Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 12, No. 03, March, 2026

Assessment of Soil Resilient Modulus Under Cyclic Loading Using Cyclic CBR Test Equipment

Lenka Ševelová [1], Aleš Florian [2*], Jaroslav Žák [2]

[1] Department of Landscape Management, Faculty of Forestry and Wood Technology, Mendel University in Brno, Brno 61300, Czech Republic.

[2] Department of Civil Engineering, Institute of Technology and Business in České Budějovice, Ceske Budejovice 370 01, Czech Republic.

Received 06 August 2025; Revised 17 February 2026; Accepted 21 February 2026; Published 01 March 2026

Abstract

Soil materials and road pavement construction materials are subjected to dynamic and repetitive loading of different intensity from vehicle traffic. To account for the cyclic nature of material loading and its non-linear behavior, the concept of the resilient modulus has been adopted. It is a fundamental property of unbound pavement materials, as it quantifies the stiffness of the material under repeated loading. Its real value depends on the actual material parameters—e.g., maximum dry density, moisture content, compaction method, and the number and magnitude of repeated loads—and on the state of stress of the actual pavement structure. The resilient modulus value is therefore not constant for a given material type but varies over a certain interval depending on the above-mentioned parameters and the actual test conditions. Therefore, the method of determining the resilient modulus must take into account all the above factors. The standard method for resilient modulus determination is the cyclic triaxial test, but the cyclic CBR test procedure is also used. It uses standard California Bearing Ratio (CBR) test equipment, and thus it is a very simple and very economical testing method. In the presented paper, the influence of loading force and number of loading cycles on the deformation characteristic and resilient modulus of the analyzed soil is investigated. A total of 72 soil specimens are tested at two different levels of loading force and six different numbers of loading cycles. The obtained results confirm that the resilience modulus increases with increasing loading force value and with increasing number of loading cycles. For the soil analyzed, the resilient modulus ranges in the interval 31-83 MPa.

Keywords: Low Volume Road; Pavement; Resilient Modulus; Cyclic CBR; Repeated CBR; Subgrade; Subsoil; Triaxial; Forest; Rural.

1. Introduction

Low-traffic roads are mainly used in rural and forest areas with lower demand for transportation and therefore lower traffic intensity. These roads generally connect remote sparsely populated communities with centers to ensure their accessibility for economic, social, recreational, educational, and safety reasons [1]. Although traffic on these roads may be limited, they are important from a socioeconomic perspective and must therefore meet certain technical requirements. When designing pavement layers, special attention must be paid to natural conditions. These roads often wind through terrain with unfavorable water conditions, low load-bearing capacity, or high longitudinal slopes, which accelerate pavement degradation [2]. Natural materials are preferred for the construction of all pavement layers, including the surface layer. The reasons for this are the availability of local materials and economic and environmental considerations. The use of local materials reduces the need for transportation and thus helps to protect adjacent ecosystems [3]. In recent years, recycled materials have also been used, reducing the need for natural, non-renewable materials.

* Corresponding author: ales.florian@seznam.cz

https://doi.org/10.28991/CEJ-2026-012-03-012

Although low-traffic roads in the Czech Republic belong to the lowest category of roads, they must still meet the load-bearing capacity requirements according to standard TP 170 [4] and the methodology for designing low-traffic roads [5]. The most important non-European regulation for road pavement design is the methodology of the American Association of State Highway and Transportation Officials (AASHTO), which is mechanistic-empirical [6]. Pavement design is based on knowledge of the resilient modulus M_r, which is a fundamental property of unbound pavement materials, such as granular bases and subgrades. It quantifies the stiffness of the material under repeated traffic loading conditions. When a car drives over a road, the road pavement is subjected to short-term stress as the weight of compresses the pavement material. However, the pavement does not remain compressed forever. To a certain extent, it returns to its original shape. This ability to recover some of the deformation after each loading cycle is called resilience, and the modulus that measures stiffness, reflects how well the material achieves this recovery. The resilient modulus is also important because it allows predicting the pavement performance. A material with a high resilient modulus indicates a stiffer and more resistant pavement structure. This means a lower probability of permanent deformation, cracking, and overall pavement damage under repeated traffic loads. Conversely, a low resilient modulus means a more flexible material that may be vulnerable to excessive deformation and rutting.

The AASHTO manual categorizes pavement design into three levels based on the average daily intensity of heavy vehicles during the design period and defines the method for calculating the resilient modulus. For the first design level, where high traffic loads are expected, the resilient modulus is determined by the cyclic triaxial test [7]. For the second and third design levels, where the maximum daily traffic volume is 400 heavy vehicles, this test is not recommended due to its complexity. It is possible to replace resilient modulus with so-called design modulus, which is determined using other soil characteristics, e.g., the California Bearing Ratio (CBR) test [8]. However, the pavement layer design based on CBR has gradually become insufficient, even for the third design level. The reason is that it does not describe the material's real deformation behavior, does not allow the use of new materials or the assessment of layer thickness, and also does not allow the use of numerical analyses that would minimize the consumption of natural, non-renewable resources of materials [9, 10]. In addition, the use of conversions between CBR and the design modulus causes inaccuracies in road pavement design [11]. It is therefore strongly recommended to replace these conversions with the resilient modulus or its estimate based on laboratory cyclic tests.

In response to the global trend of designing road pavements for sustainable development and the conservation of non-renewable resources, the cyclic CBR test procedure has been proposed for estimating the resilient modulus using standard California Bearing Ratio (CBR) testing equipment. Compared to the traditional CBR test, cyclic loading is used. Repeated loadings on the specimen simulate the effect of moving vehicles (see Figure 1). At the same time, the above procedure allows irreversible plastic deformations to be separated from reversible elastic deformations, which enables the calculation of the resilient modulus.

In recent years, the cyclic CBR test has been tested and used in many countries – e.g., the Netherlands [12], Poland [13, 14], the Czech Republic [15, 16], Colombia [17, 18], Iraq [19], Iran [20], Hungary [21], the USA [22], Australia [23, 24], Morocco [25], Indonesia [26], India [27, 28], and Canada [29]. The cyclic CBR test was used to evaluate, e.g., the influence of fines content on the subgrade mechanical properties [19], the impact of reinforcing the sand on its mechanical response [20], the influence of using hydraulic binders on the load-bearing capacity [21], the effect of moisture content on the pavement rutting [22], or to compare mechanical properties of marginal material to high-quality ones [23].

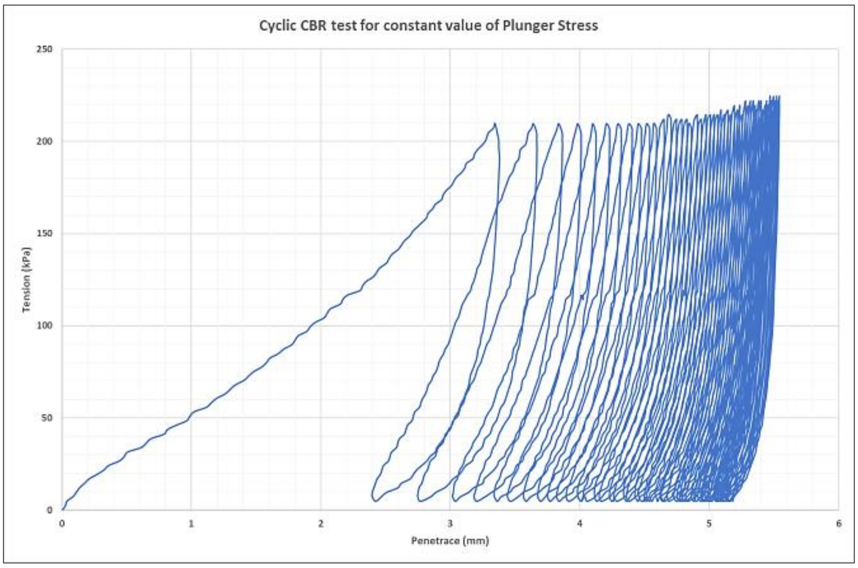


Figure 1. Cyclic loading, plunger penetration in individual loading cycles

The cyclic CBR test uses standard CBR equipment in accordance with applicable technical standards for specimen preparation [30] and for performing the CBR test [8], i.e., penetration at a standard speed of 1.27 mm/min, a penetration depth of 2.54 mm, and a plunger with a diameter of 50 mm. The value of the force acting on the specimen, and thus also the value of the plunger stress, is determined primarily in the first loading step, when the specimen is loaded to a penetration depth of 2.54 mm and then unloaded. In the subsequent loading steps, cyclic loading is performed with the force value set to the value reached in the initial step. The cyclic CBR test equipment and the tested material specimen after finishing the cyclic loading are shown in Figure 2.

Figure 2. Cyclic CBR test equipment and the tested material specimen

The problem with this procedure is that the force value determined in this way varies depending on the type of material [15]. As a result, the resilient moduli are determined at different plunger stress values, which make it impossible to compare them because they were determined under different stress conditions. In addition, the plunger stress often exceeds the load-bearing capacity of the material. According to Terzaghi's classical theory, the maximum soil load-bearing capacity is assumed to be between 150 and 650 kPa [31], depending on the type of soil [11]. For many materials, the resilient modulus is therefore determined on a damaged specimen. The reason why the specimen can withstand such high stress value is that it is unrealistically placed in the CBR mold. The specimen is confined by a steel ring with high stiffness, allowing it to withstand stress values significantly exceeding its load-bearing capacity.

The first paper dealing with this issue [15] measured and analyzed the effect of plunger stress on the calculated resilient modulus. Based on this, the authors modified the original CBR test procedure so that tests could be performed on undamaged material specimens under stress conditions corresponding to those expected in real pavement structure [16]. For cyclic loadings, the applied load force is not determined by the plunger penetration to a specified depth in the first loading step, but rather by the expected stress value in the actual real pavement structure. The applied load force therefore does not depend on the depth of penetration, but rather on the plunger stress value. It should be noted that the tested material may occur in different layers of the pavement structure and may therefore be exposed to different stress conditions. Consequently, the same material should be tested under different stress conditions depending on its placement depth, as the plunger stress value may vary and consequently affect the calculated value of the resilient modulus.

The present study analyzes the influence of the magnitude of the applied load and the number of repetitions of this load on the deformation behavior and the resilient modulus of soils. The magnitude of the load simulates both the possible influence of the weight of passing vehicles and the influence of the thickness of the road pavement structure, since the thinner it is, the greater the stress acting on the material. The influence of the number of repetitions then simulates the intensity of traffic. A cyclic CBR test is used to determine the influence of the above-mentioned variables. A total of 72 material specimens are tested and statistically analyzed, taking into account two load force magnitudes and six different numbers of load repetitions.

2. Materials and Methods

2.1. Cyclic CBR Test

The updated version of the cyclic CBR test [16] was used in the presented study with a standard loading speed of 1.27 mm/min and a 50 mm diameter plunger. The loading force applied for cyclic loading was determined based on the stress value expected in a real pavement structure. Stress values of 210 and 450 kPa were set for plunger stress analysis. These two selected stress levels correspond to the expected stress acting on the soil in two standard forest road structures [5] loaded with the design axle load of 100 kN [4]. The stress values were obtained by calculation using the finite element method. The number of loading cycles under which the deformation behavior and resilient modulus were studied was set to 50, 100, 150, 200, 250, and 300.

To calculate resilient modulus, the following equation was used [12, 16]:

$$M_r = \frac{C_1(1-\mu^{C_2})\sigma_0 a}{w^{C_3}} \tag{1}$$

where: M_r = resilient modulus of the material tested (MPa), w = elastic deformation (mm), a = radius of the circular plunger (mm), σ_0 = stress under the plunger (kPa), μ = Poisson's ratio of the material tested, C_1 = 1.5865, C_2 = 1.0875, C_3 = 1.0920.

2.2. Study Area, Soil Sampling, and Specimen Preparation

The soil sample for testing was collected at a depth of 500 mm over an area of 2 m². The surface of the area was first cleaned of all remains of original vegetation, roots, and other biological material to ensure that the tested material would be uncontaminated. After performing a geotechnical analysis of the sampled soil, the material was divided into 12 individual soil batches. Each batch was then used for a specific combination of plunger stress and number of loading cycles. Six batches were used for a plunger stress of 210 kPa, and six batches were used for a plunger stress of 450 kPa.

Six specimens were prepared from each batch. A total of 36 specimens were prepared for individual plunger stress analysis and a total of 72 specimens were prepared for the deformation behavior and the resilient modulus analysis performed by the cyclic CBR test. Deformation is understood as the depth of plunger penetration into the material after completion of the entire cyclic loading procedure. Deformation is therefore equal to the magnitude of irreversible plastic deformation.

The specimens were adjusted to optimum moisture content and maximum dry density in accordance with standard CSN EN ISO 17892-1 [32]. They were prepared in a standard manner in a CBR mold with a diameter of 152 × 117 mm, using Proctor standard energy in accordance with standard CSN EN ISO 13286-2 [30]. The material was compacted with a 2.5 kg mortar in three layers, with a total of 56 strokes in each layer.

2.3. Geotechnical Analysis

Geotechnical tests necessary for soil classification according to relevant European standards (EN standards) were performed before dividing the soil sample into individual batches. These tests include a moisture test according to standard CSN EN ISO 17892-1 [32], a sieving and aerometry test according to standard CSN EN ISO 17892-4 [33], and a consistency (plastic-liquid limit) test or Atterberg limit test according to standard CSN EN ISO 17892-12 [34]. These tests were used for the basic classification of soil based on its granulometric composition and Atterberg plastic-liquid limits. The soil was classified according to the Unified Soil Classification System (USCS) using standards CSN EN ISO 14689-1 [35] and CSN EN ISO 14688-2 [36].

2.4. Statistical Analysis

A total of 72 specimens from 12 batches were tested to obtain deformation and resilient modulus values. Each set of six values from each soil batch was statistically analyzed. The following statistics were calculated for each data set: mean value (MEAN), coefficient of variation (COV), minimum (MIN) and maximum (MAX) values, and 0.05 and 0.95 quantiles [16].

3. Results and Discussion

3.1. Geotechnical Analysis

Geotechnical test were performed on the soil sample taken from the analyzed area. Based on the results obtained, the soil was classified as SiCL soil according to the USCS system, see Figure 3. The optimum moisture content and dry density were 18.95 % respectively 1625 kg/m^3, see Figure 4.

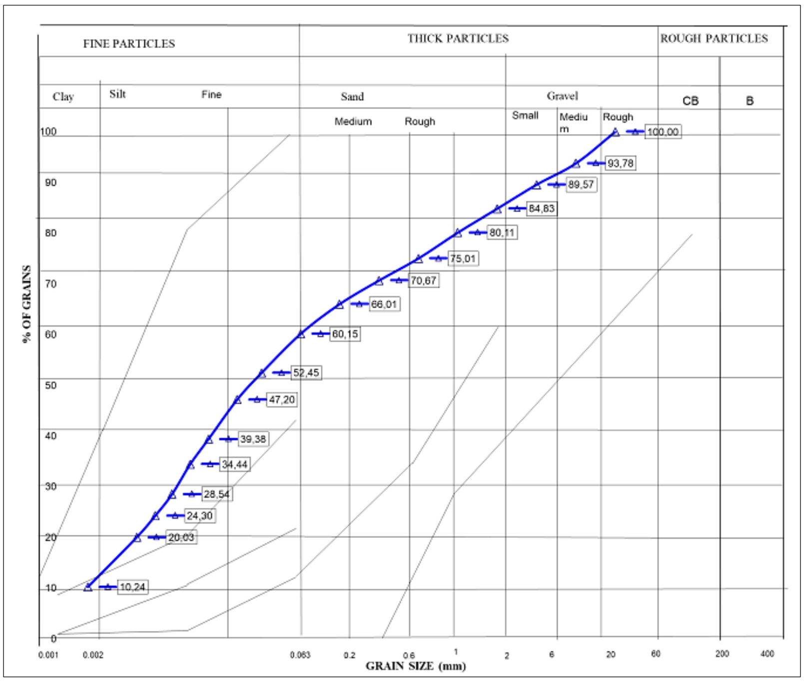


Figure 3. Grain size distribution of analyzed soil

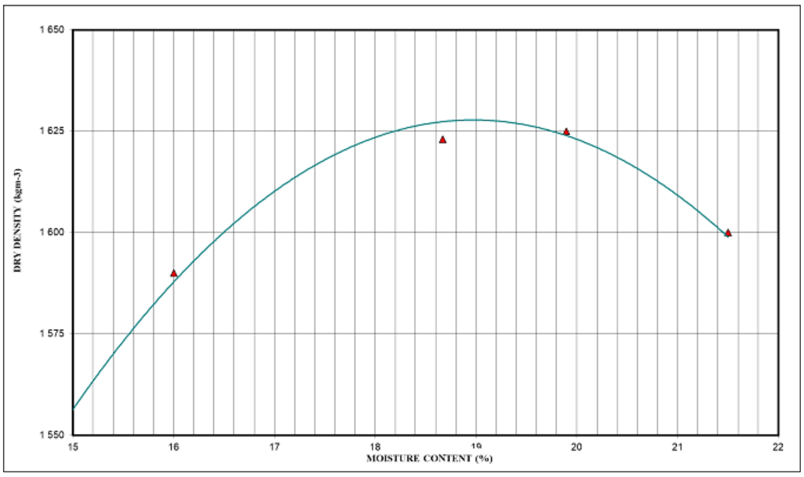


Figure 4. Optimum moisture content and dry density of analyzed soil

3.2. Deformation Analysis

The results of the deformation analysis are presented in Table 1 and Figure 5. Table 1 summarizes the statistical analysis results of plunger penetration for each plunger stress level and number of loading cycles. Figure 5 illustrates the relationship between plunger penetration and the number of loading cycles applied to the specimen for both plunger stress values. The mean values, as well as the 0.05 and 0.95 quantiles, are plotted. The area between the two quantile lines represents the penetration values that can be expected with a probability of 90%.

It can be observed that deformation—specifically irreversible plastic deformation—increases with both increasing plunger stress and a higher number of loading cycles. This observation aligns with theoretical expectations, as a greater loading force and/or a larger number of loading cycles results in higher penetration energy and therefore deeper plunger penetration into the soil. At a plunger stress of 210 kPa, irreversible plastic deformation begins at a mean value of 2.67 mm for 50 loading cycles and gradually increases to 6.68 mm for 300 loading cycles. At a plunger stress of 450 kPa, irreversible plastic deformation starts at a mean value of 12.70 mm for 50 loading cycles and increases continuously to 17.94 mm for 300 loading cycles.

As shown, although increasing the plunger stress from 210 kPa to 450 kPa represents an increase of approximately 2.14 times, the resulting deformation increases by about 4.76 times for the first 50 loading cycles and about 2.69 times for 300 loading cycles. This finding is also consistent with general observations of road usage, where heavier vehicles cause significantly greater pavement damage than lighter ones, and the level of damage is not a linear function of axle load but rather a strongly nonlinear one.

When comparing the coefficient of variation for both plunger stress values, we can observe different trends. At a plunger stress of 210 kPa, the coefficient of variation gradually decreases from a value of 0.28 for 50 loading cycles to a value of 0.15 for 300 loading cycles. This can be explained as a result of improved stiffness homogeneity due to material compaction by a larger number of loading cycles. The smaller stiffness variability leads to smaller deformation variability. At a plunger stress of 450 kPa, the coefficient of variation ranges from a value of 0.15 to a value of 0.18 with very weak dependence on the number of loading cycles. This can be explained by the better ability of a larger loading force to provide better homogeneity of stiffness even with a smaller number of loading cycles compared to a smaller loading force.

Table 1. Results of deformation analysis, plunger stress 210 kPa and 450 kPa, different number of loading cycles

Plunger stress	**210 kPa**						**450 kPa**					
Loading cycles	**50**	**100**	**150**	**200**	**250**	**300**	**50**	**100**	**150**	**200**	**250**	**300**
MEAN mm	2.67	3.67	4.56	5.43	6.13	6.68	12.70	14.67	15.90	16.88	17.96	18.87
COV	0.28	0.23	0.20	0.19	0.16	0.15	0.18	0.18	0.16	0.17	0.16	0.15
MIN mm	1.87	2.61	3.35	3.98	4.77	5.29	9.78	10.93	12.04	12.63	13.59	14.47
MAX mm	4.01	5.17	6.09	6.94	7.49	7.97	14.96	18.15	19.32	20.17	21.15	22.29
0.05 mm	1.43	2.26	3.05	3.71	4.47	5.05	9.25	10.22	11.58	12.26	13.18	14.06
0.95 mm	3.90	5.09	6.08	7.15	7.79	8.30	16.15	19.12	20.21	21.51	22.71	23.67

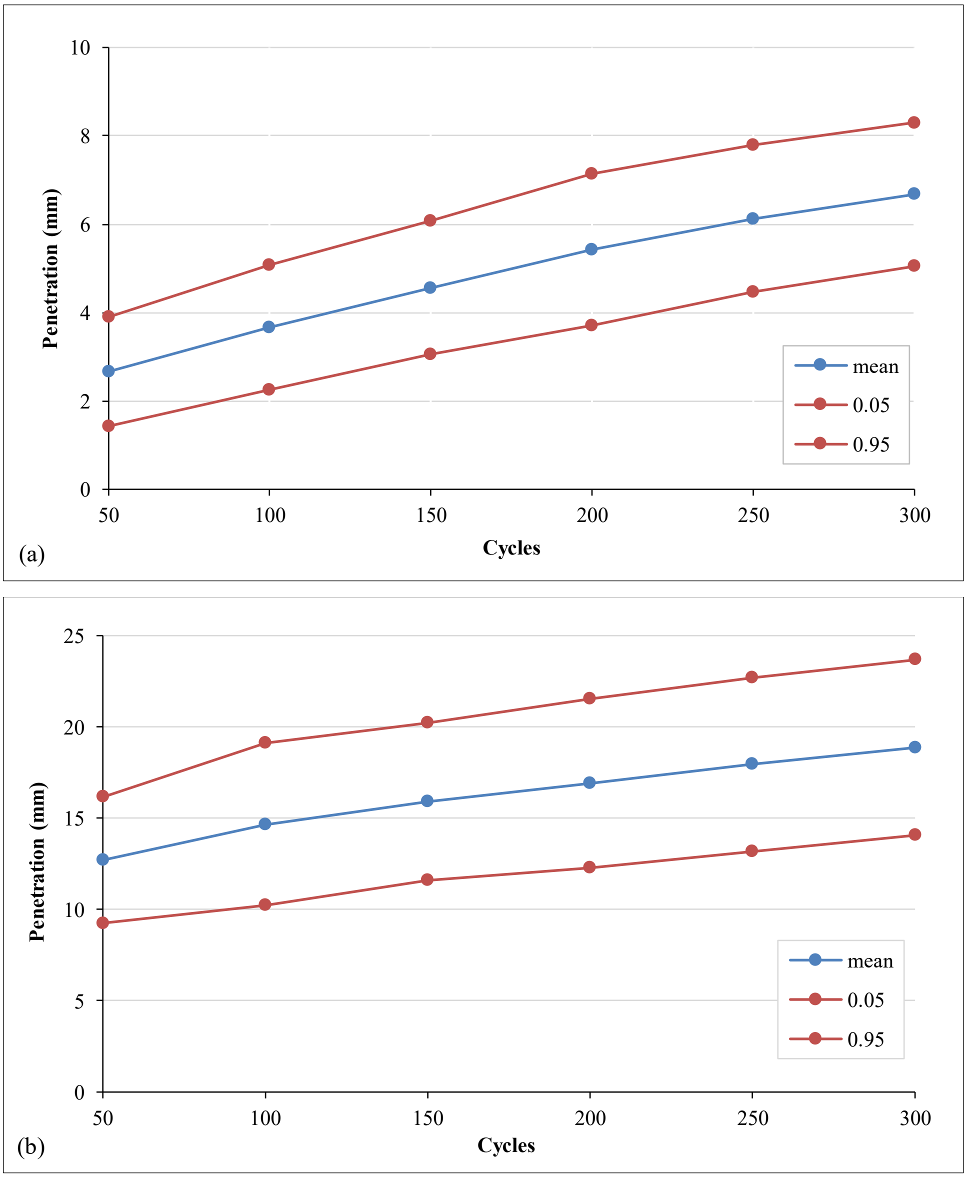


Figure 5. Plunger penetration dependence on the number of loading cycles, plunger stress (a) 210 kPa and (b) 450 kPa

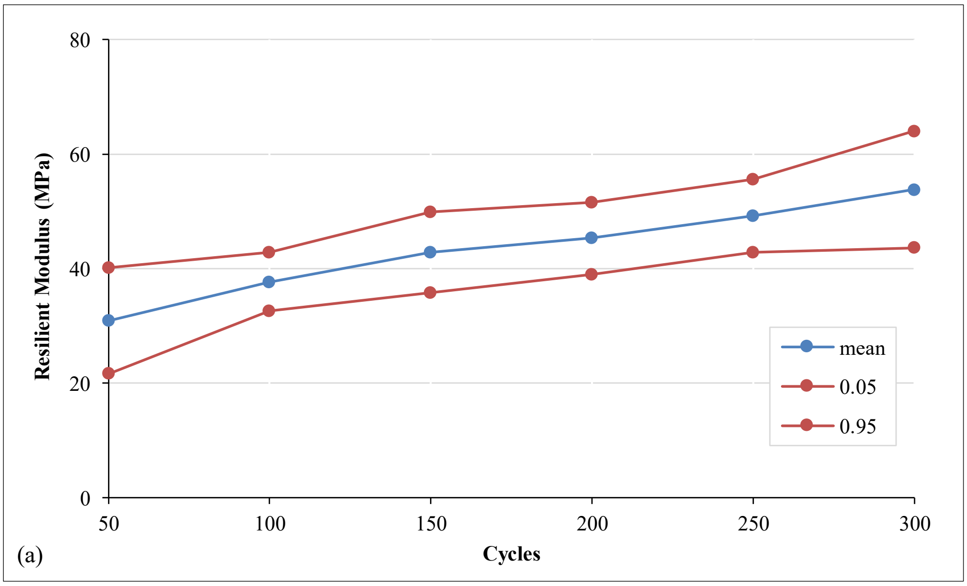
It should also be noted that the deformation increments for every 50 loading cycles gradually slow down during the loading process. For example, for the first 50 cycles, the deformation increment is 2.67 mm; for the second 50 cycles, it is 1.00 mm, etc.; and for the last 50 cycles, the deformation increment is 0.55 mm for a plunger stress of 210 kPa. The same can be observed for a plunger stress of 450 kPa: for the first 50 cycles, the deformation increment is 12.70 mm; for the second 50 cycles, it is 1.97 mm, etc.; and for the last 50 cycles, the deformation increment is 1.06 mm. In fact, in all cases the dominant increment of irreversible plastic deformation—plunger penetration depth—is achieved in the first few loading cycles at the beginning of the loading process; see Figure 1. This finding can also be explained because during the cycling process, the material is more and more compacted, and thereby further irreversible plastic deformations are slowing down. As a result, the increase in deformation for any number of subsequent loading cycles is also slowed down.

3.3. Resilient Modulus Analysis

The results of the resilient modulus analysis are shown in Table 2 and Figure 6. Table 2 shows the results of the statistical analysis of the resilient modulus for each plunger stress value and each number of loading cycles. Figure 6 shows the dependence of the resilient modulus on the number of loading cycles applied to the specimen for both plunger stress values. The mean values and 0.05 and 0.95 quantiles are plotted. The area between the two quantile lines indicates the resilient modulus values that can be expected with a probability of 90%. It can be seen that the resilient modulus increases with increasing plunger stress value and also with increasing number of loading cycles. This is in accordance with theoretical expectations, because a greater loading force and/or a greater number of loading cycles lead to higher compaction energy and thus to larger soil stiffness. And greater soil stiffness means a greater resilient modulus value. At a plunger stress of 210 kPa, the resilient modulus value for 50 loading cycles starts at 30.88 MPa and continuously increases to 53.82 MPa for 300 loading cycles. The rate of change in modulus per cycle range of 50–150 loading cycles is approximately 1.39; for the cycle range of 150–300 loading cycles, it is approximately 1.26. At a plunger stress of 450 kPa, the resilient modulus value for 50 loading cycles starts at 61.44 MPa and continuously increases to 82.67 MPa for 250 loading cycles, but then decreases to 79.92 MPa for 300 loading cycles. The rate of change in modulus per cycle range of 50–150 loading cycles is approximately 1.20; for the cycle range of 150–300 loading cycles, it is approximately 1.08. As can be seen, although the increase in plunger stress from 210 kPa to 450 kPa is approximately 2.14, the increase in the modulus value is approximately 1.99 for 50 loading cycles and approximately 1.48 for 300 loading cycles. This finding can be related to the generally accepted fact that compaction of unbound materials with heavy compaction machines or with higher compaction energy does not generally ensure sufficiently better compaction of the material and, therefore, better soil stiffness.

Table 2. Results of resilient modulus analysis, plunger stress 210 kPa and 450 kPa, different number of loading cycles

Plunger stress	210 kPa						450 kPa					
Loading cycles	50	100	150	200	250	300	50	100	150	200	250	300
MEAN MPa	30.88	37.69	42.79	45.27	49.16	53.82	61.44	67.66	73.82	78.65	82.67	79.92
COV	0.18	0.08	0.10	0.08	0.08	0.12	0.26	0.24	0.22	0.19	0.19	0.19
MIN MPa	21.15	33.54	37.65	41.00	42.13	43.85	43.66	46.01	54.53	57.60	62.54	61.43
MAX MPa	38.55	40.75	48.68	49.42	53.82	61.15	82.72	88.71	96.26	97.49	103.74	98.11
0.05 MPa	21.61	32.52	35.72	38.99	42.79	43.59	34.73	41.02	47.35	53.84	56.95	55.17
0.95 MPa	40.15	42.85	49.85	51.55	55.53	64.05	88.15	94.31	100.30	103.46	108.39	104.68



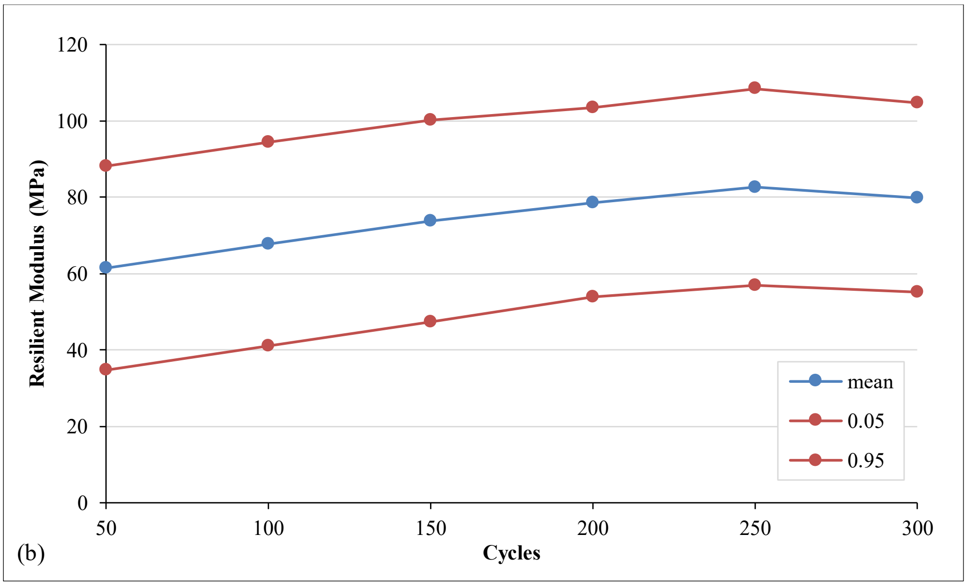


Figure 6. Resilient modulus dependence on the number of loading cycles, plunger stress (a) 210 kPa and (b) 450 kPa

When comparing the coefficient of variation for both plunger stress values, different trends can be observed. For a plunger stress of 210 kPa, the coefficient of variation is approximately 0.18 for 50 loading cycles, then decreases to 0.10–0.08 for 100–250 loading cycles, and increases again to 0.12 for 300 loading cycles. The larger variability for 50 cycles can be explained by the lower level of compaction due to the lower plunger stress and the smaller number of loading cycles. As a result, the elastic deformation from which the modulus is calculated may show greater variability, leading to larger variations in the modulus values.

The increase in variability for 300 loading cycles is likely related to the results obtained for a plunger stress of 450 kPa. As shown, the coefficient of variation decreases from 0.26 for 50 loading cycles to 0.19 for 200 cycles and remains at a similar level thereafter. As previously mentioned, for 300 loading cycles the resilient modulus decreases compared with the value for 250 loading cycles. This can be explained by "over-compaction" caused by the combination of higher compaction stress and a larger number of loading cycles. This may also explain why the coefficient of variation for a plunger stress of 210 kPa and 300 loading cycles shows greater variability compared with cases involving fewer loading cycles.

Finally, the results obtained in the present study can be compared with those from a previous study [16]. In that study, a total of 18 material specimens from three soil samples classified as SiCL soil were tested under a plunger stress of 210 kPa using 50 loading cycles. The mean value of the resilient modulus was 28.2 MPa. In the present study, the corresponding mean value is 30.9 MPa, indicating very good agreement. Comparison with other studies is not possible because they were conducted under different loading force magnitudes and numbers of loading cycles.

4. Conclusion

Soil materials and road pavement construction materials are subjected to dynamic and repeated loads of varying intensity caused by vehicle traffic. To account for the cyclic nature of material loading and its nonlinear behavior, the concept of the resilient modulus has been adopted. Its actual value is related to the repeated loading process and depends on the material parameters—such as dry density, moisture content, compaction method, and the number and magnitude of repeated loads—as well as the stress state within the pavement structure. Therefore, the resilient modulus is not a constant value for a given material type but varies within a certain range depending on these parameters and the specific testing conditions. Consequently, the method used to determine the resilient modulus must consider all of these factors.

Although the cyclic triaxial test meets all the requirements for determining the resilient modulus, alternative methods are being explored due to its complexity and high cost. One promising approach is the cyclic CBR test, in which repeated loading is applied to a material specimen that can be prepared and tested under various conditions. However, it is important that the plunger stress applied to the specimen has realistic values; only in this case can the resilient modulus obtained be comparable with values derived from the cyclic triaxial test. This study confirmed that the method is capable of determining deformation characteristics and the resilient modulus at different load levels and numbers of loading cycles. The results demonstrate that both the resilient modulus and deformation characteristics are not constant for a given material but vary within a certain interval. Furthermore, the capabilities of the cyclic CBR test appear to correspond closely with results obtained from cyclic triaxial testing. Therefore, it may be suggested that the application of this method should not be limited to low-traffic roads but could also be extended to roads designed for higher traffic volumes. In such cases, future studies would need to calibrate cyclic CBR test results with data obtained from cyclic triaxial tests.

5. Declarations

5.1. Author Contributions

Conceptualization, A.F., and L.Š.; methodology, L.Š.; software, A.F. and L.Š.; validation, A.F. and J.Ž.; formal analysis, J.Ž.; investigation, L.Š.; resources, J.Ž.; data curation, L.Š. and J.Ž.; writing—original draft preparation, A.F.; writing—review and editing, A.F.; visualization, A.F. and L.Š.; supervision, J.Ž. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

6. References

[1] Heinimann, E. H. R. (2021). Pavement engineering for forest roads: Development and opportunities. Croatian Journal of Forest Engineering, 42(1), 91–106. doi:10.5552/crojfe.2021.860.

[2] Ševelová, L., Florian, A., & Hrůza, P. (2020). Using Resilient Modulus to Determine the Subgrade Suitability for Forest Road Construction. Forests, 11(11), 1208. https://doi.org/10.3390/f11111208

[3] Ševelová, L., Arias, P. F., & Šlezingr, M. (2020). Influence of improving materials of forest roads on the surrounding environment. Polish Journal of Environmental Studies, 29(5), 3821–3830. doi:10.15244/pjoes/115272.

[4] Ministry of Transport of the Czech Republic. (2023). TP 170: Design of pavement structures. Prague, Czech Republic.

[5] Hauser, J., Ševelová, L., Matula, R., & Zedník, P. (2018). Optimization of low volume road pavement design and construction. Journal of Forest Science, 64(2), 74–85. doi:10.17221/109/2017-jfs.

[6] American Association of State Highway and Transportation Officials (AASHTO). (2008). Mechanistic–empirical pavement design guide (MEPDG). AASHTO, Washington, DC, USA.

[7] Czech Office for Standards, Metrology and Testing. (2004). ČSN EN ISO 13286-7: Unbound and hydraulically bound mixtures—Part 7: Cyclic load triaxial test for unbound mixtures. Prague, Czech Republic.

[8] Czech Office for Standards, Metrology and Testing. (2015). ČSN EN ISO 13286-47: Unbound and hydraulically bound mixtures—Part 47: Test method for the determination of California bearing ratio, immediate bearing index and linear swelling. Prague, Czech Republic.

[9] Rahim, A. M. (2005). Subgrade soil index properties to estimate resilient modulus for pavement design. International Journal of Pavement Engineering, 6(3), 163–169. doi:10.1080/10298430500140891.

[10] Nguyen, B. T., & Mohajerani, A. (2016). Resilient modulus of fine-grained soil and a simple testing and calculation method for determining an average resilient modulus value for pavement design. Transportation Geotechnics, 7, 59–70. doi:10.1016/j.trgeo.2016.05.001.

[11] Park, T., & Lovell, C. (1996). Using Pyrolized Carbon Black (PCB) from Waste Tires in Asphalt Pavement (Part 1, Limestone Aggregate). Purdue University. doi:10.5703/1288284313345.

[12] Molenaar, A.A.A. (2008). Repeated Load CBR Testing, a Simple but Effective Tool for the Characterization of Fine Soils and Unbound Materials; Delft University of Technology: Delft, The Netherlands.

[13] Sas, W., Głuchowski, A., & Miturski, M. (2017). Studies on resilient modulus value from cyclic loading tests for cohesive soil. Annals of Warsaw University of Life Sciences – SGGW. Land Reclamation, 49(2), 117–127. doi:10.1515/sggw-2017-0010.

[14] Głuchowski, A., Nagy, A. C., & Sas, W. (2025). Evaluation of Cyclic CBR Test for Soils Reinforced with Geosynthetics. Springer Proceedings in Materials, 93, 157–164. doi:10.1007/978-3-032-02849-5_16.

[15] Ševelová, L., Florian, A., & Žák, J. (2021). Influence of plunger stress on resilient modulus of forest subgrade soils obtained from cyclic CBR test. Forests, 12(11), 1456. doi:10.3390/f12111456.

[16] Florian, A., Ševelová, L., Žáková, K., & Žák, J. (2023). An Updated Cyclic CBR Test with Realistic Stress Values under the Plunger for Resilient Modulus Calculation. Forests, 14(12), 2425. doi:10.3390/f14122425.

[17] Rincón-Morantes, J. F., Alvarez, A. E., & Reyes-Ortiz, O. J. (2022). Estimación de la rigidez de materiales granulares marginales no ligados mediante ensayo CBR dinámico. Ingeniería y Desarrollo, 40(01), 92–113. doi:10.14482/inde.40.01.621.992.

[18] Bojacá Torres, D. C., & Campagnoli Martínez, S. X. (2022). CBR cíclico como método alternativo para la determinación del módulo resiliente en suelos blandos de subrasante. Ciencia e Ingeniería Neogranadina, 32(2), 85–98. doi:10.18359/rcin.5896.

[19] Abid, A. N., Salih, A. O., & Nawaf, E. A. (2017). The Influence of Fines Content on the Mechanical Properties of Aggregate Subbase Course Material for Highway Construction using Repeated Load CBR Test. Al-Nahrain Journal for Engineering Sciences, 20(3), 615-624.

[20] Mehrpazhouh, A., Moghadas Tafreshi, S. N., & Mirzababaei, M. (2019). Impact of repeated loading on mechanical response of a reinforced sand. Journal of Rock Mechanics and Geotechnical Engineering, 11(4), 804–814. doi:10.1016/j.jrmge.2018.12.013.

[21] Primusz, P., Kisfaludi, B., & Péterfalvi, J. (2023). Using Cyclic CBR Method to Determine Resilient Modulus of Hydraulic Binder Stabilised Road Pavement Base Layers. Croatian Journal of Forest Engineering, 45(1), 125–138. doi:10.5552/crojfe.2024.2214.

[22] Rahman, M. M., Gassman, S. L., & Islam, K. M. (2023). Effect of Moisture Content on Subgrade Soils Resilient Modulus for Predicting Pavement Rutting. Geosciences (Switzerland), 13(4), 103. doi:10.3390/geosciences13040103.

[23] Haghighi, H., Arulrajah, A., Mohammadinia, A., & Horpibulsuk, S. (2018). A new approach for determining resilient moduli of marginal pavement base materials using the staged repeated load CBR test method. Road Materials and Pavement Design, 19(8), 1848–1867. doi:10.1080/14680629.2017.1352532.

[24] Carlos, D. M., Macedo, J., & Pinho-Lopes, M. (2025). Natural Reinforcement of a Fine Soil for Unpaved Forest Roads—Cyclic CBR Tests. Lecture Notes in Civil Engineering, 408 LNCE, 155–164. doi:10.1007/978-981-97-8237-6_16.

[25] Salmi, A., Bousshine, L., & Lahlou, K. (2020). A new model of equivalent modulus derived from repeated load CBR test. International Journal of Engineering, Transactions A: Basics, 33(7), 1321–1330. doi:10.5829/ije.2020.33.07a.19.

[26] Arrazi, S., Nurtjahjaningtyas, I., & Wicaksono, L. A. (2025). The Effect of Cyclic Loading on Lime Stabilised Soil to CBR Values. Media Komunikasi Teknik Sipil, 31(1), 98–105. doi:10.14710/mkts.v31i1.71273.

[27] Narzary, B. K., & Narzary, J. (2025). Estimating Resilient Modulus of Fine-Grained Subgrade Soil from Repeated Load CBR Test. Transportation Infrastructure Geotechnology, 12(5). doi:10.1007/s40515-025-00587-8.

[28] Kaushik, S., Kumar, S., & Siddagangaiah, A. K. (2024). Experimental and numerical based model formulation for estimation of subgrade resilient modulus using the repeated load CBR test considering in situ state of stress. Transportation Geotechnics, 48. doi:10.1016/j.trgeo.2024.101331.

[29] Hao, S., & Pabst, T. (2021). Estimation of resilient behavior of crushed waste rocks using repeated load CBR tests. Transportation Geotechnics, 28. doi:10.1016/j.trgeo.2021.100525.

[30] Czech Office for Standards, Metrology and Testing. (2015). ČSN EN ISO 13286-2: Unbound and hydraulically bound mixtures—Part 2: Test methods for the determination of the laboratory reference density and water content—Proctor compaction. Prague, Czech Republic.

[31] Hauser, J., Kozumplikova, A., & Sevelova, L. (2013). The Influence of the Soil Treatment on CBR Test Values. Proceedings of the Int. Conf. on Ground Improvement and Ground Control: Transport Infrastructure Development and Natural Hazards Mitigation-ICGI 2012, 1623–1629. doi:10.3850/978-981-07-3560-9_09-0916.

[32] Czech Office for Standards, Metrology and Testing. (2015). ČSN EN ISO 17892-1: Geotechnical investigation and testing—Laboratory testing of soil—Part 1: Determination of water content. Prague, Czech Republic.

[33] Czech Office for Standards, Metrology and Testing. (2017). ČSN EN ISO 17892-4: Geotechnical investigation and testing—Laboratory testing of soil—Part 4: Determination of particle size distribution. Prague, Czech Republic.

[34] Czech Office for Standards, Metrology and Testing. (2018). ČSN EN ISO 17892-12: Geotechnical investigation and testing—Laboratory testing of soil—Part 12: Determination of the liquid and plastic limits. Prague, Czech Republic.

[35] Czech Office for Standards, Metrology and Testing. (2004). ČSN EN ISO 14689-1: Geotechnical investigation and testing—Identification and classification of rock—Part 1: Identification and description. Prague, Czech Republic.

[36] Czech Office for Standards, Metrology and Testing. (2005). ČSN EN ISO 14688-2: Geotechnical investigation and testing—Identification and classification of soil—Part 2: Principles for classification. Prague, Czech Republic.