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Research Article

Effect of Soil Moisture on the Deformation Characteristics of Forest Road Subgrade Soils Due to Climatic Change

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The service life of road pavements, including forest roads, depends on many factors. When designing forest road pavements, it is essential to take into account the behaviour of the subgrade and the factors affecting its physical-mechanical properties, especially soil moisture, which significantly affect the deformation characteristics of the soil. This issue is becoming increasingly important with the increasing climate change. Poor design or intensive use can accelerate the road degradation, leading to environmental damage and reduced exploitation potential. A fundamental parameter for assessing the resistance of soil to repeated loading is the resilient modulus Mr, which is determined from a cyclic load test that simulates the effect of passing traffic. For low-volume roads, including forest roads, this modulus can be determined using a cyclic test with standard California Bearing Ratio testing equipment by applying repeated cyclic loading. One of these innovative cycling test machines was developed at the Mendel University in Brno. The paper presents the results of tests investigating the effect of soil moisture and compaction level on both the resilient modulus and the permanent and elastic deformations of two soil types. The obtained results confirm that the soil moisture content far from the optimum value should result in lower material stiffness and thus to smaller resilient modulus value. Also, they confirm that a larger resilient modulus should be obtained when the soil is compacted with higher compacting energy.

Keywords: resilient modulus, cyclic test, low volume road, pavement, soil, CBR, soil moisture, subgrade, subsoil

1 Introduction

Forest and rural roads are an integral part of the road transport system. They are classified by the American Association of State Highway and Transportation Officials (AASHTO) as low-volume roads based on traffic volume (AASHTO, 2001). They serve to provide access to areas that need to be made accessible for economic, social, and safety reasons. These roads also often pass through areas with high recreational potential and must meet several criteria, ranging from full functionality for serving visitors to reliability, functionality, and aesthetic appeal for leisure and recreational use. They often pass through valuable natural areas and become part of unique ecosystems, so their design must be approached with the protection of adjacent ecosystems in mind (Kuloglu et al., 2019). Thus, these roads often have to meet conflicting criteria. Compared to other roads, forest roads are less traffic-intensive, but natural conditions require special consideration when designing pavement layers. Roads often run through terrain where the subgrade has an unfavourable water regime, low bearing capacity, and high longitudinal gradients, leading to faster degradation of the road surface (Ševelová et al., 2020). Given current climate change and the need to retain water in nature, it is essential to incorporate these factors into road pavement design, as they directly affect its reliability and durability of the pavement structure.

Although forest roads in the Czech Republic belong to the lowest category of roads with the lowest requirements for the quality of input characteristics, they must at the same time meet the requirements for bearing capacity according to the Technical Guide TP 170 (2023)

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and the methodology for the design of low volume road pavements (Ševelová et al., 2015). Currently natural materials are preferred and are generally used for both subgrade improvement and pavement layers, but the aim is to minimize the use of nonrenewable resources and to use recycled materials. The design as well as durability of structures depends on several factors, including the physical-mechanical properties of construction materials, used, the analytical model accuracy, the methodology for determining material properties, and the technological procedure used. Uncertainties and human errors can arise during these processes (Ortiz De Zarate & Ševelová, 2015) in both material selection and testing. When designing road pavements, it is crucial to understand how the subgrade behaves and what influences its physical-mechanical properties. Soil moisture significantly affects the deformation of unconsolidated soils or soils improved with secondary materials, especially under climate change conditions (Ševelová et al., 2020).

The most important non-European standard for pavement design is the AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) based on the mechanistic-empirical method (AASHTO, 2008). This guide divides pavement design into three levels based on the average daily heavy vehicle volumes during the design period and defines the method for determining the resilient modulus Mr of the unbound materials used for the pavement design layers. Resilient modulus characterizes the stiffness of unbound material under cyclic loading. For the first design level, where high traffic loads are expected, resilient modulus is determined using the cyclic triaxial test (ČSN EN 13286-7, 2004). For the second and third design levels, where the daily intensity is a maximum of 400 heavy vehicles, this test is not recommended due to its complexity. Therefore, the current MEPDG methodology recommends replacing this test with another laboratory cyclic test. A generally accepted solution to this problem is the cyclic CBR test, which uses the California Bearing Ratio (CBR) test equipment (Nguyen & Mohajerani, 2016) that is part of the equipment of every geotechnical laboratory. The cyclic CBR test simulates loading by passing vehicles as well as separates plastic deformations from elastic ones (Bojacá Torres & Campagnoli, 2022), (Abid et al., 2017), (Mehrpazhouh et al., 2019).

To demonstrate how the soil moisture influences the deformation behaviour of two typical fine-grained alluvial soils from South Moravia in the Czech Republic, the cyclic CBR test was used and elasticity deformations and resilient modulus were calculated. The fine-grained alluvial soils of southern Moravia have a low bearing capacity and are highly sensitive to soil moisture, making them sensitive to deformation. Thus, knowledge of their deformations and resilience modulus is of interest.

2 Material and Methods

2.1 Material, Geotechnical Analysis

Two samples of alluvial soils, marked Soil A and Soil B, were collected and tested. Each soil sample was collected for testing at a depth of 500 mm in an area of 2 m^2 near the forest road. The surface of the area was first cleaned of all remains of the original vegetation, roots, and other biological material to ensure that the testing material would be uncontaminated. For each soil sample, the geotechnical tests necessary for classification according to the relevant European standards were carried out. The geotechnical analyses consisted of a soil moisture test according to the standard ČSN EN ISO 17892-1 (2015), a sieving and aerometric test according to the standard ČSN EN ISO 17892-4 (2017) and a consistency test (plasticity and liquid limit) or Atterberg limit according to the standard ČSN EN ISO 17892-12 (2018). These tests are used for the basic classification of soils based on their granulometric composition and the Atterberg plasticity and liquid limit for the classification of soils according to the Unified Soil Classification System (USCS) (ČSN EN ISO 14688-2, 2005; ČSN EN ISO 14689-1, 2004).

2.2 Preparing of Specimens

The individual specimens from Soil A and Soil B were compacted into a CBR test mold with a diameter of 152 mm and a height of 117 mm using Proctor standard energy (ČSN EN ISO 13286-2, 2015, ČSN EN ISO 17892-1, 2015). They were prepared at different soil moisture contents, including those below and above the optimum soil moisture content. For Soil A, a total of 8 specimens with soil moisture content in the range 12.54–18.97% (mass water content), and for Soil B, a total of 9 specimens with soil moisture content in the range of 11.60–17.15% (Table 1). The water content was added to the soil specimen randomly. The prepared specimens were subjected to the appropriate cyclic CBR test. Cyclic CBR tests were carried out on both sides of the specimens – on the upper side they are marked Upper, on the lower side, they are marked Lower. As a result, 16 cyclic CBR tests were performed for Soil A, and 18 for Soil B.

2.3 Cyclic CBR Test

The cyclic CBR test device was developed at the Mendel University in Brno (Ševelová & Hauser, 2013). The standard CBR test device is used in cyclic CBR testing in accordance with the current standards for sample preparation and testing, i.e. penetration with a standard

Table 1 Moisture content and dry density of specimens, Soil A, Soil B

Specimen	Soil A		Soil B	
	soil moisture content (%)	dry bulk density (kg.m^{-3})	soil moisture content (%)	dry bulk density (kg.m^{-3})
1	12.54	1 740	11.60	1 884
2	15.24	1 738	13.05	1 823
3	15.88	1 718	13.52	1 828
4	16.39	1 705	13.75	1 801
5	16.53	1 669	13.96	1 759
6	17.54	1 666	15.45	1 751
7	17.77	1 646	15.49	1 761
8	18.97	1 625	16.56	1 703
9			17.15	1 705

speed of 1.27 mm.min^{-1}, and a 50 mm diameter plunger (ČSN EN ISO 13286-47, 2015). The application of repeated loads to the specimen simulates the effect of moving vehicles. This procedure also makes it possible to separate the non-reversible plastic deformations from the reversible elastic deformations and thus calculate resilient modulus. The cyclic loading and unloading procedure is automated and controlled by a control unit with appropriate software. It is repeated until a certain condition is met, most commonly until a predetermined number of loading cycles is reached or some iteration criteria are fulfilled. The loading force for repeated loading is set up by the expected stress value acting on the material in the real pavement structure (Ševelová et al., 2021; Ševelová et al., 2023). In our analysis, the plunger stress value was set to 210 kPa.

3 Results and Discussion

3.1 Material, Geotechnical Analysis Results

After performing all geotechnical tests, Soil A was classified as siCl class soil (Clay loam) and Soil B as csaCl class soil (Sandy loam). The optimum soil moisture content and the dry bulk density were 16.45% and 1,725 kg.m^{-3} respectively for Soil A and 13.70% and 1,820 kg.m^{-3} respectively for Soil B.

3.2 Cyclic CBR Test Results

During the testing, deformations as well as resilient modulus of materials were calculated. Deformation refers to the magnitude of the plunger penetration into the material after finishing the whole cyclic loading. It is equal to the magnitude of non-reversible plastic deformations.

Results of deformation analysis are shown in Fig. 1 and Fig. 2. Fig. 1 shows the dependence of deformation on material dry bulk density for both soil types. It is seen that deformation decreases with increasing dry bulk density. It is in accordance with presumed theoretical expectation, because a larger dry bulk density results in greater material stiffness. Greater stiffness results in smaller deformations. Fig. 1 also clearly shows how different compaction energy (resulting in different dry bulk densities) can influence deformation. The lower side of the specimen was compacted with higher energy

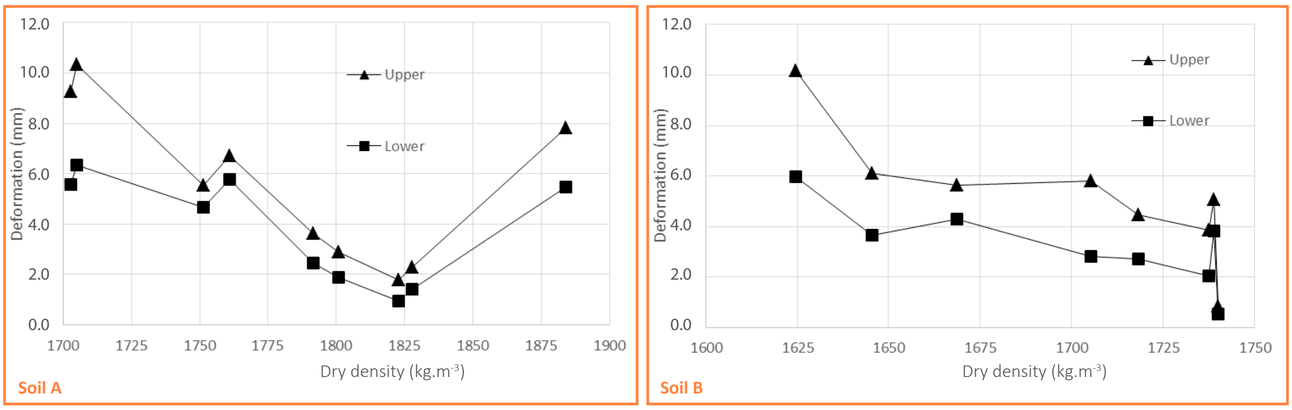


Figure 1 Dependence of deformation on material dry bulk density, Soil A, Soil B

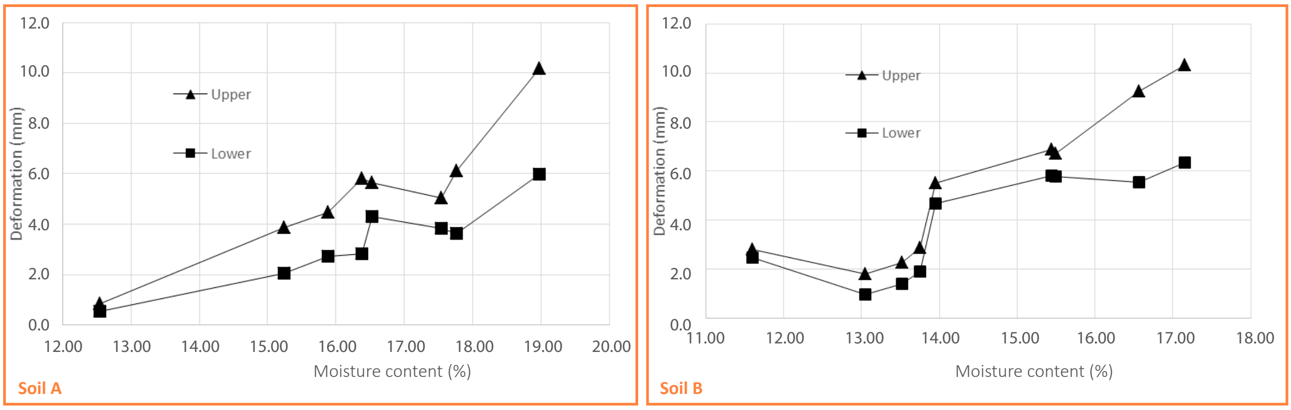


Figure 2 Dependence of deformation on soil moisture content, Soil A, Soil B

compared to the upper side; thus, deformation measured on the lower side should be lower than on the upper side. A slightly different behaviour can be seen for both soils for high values of dry bulk density. For Soil A, at high dry bulk density, the material stiffness increased, and thus deformation decreased. For Soil B, at high density, the material stiffness decreased, and thus, deformation increased. This should be due to the different responses of both soils to high soil moisture content above the optimum value. For Soil A, the maximal deformation reached values around 10 mm on the upper side and around 5 mm on the lower side at a dry bulk density of around 1,625 kg.m^{-3}. For Soil B, the maximal deformation also reached values around 10 mm on the upper side and around 6.3 mm on the lower side at dry bulk density of around 1,710 kg.m^{-3}. For both soil types, deformation on the upper side is larger than on the lower side, in accordance with the above-stated theoretical expectation.

In Fig. 2 there is shown the dependence of deformation on soil moisture content for both soil types. It is seen that deformation increases with increasing soil moisture content. It is in accordance with the presumed theoretical expectation, because larger soil moisture content results in lower material stiffness. And lower stiffness results in larger deformations. Also in Fig. 2 it is clearly visible how weaker or stronger compaction energy can influence deformation. The lower side of the specimen is compacted with higher energy compared to the upper one, and thus deformation measured on the lower side should be lower compared to the upper one. There can be seen a slightly different behaviour of both soils for low values of soil moisture content. For Soil A, with increasing soil moisture the content deformation increases, too. For Soil B the deformation decreases and then increases. This should be due to the different responses of both soils on dry bulk density outside their optimum value. For both soil types, deformation on the upper side is larger than on the lower side in accordance with the above-stated theoretical expectation.

Results of resilient modulus analysis are shown in Fig. 3 and Fig. 4. In Fig. 3 there is shown dependence of calculated resilient modulus on material dry bulk density for both soil types. From the presumed theoretical point of view, the larger material dry bulk density results in larger material stiffness and thus to larger resilient modulus values. Also, it should be larger on the lower side of the specimen, because it is compacted with higher energy. But the soil moisture content should also be taken into account. Both soils probably have slightly

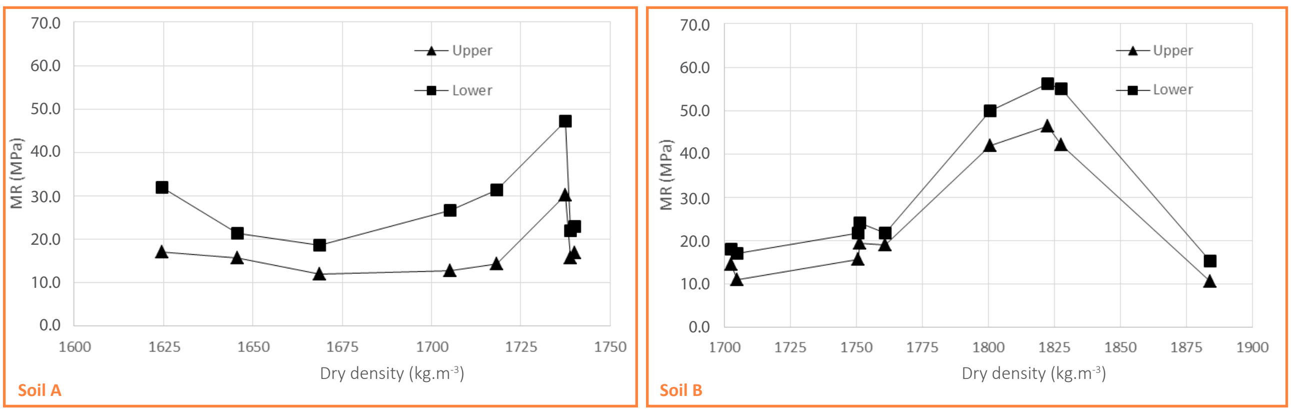
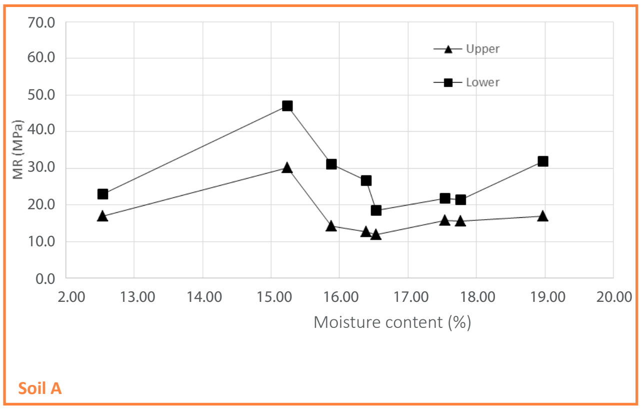


Figure 3 Dependence of resilient modulus Mr on dry bulk density, Soil A, Soil B



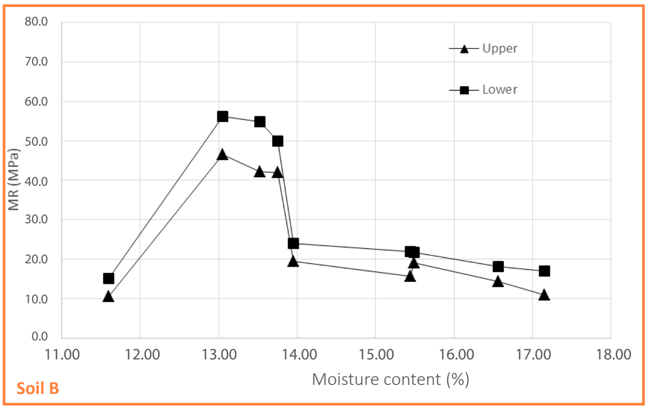


Figure 4 Dependence of resilient modulus Mr on soil moisture content, Soil A, Soil B

different responses to soil moisture content, because they were sorted to different soil classes. For Soil A, the resilient modulus with increasing dry bulk density firstly decreases and then increases. In contrast, for Soil B, the resilient modulus increases with increasing dry bulk density and then decreases. For Soil A, maximal resilient modulus value is around 47 MPa for the lower side and around 30 MPa for the upper side for a dry bulk density of around 1,740 kg.m^{-3}. For Soil B, maximal resilient modulus value is around 56 MPa for the lower side and around 46 MPa for the upper side for dry bulk density of around 1,820 kg.m^{-3}. For both soil types the resilient modulus measured on the upper side is smaller than on the lower side in accordance with the above stated theoretical expectation.

In Fig. 4 there is shown dependence of calculated resilient modulus on soil moisture content for both soil types. From the presumed theoretical point of view, the soil moisture content far from optimum value should result in lower material stiffness and thus to smaller resilient modulus values. Also, it should be larger than on lower side of the specimen, because compacted with higher energy. But the dry bulk density should also be taken into account. Both soils probably have slightly different responses to soil moisture content, because they were sorted to different soil classes. For Soil A, the resilient modulus with increasing soil moisture content firstly increases, then decreases and at the end increases again. For Soil B, the resilient modulus behaviour is at the beginning more or less the same as for Soil A, but it decreases at the end.

4 Conclusions

The design of forest road pavements requires a correct estimation of resilient modulus Mr, because it plays a key role in the optimization of the design of the pavement layers. The quality, durability, service life and level of damage of forest roads is fundamentally influenced by the quality of the subgrade, which is characterized by its bearing capacity. Both subgrade and pavement structural layer materials are subjected to repeated loads of varying magnitude imposed by moving vehicles. The specific material in the pavement structure is soil. It is a natural, heterogeneous and discontinuous medium whose variability of deformation behaviour, stiffness, strength and generally any physical-mechanical properties depend on many factors, including genesis, soil type, bearing capacity, dry bulk density, soil moisture content, degree and method of compaction, number and magnitude of loads, amount of liquid phase etc. In this context, it should be noted that resilient modulus is not a constant property of materials but depends on the factors mentioned above. Depending on the type of material, it is mostly influenced by dry bulk density, soil moisture content, magnitude of transverse stresses, magnitude of applied load, etc. As a result, it is not possible to assume a single value of resilient modulus for one type of soil, as there are infinite possible values depending on the test conditions. It should also be remembered that resilient modulus obtained by any laboratory test procedure is not a real characteristic of the material as such, but is specific to the specimen prepared from it.

Cyclic CBR test offers a more realistic view on the behaviour of materials under repeated loading, allows for optimizing pavement design, careful monitoring of drainage and the compaction level of subgrade soils, and thus improving the durability of roads in the context of current global change. From the comparison of the obtained results of deformations and resilient modulus calculation of two different soil classes under different soil moisture content and level of compaction, it was verified that good compaction of the subgrade leads to greater stiffness and thus improved pavement durability. Although the plastic deformations increase with increasing soil moisture content, the elastic deformation can be reduced by good compaction. Ensuring proper design and maintenance can help mitigate these negative impacts while promoting sustainable infrastructure.

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