lowly silty sand soil and lime treatment. The lowest autumn and spring $E_{0,surf}$ modulus values were achieved in No. 3425 road pavement structure with a composition of 66 cm in total and 6 cm thickness of total asphalt layers and subgrade of silty sand soil and hydraulic road binders treatment.
4. Analysis of research results revealed that the subgrade area, compared to pavement structure layers, expresses the lowest $E_{600,sub}$ modulus values independently from road structure composition. The bearing capacity of the measured subgrade expressed with $E_{600,sub}$ modulus, varied from 159 MPa to 219 MPa in the dry autumn period and from 131 MPa to 189 MPa in the spring thaw period. Both for the autumn and spring periods highest $E_{600,sub}$ modulus values were achieved in No. 2008 road pavement structure which composition is detailed in the third conclusion. The lowest autumn and spring $E_{600,sub}$ modulus values were achieved in No. 3118

road pavement structure with a composition of 65 cm in total and 10 cm thickness of total asphalt layers and subgrade of low plasticity clay soil and cement treatment.

5. The bearing capacity of the same road subgrade constantly changes at every measured section and is never uniform. Both for the autumn and spring periods the most stable subgrade was recorded to be on road No. 3118 which composition is detailed in the fourth conclusion. $E_{600,sub}$ modulus values changed from 133 MPa to 185 MPa during the dry period and from 115 MPa to 147 MPa during the spring thaw period. The most unstable subgrade during the dry period with the change from 186 MPa to 303 MPa was recorded to be on road No. 2008 which composition is detailed in the third conclusion. The most unstable subgrade during the spring thaw period with the change from 119 MPa to 206 MPa was recorded to be on road No. 5120 with a composition of 65 cm in total and 10 cm thickness of total asphalt layers and subgrade of silty sand soil and without any treatment.
6. The highest annual average subgrade modulus $E_{600,sub}$ of 204 MPa was recorded on the lime improved road which had a 0,12 m thick asphalt layer, was built on F2 class lowly silty sand soils and is situated in a 1,40 m frost depth zone. While the lowest annual average subgrade modulus $E_{600,sub}$, yet the most stable with little deviation, was measured on cement improved road of 145 MPa which had a 0,10 m thick asphalt layer and was built on F3 class low-plasticity clay soils and is situated in a 1,50 m frost depth zone. However, experiment data showed that subgrades that were improved or unimproved presented a similar performance tendency in terms of the subgrades $E_{600,sub}$ modulus values magnitude. The bearing capacity decreases dramatically during the spring thaw period on both improved and unimproved subgrades.
7. Subgrade soil improvement or stabilization reduces the seasonal impact on the pavement structure performance by reducing the difference of the stiffness at the surface of the pavement structure during spring thaw and dry autumn periods since the difference of stiffness on unimproved roads is 32% and 8% on improved roads. The difference is mainly dependent on the stiffness of the subgrade which decreases during spring thaw by 24% on unimproved roads and by 17% on improved roads. The investigation also has partially proven that the right type of improvement binder has to be used on corresponding soils as recommended by technical norms since the right choice of binder can actually improve the subgrade performance.
8. The tensile strain at the bottom part of the asphalt layer on roads without subgrade soil improvements is significantly higher compared to roads that subgrade are improved or stabilized. The average strain during spring thaw on unimproved roads is 16% higher compared to improved roads while during the dry autumn period the strain is 37% higher respectively. Subgrade improvements also affect the change of strains on the same road during different seasons since strains increase during the autumn period by 31% on unimproved roads while on improved roads

strains increase only by 9%. Research presented that fatigue cracking at the bottom of the asphalt layer on roads that receive the highest deflections can occur ten times faster compared to the roads that receive the lowest deflections.

9. Researchers determined that the measured $E_{600,sub}$ modulus of not less than 160 MPa on the Regional road subgrade guarantees that the deformation modulus of the subgrade is not less than 45 MPa. The analysis presented that the deformation modulus of the subgrade still often decreases below 45 MPa during the spring thaw period even if the subgrade was improved. It means that the KPT SDK 19 objective of reducing the subgrade‘s deformation modulus decrease possibility below 45 MPa is not reached.

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