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EXPERIENCE WITH THE RESILIENT MODULUS DETERMINATION FOR FOREST ROADS DESIGN USING CYCLIC CBR TEST

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Abstract

The design and assessment of road pavement structural layers made of natural and recycled materials requires careful determination of their physical-mechanical properties. The resilient modulus M_r, which characterizes the stiffness of the material under cyclic loading, is considered to be a fundamental parameter for characterizing material properties. The standard test for its determination is the cyclic triaxial test. An alternative solution is the cyclic CBR test, which uses a standard California Bearing Ratio device. The paper presents the experience and results obtained by its long-term use. Studies show that resilient modulus increases with increasing loading force and/or position of material in pavement construction, because the higher the layer of material is located, the greater the load acting on it. With increasing material moisture content or dry density resilient modulus is increasing up to the threshold level – optimum moisture content. Beyond this limit resilient modulus is decreasing. The larger is compacting level, the larger resilient modulus can be expected. But this compaction ability is strongly influenced by moisture content.

Keywords: resilient modulus, cyclic CBR, repeated CBR, low volume road, pavement, soil, moisture, subgrade, subsoil, compaction, soil density

INTRODUCTION

The efficiency of forest and agricultural management and the accessibility of landscapes require an extensive network of forest and rural roads. Although these types of roads are characterized by low traffic volume, they are essential for the social and economic development of small, often mountainous, forested or semi-desert human communities. They provide access to areas that need to be made accessible for economic, social, recreational or security reasons, for example, and ensure accessibility to the area outside public transport. These roads are part of the low volume road network, but they can form a large part of the national road networks in different countries and are therefore an integral part of the road transport system, not only in developing countries but also, for example, in the USA, Canada, Australia, etc. Especially in developing countries, their presence and quality is particularly important as they connect remote, often densely populated regions with essential social and economic centers.

These roads often have to meet criteria that conflict with each other. Compared to other roads, forest roads are less impacted by traffic, but the natural conditions require special consideration in the design of the pavement layers. Roads often run through terrain where the subgrade has an unfavorable water regime, low load-bearing capacity, and large longitudinal gradients, leading to more rapid degradation of the pavement, Kuloglu *et al.* (2019). These roads often lead through valuable natural areas and become part of unique ecosystems, so their design must be sensitive to the protection of adjacent ecosystems, Ševelová *et al.* (2020).

Although forest roads in the Czech Republic belong to the lowest category of roads with the lowest requirements for the quality of the materials used, they must also meet the minimum load-bearing capacity requirements according to Technical Standard TP 170 (2023). The composition of the structural layers of all types and categories of roads in the Czech Republic is designed according to the valid regulations and standards - CSN 736114 Road pavements. Basic requirements for design (1995), TP 170 Design of road pavement structures (2023), and Methodical Guide to the Design and Implementation of Pavement of Low Volume Roads (2015). The method for actual pavement design for all levels of traffic loading is based on an empirical approach and knowledge of the California Bearing Ratio (% CBR), AASHTO Guidelines for Geometric Design of Very Low-Volume Local Roads (2001), and CSN EN ISO 13286-47 (2015).

Natural and recycled materials are used for the construction of forest road pavements. The physical-mechanical properties of these materials are variable and uncertain, which makes it very difficult to study them in situ and in the laboratory. The quality, durability, service life and level of damage of forest roads are fundamentally influenced by the quality of the subgrade, which is characterized by its stiffness, and by the quality of materials of individual pavement layers. There are many uncertain factors or phenomena of natural origin that directly affect the underlying soils - in particular moisture, unfavorable water regime and also variable levels of material compaction. A similar situation applies to the materials of the structural layers.

One of the global trends in pavement design and sustainable development with respect to the protection of non-renewable resources is the requirement to refine pavement design to respect the realistic stiffness characteristics of materials subjected to repeated loading by road traffic. The most important non-European road design code that respects this is the American Association of State Highway and Transportation Officials (AASHTO) methodology. AASHTO has long been involved in road design procedures and publishes manuals for both design and laboratory procedures for determining the required material characteristics. The AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) (2008) methodology for pavement design and construction used by AASHTO is based on the mechanical-empirical method, Díaz and Peréz (2015). It considers the resilient modulus M_r as the fundamental parameter for characterizing the material stiffness under cyclic loading. Resilient modulus provides a means for analyzing the material stiffness under various changing conditions, e.g. moisture content, dry density, compaction level, state of stress, etc.

This paper summarizes the results of long-term research of the deformation behavior and the resilient modulus calculation of soils and pavement construction materials (hereafter materials) at Mendel University in Brno carried out with the help of cyclic CBR test equipment under different conditions of their functioning.

Resilient Modulus M_r

Soil, as well as most of the materials used in road pavement structures, do not show a completely elastic response, but undergo irreversible plastic deformation after each loading. The deformation behavior, stiffness and strength, as well as the variability of physical-mechanical properties, depend on many factors. These factors include, but are not limited to, the genesis of the material, the type of material, the method of placement of discontinuous materials, the level of compaction given by the standard Proctor energy, moisture content, the number of repeated loading cycles, chemical composition, and maximum load-bearing capacity, Florian *et al.* (2015), Hauser *et al.* (2018), Nguyen and Mohajerani (2016). The design of pavement structures - not only forest roads - requires the correct determination of resilient modulus M_r as it plays a crucial role in optimizing the design of pavement layers. It is considered to be a fundamental parameter for characterizing the material stiffness under cyclic loading, which is typical for roads loaded by vehicle traffic. It is a measure of the material stiffness and provides a means for its analysis under different conditions. The resilient modulus should be obtained from a suitable laboratory test that realistically simulates the expected loading from repeated vehicle passes and should take into account the above mentioned factors including expected state of stress of materials in the real structure. At the same time, the test must not damage the soil specimen under test or exceed the maximum load-bearing capacity of the material, Yang *et al.* (2008), Brinch Hansen (1961).

For roads with high daily vehicle traffic intensity, resilient modulus is determined by using cyclic triaxial test, CSN EN ISO 13286-7 (2004). For less loaded roads, including forest roads, where the daily intensity is lower, cyclic triaxial test can be replaced by a suitable laboratory method using cyclic loading and providing a sufficiently accurate and reliable estimate of resilient modulus, Díaz and Peréz (2015). Of course, in addition to meet the cyclic loading requirement, this method is expected to be inexpensive in terms of time and cost, thus creating an alternative to cyclic triaxial test. As alternative method, different modifications of standard California Bearing Ratio test, CSN EN ISO 13286-47 (2015), have been tested and validated in practice. The theoretical backgrounds of cyclic CBR test, Molenaar (2008), which uses a standard device to determine California Bearing Ratio and applies repeated loading to the material specimen, assumes that this procedure provides accurate deformation characteristics as well as resilient modulus of the tested materials. Repeated loading not only simulates the loading of vehicle traffic, but also eliminates plastic deformation. Only after the application of multiple load cycles does the irreversible plastic deformation in the last load cycle decrease compared to the total deformation. It is in this phase of cyclic loading that resilient modulus can be calculated. The datails of resilient modulus calculation can be found e.g. in Molenaar (2008), Araya (2011), Sas *et al.* (2017), Ševelová *et al.* (2021), Florian *et al.* (2023).

MATERIALS AND METHODS

Soil Sampling, Specimen Preparation

Soil samples for testing are always collected at a depth of 500 mm in an area of 2 m^2 near the forest road. There are two reasons why material is collected from this depth: i) it is the depth at the bottom edge of the active zone of the pavement structure, ii) it is necessary to ensure that the material is not contaminated with biological material in the upper part of the terrain. The surface of the area is first cleaned of all remains of the original vegetation, roots, and other biological material to ensure that the testing material would be uncontaminated. After performing the geotechnical analysis of the sampled soil, the material is divided, if necessary, into individual soil batches. Each batch is then used for a specific testing purpose – e.g. combination of plunger stress value, and/or soil moisture content, and/or number of loading cycles etc. Six specimens are always prepared from each individual batch to enable statistical analysis of obtained values. Finally, individual specimens are prepared for the deformation behavior and/or resilient modulus analysis performed by the cyclic CBR test. Deformation refers to the depth of plunger penetration into the material after the entire cyclic loading procedure is completed. Deformation is thus equal to the magnitude of irreversible plastic deformation.

The individual specimens are compacted into a standard CBR test mold with a diameter of 152 mm and a height of 117 mm with Proctor standard energy, CSN EN ISO 13286-2 (2015), using a 2.5 kg mortar, material is placed in three layers, total number of strokes in each layer is 56. Specimens are standardly conditioned to the optimum moisture content and the maximum dry density according to standard CSN EN ISO 17892-1 (2015). If needed for the particular analysis, they are prepared at different soil moisture content, including those below and above the optimum moisture content and/or at different compaction level etc.

Geotechnical Analysis

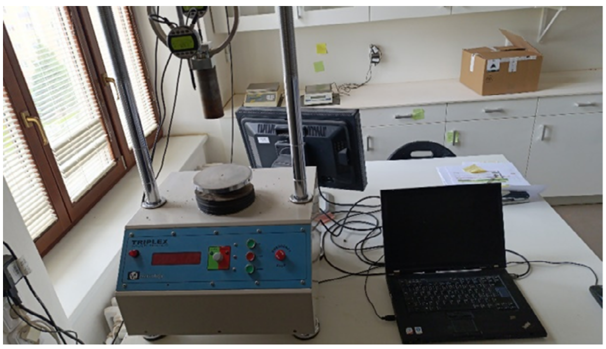
For each soil sample, the geotechnical tests necessary for classification according to the relevant European standards are carried out. The geotechnical analyses consists of a soil moisture test according to standard CSN EN ISO 17892-1 (2015), a sieving and aerometric test according to standard CSN EN ISO 17892-4 (2017) and a consistency test (plasticity and liquid limit) or Atterberg limit according to standard CSN 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), CSN EN ISO 14688-2 (2005), CSN EN ISO 14689-1 (2004).

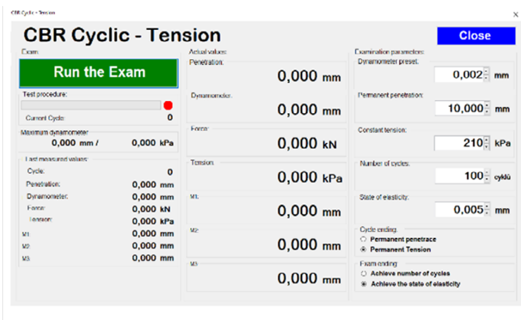
Statistical Analysis

Each set of six values obtained from cyclic CBR test for each individual soil batch is statistically analyzed. The following statistics are calculated for each dataset: mean value, coefficient of variation, minimum and maximum values, 0.05 and 0.95 quantiles, and – if needed – correlation coefficient, Ševelová *et al.* (2021).

Cyclic CBR Test

The test device for cyclic CBR test was developed at Mendel University in Brno. The test uses a standard California Bearing Ratio (standard CBR test) device in accordance with the current standards for sample preparation, CSN EN ISO 13286-2 (2015), and for test execution, CSN EN ISO 13286-47 (2015),



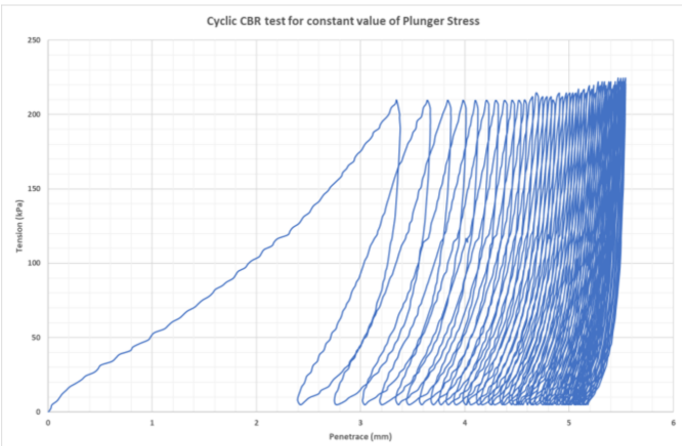


1: *Cyclic CBR test device, control unit* i.e. penetration with a standard speed of 1.27 mm/min and a 50 mm diameter plunger, Fig. 1. The test specimens are moisturized to the optimum moisture content, CSN EN ISO 17892-1 (2015). and compacted into a standard CBR test mold with a diameter of 152 mm and a height of 117 mm using Proctor standard energy according to CSN EN ISO 13286-2 (2015). However, compared to the standard CBR test, cyclic loading and a penetration depth of 2.54 mm is used. The application of repeated loading to the specimen simulates the effect of passing vehicles. This procedure also allows separating the irreversible plastic deformations from the reversible elastic deformations, thus allowing the calculation of the resilient modulus. The cyclic loading and unloading procedure is automated and controlled by a control unit with appropriate software, Fig. 1.

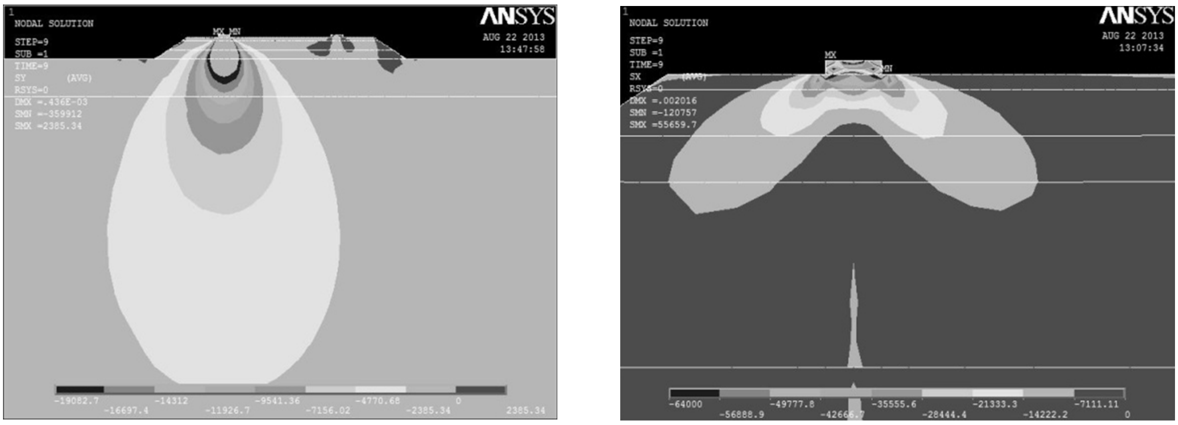
In the first loading step (cycle), the specimen is loaded to a plunger penetration depth of 2.54 mm and then unloaded. In subsequent steps (cycles), repeated loading is performed with the force value set to the force value required in the first step for a penetration to depth of 2.54 mm. The loading and unloading is repeated until a certain condition is met, most commonly the completion of a predetermined number of loading cycles, Fig. 2.

For the verification of cyclic CBR test, soil samples were collected from the subsoil of a total of 11 sites across the Czech Republic. The material was always taken from the depth of 500 mm. A total of 46 soil samples covering nine soil types according to the USCS classification, CSN EN ISO 14688-2 (2005), CSN EN ISO 14689-1 (2004), were taken to obtain a representative number of resilient modulus values. Six test specimens were made from each sample and thus a total of 276 specimens were tested. The specimens were subjected to the appropriate cyclic test and the set of six resilient modulus values for each soil sample was statistically evaluated. Similarly, the results obtained for each individual soil type were statistically evaluated. As the number of soil samples for each soil type was different, the number of tested specimens was also different.

The results of the statistical analysis showed an extremely high random variability of the modulus, Ševelová *et al.* (2021). In addition, the possible intervals of occurrence of the modulus values for each soil type were found to more or less be overlapping. An even greater surprise, however, was the large random variability of the six specimens within a single soil sample and also the large variation between soil samples of a particular soil type. These findings were in contrast to expectations. The results obtained were analyzed in detail, focusing on the main factors having the expected influence, such as moisture content, maximum dry density and the magnitude of the applied force. It was found that individual specimens, even within the same soil sampling - i.e. with nominally identical properties - are tested at often completely different values of applied force and therefore completely different values of plunger stress. It should be noted that the plunger stress is determined by the force that must be developed in the first cycle - in accordance with standard CBR test - to penetrate the plunger to the prescribed depth. In many cases the applied force is so large, that plunger stress exceeds during cyclic CBR testing material load-bearing capacity and the resilient modulus is therefore determined for a large number of specimens on the damaged material. The reason why soil specimen can withstand such a high stress value may be due to the unrealistic confinement of the specimen in the CBR mold. The specimen is confined by a high stiffness steel ring, so that it can withstand stress values exceeding its load-bearing capacity. Important consequence of high plunger stress values is high resilient modulus value, as there is a high positive correlation between modulus and stress, Ševelová *et al.* (2021), Florian *et al.* (2023). As a result, the original cyclic CBR test based on a penetration depth of 2.54 mm generally does not meet the basic requirement for determining the deformation characteristics and resilient modulus of materials, which is to perform the test on intact specimens and optimally at plunger stress that



2: *Cyclic loading, plunger penetration, the dependence on number of loading cycles*



3: *Stress distribution in real pavement obtained by FEM: vertical, horizontal stresses*

correspond to the expected state of stress that will be applied to the material in a real pavement structure.

Taking into account the above findings, the original version of cyclic CBR test was modified to eliminate the shortcomings of the original version, Florian *et al.* (2023). In updated version, the applied loading force for repeated loading is not determined in the first loading step by the plunger penetration to the prescribed depth, but by the stress value that will be acting on material in the real pavement structure. This means that the applied loading force is not dependent on the penetration depth but is defined by the plunger stress value.

To determine the plunger stress value and thus the value of the loading force for cyclic loading, the finite element method (FEM) is currently the only correct method, Florian *et al.* (2015), Florian *et al.* (2016), Ševelová and Florian (2013), Florian and Ševelová (2013). The commonly used assumption of a stress propagation angle of 45 degrees is completely inaccurate. A typical illustrative example of the stress distribution in pavement structures is shown in Fig. 3. The stresses shown, both vertical and horizontal, were obtained in a study, Florian and Ševelová (2013), which used a nonlinear FEM model that respects the real behavior of the materials that form the individual pavement layers, Ševelová and Florian (2013).

The same methodology was used to verify the updated variant of cyclic CBR test as for the original variant. Soil samples were collected from the depth of 500 mm from a total of 11 sites across the Czech Republic. A total of 40 soil samples were collected and always 6 soil specimens were prepared from each soil sample, i.e. a total of 240 specimens. The specimens were subjected to an appropriate cyclic CBR test with a plunger stress of 210 kPa being considered. The set of six modulus values for each soil sample was statistically evaluated. Similarly, the results obtained for each soil type were statistically evaluated. Since the number of soil samples for each soil type was again different, the number of tested specimens for each soil type was also different.

When comparing results obtained by both variants of cyclic CBR tests, study clearly shows that resilient modulus values obtained by original cyclic CBR test are significantly higher than those obtained by updated cyclic CBR test or even cyclic triaxial test. It also shows, that results obtained from updated cyclic CBR test and cyclic triaxial test are in concordance and are fully comparable, see Tab. I. However, it should be noted that cyclic triaxial

I: *Resilient modulus values from cyclic CBR test, indicative values from cyclic triaxial test*

Soil Type	Mean Value [MPa]	Interval of Obtained Values [MPa]		Indicative Values Triaxial Test [MPa]
Cl	63.8	31.3	96.2	20–134
siCl	28.2	12.2	44.2	-
saclSi	64.0	46.4	81.6	58–102
csaCl	79.3	52.4	106.2	11–84
sagrSi	42.9	13.4	72.4	-
grsaCl	71.2	43.7	98.8	-
siSa	65.2	42.0	88.3	32–111
grsiSa	27.4	18.7	36.1	57–148
siGr	56.5	27.6	85.3	88–141

test results are only indicative, because they have been always obtained by testing only one specimen under a variety of incompatible stress and moisture conditions and, in particular, on soil material from all over the world.

Resilient Modulus Under Different Experimental Conditions

As noted above, resilient modulus for a given material is not constant, but depends on a number of factors – e.g. magnitude of the plunger stresses (i.e. the depth of material placement in real pavement structure), compaction level, number of loading cycles applied, moisture content and dry density of material, possible water saturation etc. In the following section, we present some illustrative results of performed studies investigating the influence of the above factors on material deformation behavior and/or resilient modulus value.

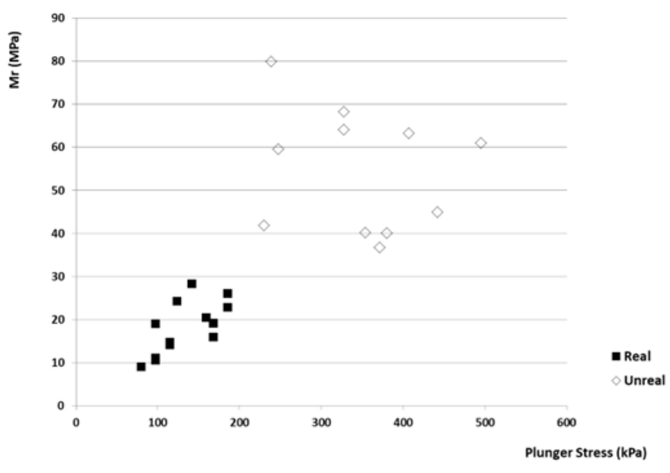
RESULTS

Influence of Loading Force Magnitude

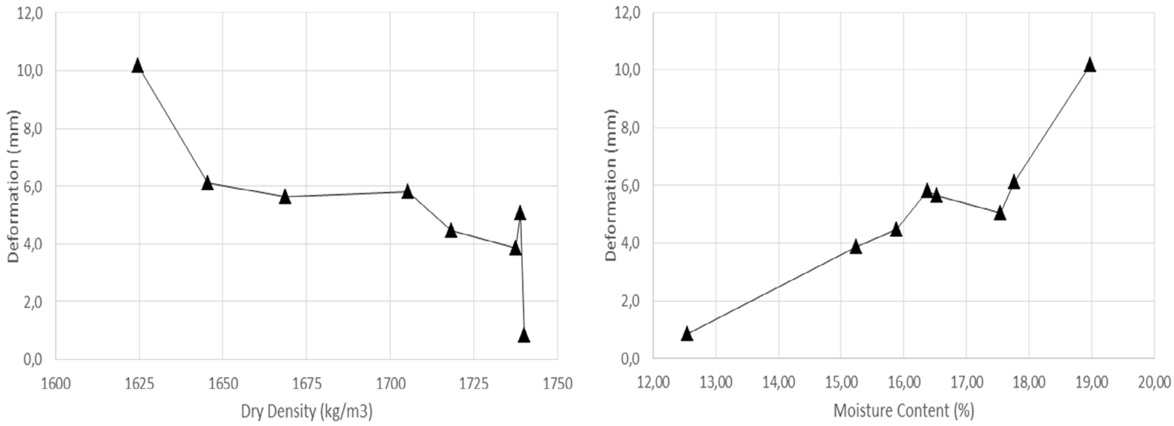
The magnitude of the applied load under cyclic loading simulates the influence of weight of passing vehicles and also the effect of the depth of material placement in real pavement structure. Obviously, the deeper the material is, the smaller the stress applied to it and therefore the smaller plunger stress applied to the specimen in cyclic CBR test.

In performed study, soil sample was collected in a standard manner from subsoil and classified as siGr soil type according to the USCS classification. A total of 24 test specimens were prepared from the collected material and subjected to cyclic CBR test with 50 loading cycles. The applied plunger stress, i.e. the applied load, was always chosen randomly to cover the interval 80–500 kPa. Taking into account the material classification and the assumptions of classical Terzaghi theory, Hauser *et al.* (2012), a stress of 190 kPa was chosen as the limiting stress that the material is realistically able to withstand. Thus, if plunger stress was less than this limit, the results were considered to be realistic to be achieved in a real pavement structure. The corresponding resilient modulus values are in this case marked as "Real". Otherwise, the results were considered unrealistic as they were achieved solely by the material specimen being placed in a rigid ring mold and in a real pavement the material would fail as the applied load would not be able to be resisted. The corresponding resilient modulus values are in this case marked as "Unreal". The results of the study are shown in Fig. 4.

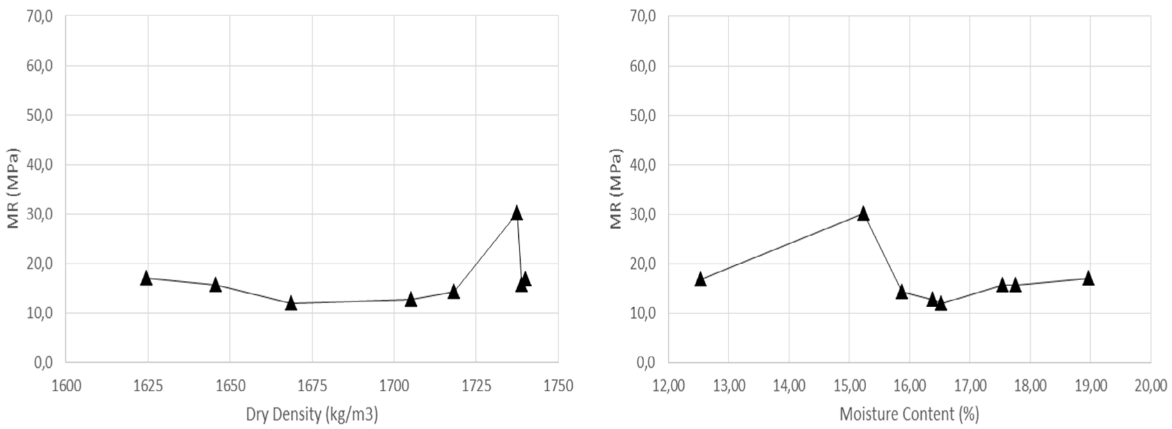
It is seen that increasing plunger stress results in increasing resilient modulus value. The resilient modulus for all 24 specimens ranges from 9.0 to 79.9 MPa and the correlation coefficient is positive and is equal to 0.74. As seen from Fig. 4 and confirmed by high correlation coefficient value, there is strong positive correlation among loading force magnitude and resilient modulus value. It is in accordance with presumed theoretical expectation, because larger plunger stress results in greater compaction energy and thus to greater material stiffness. And because resilient modulus characterizes the material stiffness, a higher value of the resilient modulus can therefore be expected for a stiffer, more compacted material. For realistic results, resilient modulus ranges from 9.0 to 28.3 MPa with an average value of 18.1 MPa. The correlation coefficient is positive and is equal to 0.67. For unrealistic results, resilient modulus ranges from 36.8 to 79.9 MPa and the correlation coefficient is negative and is equal to -0.22. This weak negative correlation means that there is a very weak opposite trend – with increasing plunger stress resilient modulus does not increase, but rather decreases. This should be probably consequence of large plunger stress over prescribed soil load-bearing capacity, as a result of which the material is unable to resist it.



4: *Resilient modulus dependence on plunger stress, realistic and unrealistic values*



5: *Dependence of deformation on material dry density and soil moisture content*



6: *Dependence of resilient modulus on material dry density and soil moisture content*

Influence of Moisture Content and Dry Density

To examine the effect of moisture content and dry density of soil on the deformation characteristics and resilient modulus of the material, soil sample was collected in a standard way. After performing all geotechnical tests, the soil was classified as siCl soil type according to the USCS classification. The optimum moisture content and maximum dry density were 16.45% and 1 725 kg/m³, respectively. The individual specimens were prepared under different moisture contents – both below and above the optimum moisture content. A total of 8 specimens with moisture content in the range of 12.54–18.97% were prepared and subjected to cyclic CBR test with 50 loading cycles and a plunger stress value of 210 kPa.

Results of deformation analysis are shown in Fig. 5. It shows the dependence of deformation, i.e. permanent plastic deformation, on material dry density and moisture content. It is seen that deformation decreases with increasing dry density. At high dry density, the material stiffness increased and thus deformation decreased. It is in accordance with presumed theoretical expectation, because larger dry density results in greater material stiffness. Greater stiffness results in smaller deformations. The maximal deformation reached values around 10 mm at dry density of around 1 625 kg/m³. Also it is seen, that deformation increases with increasing soil moisture content. It is in accordance with presumed theoretical expectation, because larger soil moisture content results in lower material stiffness. And lower stiffness results in larger deformations. The maximal deformation is reached at maximal moisture content of around 18,97%.

Results of resilient modulus analysis are shown in Fig. 6. It shows dependence of calculated resilient modulus on material dry density and moisture content. Resilient modulus with increasing dry density firstly very slowly decreases and then increases. After reaching its maximal value it lowers down. It is in accordance with presumed theoretical point of view, because the larger material dry density results in larger material stiffness and thus to larger resilient modulus values. But it should be also taken into account the influence of moisture content. The maximal resilient modulus value is of around 30 MPa for dry density of around 1 740 kg/m³. For other dry density values it is in the range 12–30 MPa.

Also it is seen dependence of calculated resilient modulus on moisture content. From the presumed theoretical point of view, the moisture content far from optimum value should result in lower material stiffness and thus to smaller resilient modulus values. But it should be also taken into account the influence of dry density. The resilient modulus with increasing moisture content firstly increases, then decreases and at the end slowly increases again.

Influence of Moisture Content and Compaction Level

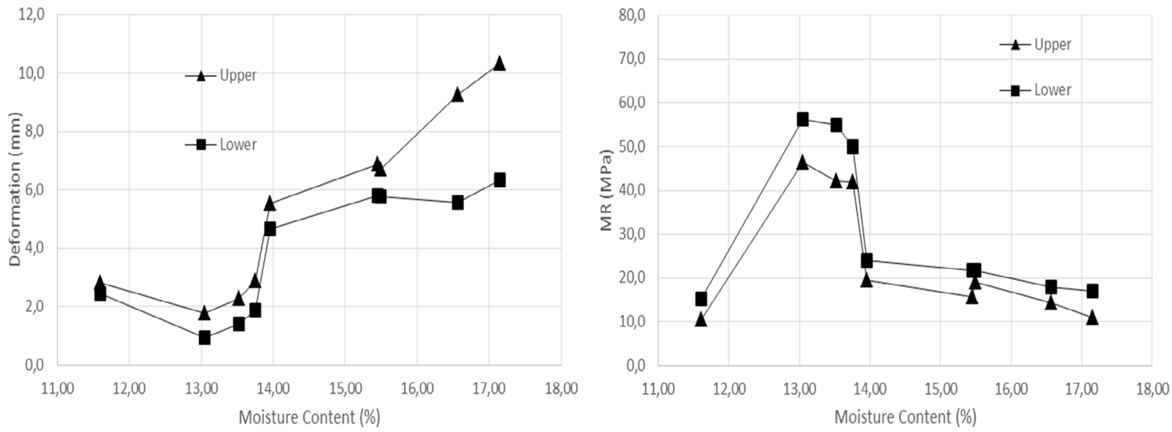
To evaluate the influence of moisture content and compaction level on deformation characteristics and resilient modulus value, soil sample was collected in a standard way. After performing all geotechnical tests, the soil was classified as csaCl soil type according to the USCS classification. The optimum moisture content and dry density were 13.70% and 1 820 kg/m^3, respectively. The individual specimens were prepared under different moisture contents – both below and above optimum moisture content. A total of 9 specimens with moisture contents ranging from 11.60% to 17.15% were prepared. The specimens prepared in this way were subjected to the appropriate cyclic CBR test with 50 loading cycles and a plunger stress value of 210 kPa. To evaluate the influence of compaction level, cyclic CBR tests were carried out on both sides of the specimens – results on the upper side are marked "Upper", and on the lower side "Lower". As a result, a total of 18 cyclic CBR tests were performed.

Results of deformation analysis and resilient modulus analysis are shown in Fig. 7. It shows dependence of deformation, i.e. permanent plastic deformation, on soil moisture content and compaction level. It is seen, that deformation firstly decreases till reaching its optimum moisture content and increases with increasing soil moisture content. It is in accordance with presumed theoretical expectation, because soil moisture far from its optimum value results in lower material stiffness. And lower stiffness results in larger deformations. In Fig. 7 is also clearly seen, how weaker or stronger compaction level (resulting in different dry densities under the same moisture content) can influence deformation. The lower side of specimen is compacted with higher energy compared to the upper one. The presumed theoretical expectation should be that deformation measured on the lower side should be lower compared to the upper one, because higher compaction level results to higher stiffness. And higher stiffness results to lower deformation. It is seen, that deformation on the upper side is constantly larger than on the lower side in accordance with the above stated theoretical expectation. The maximal deformation reached value of around 10.2 mm on the upper side and of around 6.3 mm on the lower side at moisture content of around 17.15%. The minimal deformation reached values of around 1.8 mm on the upper side and of around 1.0 mm on the lower side at moisture content of around 13.10%.

Results of resilient modulus analysis show that resilient modulus with increasing soil moisture content firstly increases and then decreases. From the presumed theoretical expectation, 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 the on lower side of the specimen, because it is compacted with higher compacting energy. But it should also be taken into account the dry density. Obtained results are in accordance with the above stated theoretical expectation. The maximal resilient modulus reached values of around 56 MPa for the lower side and of around 46 MPa for the upper side for moisture content of around 13.10%. Resilient modulus measured on the upper side is constantly smaller than on the lower side in accordance with the above stated theoretical expectation.

DISCUSSION

Results of deformation analysis and resilient modulus analysis performed with soils of different soil classes according to the Unified Soil Classification System (USCS) under different loading,



7: *Dependence of deformation and resilient modulus on soil moisture content and compaction level* moisture content, dry density and compaction level conditions proved, that resilient modulus is not a constant for the appropriate soil class, but varies depending on above mentioned conditions. Resilient modulus value increases with increasing loading force and/or position of material in pavement construction, because the higher the layer of material is located, the greater the stress acting on it, Ševelová *et al*. (2021), Rahman *et al*. (2023), Rincón-Morantes *et al*. (2022). But it should be noted that stiffness of material is limited, because load-bearing capacity of soils and also materials of construction layers is unable to carry any large load.

The found dependence of permanent plastic deformation and resilient modulus on moisture content and dry density of material confirms well-known laboratory as well as in-situ observations. With increasing material moisture content or dry density permanent plastic deformations are decreasing and resilient modulus values are increasing up to the threshold level – optimum moisture content. Beyond this limit dry density is decreasing, permanent plastic deformation grows rapidly and resilient modulus is decreasing, Rahman *et al*. (2023).

Also compaction level plays a key role when examine magnitude of permanent plastic deformation and resilient modulus value. The larger is compaction level, the smaller permanent plastic deformation and the larger resilient modulus can be expected, Mehrpazhouh *et al*. (2019). But this compaction ability is strongly influenced by moisture content. The highest compaction efficiency is in the vicinity of optimum moisture content. Especially for higher moisture content values it decreases significantly.

CONCLUSION

Existing methodologies for road pavement design are mostly empirical or mechanically-empirical and are unable to directly incorporate the necessary knowledge about the behavior of materials under various natural and loading conditions. Materials used in road construction are exposed to dynamic and repeated loads caused by traffic. In order to take into account the cyclic nature of the load on the material and also the non-linear behavior of the material, many experimental studies have been carried out around the world, both on full-scale models and on samples tested under laboratory conditions, with the aim of obtaining information on deformation behavior of materials for the adequate determination of the resilient modulus. The concept of resilient modulus is always associated with the process of repeated cyclic loading, and its value depends on the current parameters of the material, including maximum dry bulk density, moisture content, compaction level, number and magnitude of repeated loads, state of stress etc. Its value is not constant for a given type of material, but varies within a certain range depending on the current conditions. Therefore, the method for determining resilient modulus must take the above factors into account.

Based on research carried out at Mendel University in Brno, it can be concluded that cyclic CBR test procedure in its modified version, using existing equipment for determining the California Bearing Ratio, is a very suitable method for determining resilient modulus of a wide range of materials used in road pavement construction, especially when real state of stress values that can be expected in a real pavement structure are used for cyclic loading. The plunger stress values in any case must not exceed the load-bearing capacity of the material in order to ensure correct determination of resilient modulus. The advantage of this method, unlike cyclic triaxial test, is that the same specimen preparation is used as for standard California Bearing Ratio test. Specimens can be prepared e.g. with different amount of water, different compaction levels, different loading force magnitude, different number of loading cycles etc.

The cyclic CBR test offers a more realistic view of material behavior under repeated loading, allowing for optimized road pavement design, careful monitoring of drainage and subgrade compaction levels, and thus improving road durability. It can also be pointed out that the results of cyclic CBR test seems to be consistent with the results obtained by cyclic triaxial test, indicating that the use of this method may not be limited to low volume roads, but could also be applied to roads serving high traffic volumes.

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