

INFLUENCE OF RESILIENT MODULUS AND SOIL SHEAR PARAMETERS ON THE DESIGN OF FOREST AND RURAL PAVEMENTS

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Abstract

The recreational and touristic potential of landscapes depends not only on their natural components, but also on the functionality and safety of the associated road infrastructure, particularly forest and rural roads. This study evaluates, from an engineering perspective, the soils and aggregates used in the structural layers of such pavements, with special emphasis on their deformational and strength properties, which are essential for proper design.

The analysis focuses on determining the resilient modulus through laboratory cyclic loading tests that realistically simulate traffic and service conditions. This parameter is considered key for assessing the bearing capacity and long-term stability of unbound granular layers. In parallel, cohesion and internal friction angle obtained from direct shear tests are analysed and incorporated into numerical modelling using the finite element method.

The results highlight the need for a combined evaluation of strength and deformational properties to ensure pavement durability, reduce structural damage, and minimize erosive processes, thereby contributing to the sustainable management of both infrastructure and landscape.

Key words: Low Volume Road; Resilient Modulus; Finite elements; Cyclic CBR; Shear Parameters.

Introduction

Low Volume Roads (LVR) play an essential role in the territorial articulation of rural and forest areas, where they form the basis of economic, social and environmental connectivity. These infrastructures provide access to agricultural and forestry operations, facilitate natural resource management and, increasingly, support recreational and tourist activities in the natural environment. Although their traffic volume is low compared to the main networks, their design cannot be considered simplified, as the geotechnical and environmental conditions in which they are located are often particularly demanding. In the context of forest and rural roads, the mechanical behaviour of the subgrade soil is of crucial importance. Unlike conventional roads, where design typically relies on more robust structures and thicker pavement layers, on LVRs structural performance depends largely on the bearing capacity and deformation response of the natural ground. In this context, the cyclic resilient modulus (MR) has established itself as a key parameter for characterising the elastic response of the soil under repeated loads, providing a more realistic representation of the service conditions to which the pavement is subjected.

However, structural analysis cannot be limited only to resilient behaviour. The soil's shear strength parameters, obtained from shear and consolidation tests, are essential for assessing the overall stability of the system, particularly in environments with significant slopes. The slope directly influences the stresses that the ground must withstand; therefore, if the soil does not have sufficient shear strength, it could collapse. This relationship makes it essential to calculate the parameters of cohesion, angle of internal friction and edometric modulus for the correct characterisation of the material and assessment of the soil's resistance to shear stresses. At the same time, only this set of parameters is sufficient for numerical and simulation analyses when using finite element method (FEM) tools (Ševelová L., Kozumplíková A. 2010)

For all these reasons, understanding the combined influence of the resilient modulus and soil shear parameters on the design of forest and rural road pavements is essential for optimising construction solutions, improving infrastructure durability, and ensuring adequate safety and service conditions, with due consideration and respect for the impacts on surrounding ecosystems (Ševelová, L., Arias, P.F., Šlezinger, M. 2020) This paper addresses precisely this interaction, proposing an integrated analysis that will enable progress towards more efficient and sustainable designs tailored to the specific characteristics of low-volume roads in rural and forest environments.

Material and methods

Both materials represent characteristic subgrade conditions in the given region for the construction of Low Volume Roads (LVR) and were therefore analysed in accordance with the criteria established by

the American Association of State Highway and Transportation Officials (AASHTO). This study therefore focuses on assessing the influence of the resilient modulus and shear parameters of these materials in the design of forest and rural road pavements.

To determine the properties of the materials used, several classification tests have been carried out in accordance with European and Czech standards. Moisture content has been determined by the moisture test (CSN EN ISO 17892-1), the particle size distribution of the material has been determined by granulometric and aerometry tests (CSN EN ISO 17892-4), and the plasticity of the soil has been determined by the Atterberg limit test (CSN EN ISO 17892-12). These tests have made it possible to classify the materials on the basis of their particle size distribution and plastic properties; these classifications have been carried out in accordance with the Unified Soil Classification System (USCS) (CSN EN ISO 14688-2). In addition, a Proctor standard test was carried out to determine the optimum moisture content and maximum dry density of the materials (CSN EN ISO 13286-2).

With regard to the mechanical behaviour of the material, the resilience modulus, which describes the soil's elastic response to repeated loads, has been determined using the cyclic California Bearing Ratio (CBR) test (Ševelová, L., Florian, A., Žák, J. 2021) (De Zarate Gorka O., Ševelová, L. 2015). This test is a variation of the standard CBR test (CSN EN ISO 13286-47), in which the strength and deformability of the soil under repeated loads are assessed. Unlike the conventional CBR, where the applied load is static, in this test the soil is subjected to cycles of loading and unloading, in this case 210 kPa, in order to simulate real traffic conditions, this CBR test is a patented methodology developed by Mendel University and is exclusively conducted in its laboratory facilities (PV 304642). In addition to the resilience modulus, this test also yields parameters such as resistance to permanent deformation or the accumulative deformation of the material.

In addition, consolidation and shear tests have been carried out on the selected materials in order to determine the cohesion, angle of internal friction and edometric modulus. To carry out these tests, the material must first be consolidated by applying a vertical load of 25 kPa, 50 kPa or 100 kPa for 1 hour and 10 minutes, and the vertical displacement data is recorded to determine the consolidation. Once the consolidation test is complete, the shear test must be carried out, in which a shear rate of 0.05 mm/min is applied to the consolidated sample until a total shear displacement of 20 mm is reached; this test provides the cohesion and internal friction angle of the material.

Results

The classification results indicate that Material 1 is a medium-plasticity clay (F6-CI) and Material 2 is a sandy clay (F3-MS), which have an optimum moisture content of 20.8% for the F6-CI material and 12.8% for the F3-MS material.

On the one hand, tests were carried out to determine the modulus of resilience (MR in MPa) and the deformations of material F3-MS under different moisture conditions, its tests were carried out at the optimum moisture content (w_{opt} in %) and another 2% higher than the optimum. The next graph (Fig. 3) shows four different results: the one labelled 'min' is the less compacted side, which has received 56 impacts, the one labelled 'max' is the more compacted side, which has received 56 impacts on three occasions and on each of these faces of the sample, 20 and 40 loading and unloading cycles were carried out. Furthermore, the moisture and MR limits of the tests carried out can also be seen; in the case of moisture content, it can be seen that this ranges from 11.09% to 16.61%, whilst the MR values range between 25 MPa and 400 MPa, indicating that although the variation in a material's moisture content is low, 5.5% in this case, the MR values can vary significantly depending on the soil moisture content.

In the next graphs, it can be observed the dependence of Resilience Modulus (MR_{max} and MR_{min}) on moisture (Fig. 4a) and dry density (Fig. 4b), of material F3-MS.

In this case, it can be seen that the Resilience Modulus decreases significantly in tests conducted at moisture contents of approximately 15% compared to those carried out at moisture contents of around 13%, indicating a loss of elastic recovery under conditions of higher moisture (Fig. 4a). The highest MR values are observed at around 12%, indicating the optimum moisture content for achieving maximum soil strength. Higher MR values are obtained on the more compacted side of the samples, but no significant differences are observed between the trends on the less and more compacted sides of the sample. In the case of tests carried out over 20 cycles, the results obtained are very similar to those in this case.

The modulus of resilience values increases as the dry density increases, with the highest MR values occurring at around 1840 kg/m³ (Fig. 4b), suggesting that this could be the optimum density at which the material exhibits the best mechanical properties.

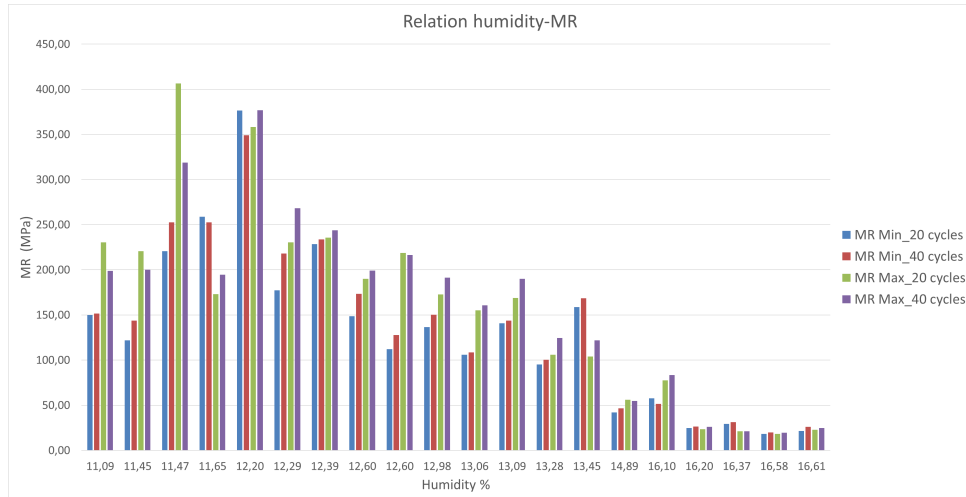


Fig. 3: Influence of humidity in MR in all cases

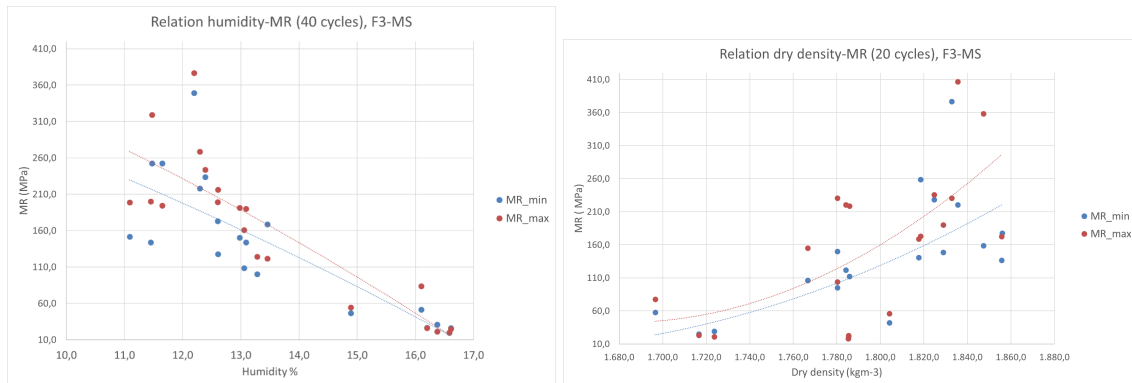


Fig. 4a: Dependence of MR on moisture after 40 cycles, b: Dependence of MR on dry density after 20 cycles

In the other hand, consolidation and shear tests were carried out to determine the cohesion (c), the angle of internal friction (ϕ) and the edometric modulus (E_{oed} in MPa) of the F6-Cl material. Firstly, the relationship between the edometric modulus and moisture content was analysed (Fig. 5), and it can be seen that it tends to decrease as moisture content increases, indicating that an increase in the material's moisture content enhances its consolidation capacity. Furthermore, a more pronounced trend is observed when greater loads are applied to the sample.

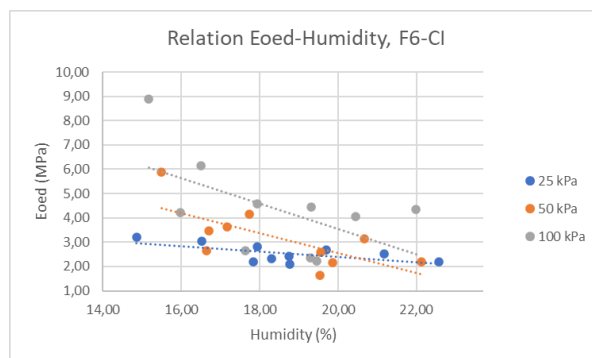


Fig. 5: Relationship between the edometric modulus and moisture content

Subsequently, the influence of moisture on the material's cohesion was analysed (Fig. 6a). It can be seen that as moisture content increases, cohesion also increases, showing an upward trend; this indicates that, in this case, an increase in the material's moisture content enhances the bonding strength between the particles.

Finally, the relationship between moisture content and the material's angle of internal friction was analysed (Fig. 6b). In this case, a clear downward trend in the values of the angle of internal friction can be observed as moisture content increases, indicating that the higher the moisture content of the material, the lower the friction between its particles.

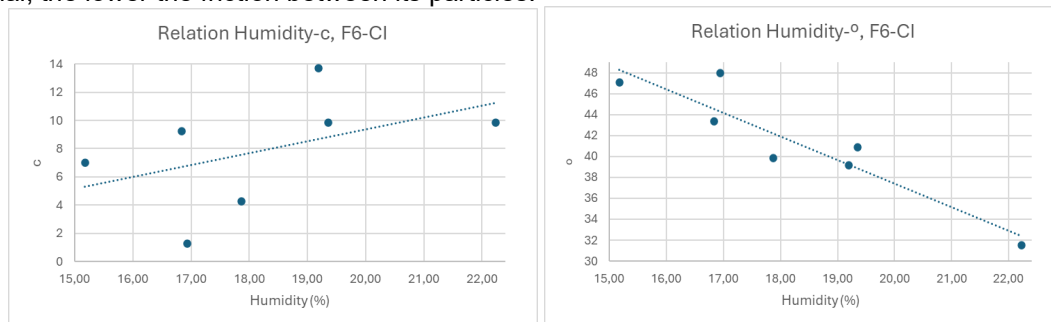


Fig. 6a: Influence of moisture on the material's cohesion, b: Relationship between moisture content and the material's angle of internal friction

Conclusion

For the design and construction of high-quality and durable Low Volume Roads (LVR), which are used not only for transportation but also for recreational and leisure activities, the use of local natural materials is appropriate. However, these materials are highly sensitive to moisture conditions and the degree of compaction, which fundamentally affects their mechanical behaviour. As demonstrated by the results of this study, all evaluated parameters—particularly the resilient modulus, the angle of internal friction, and the edometric modulus—respond to increasing moisture content with a significant decrease in their absolute values. This trend clearly indicates a reduction in the bearing capacity of the material and a deterioration of its deformation response under higher moisture conditions. Conversely, an optimal moisture regime and adequate compaction lead to improved mechanical properties and enhanced structural stability. These findings highlight that, in LVR design, it is essential to carefully consider the moisture conditions of the subgrade and ensure appropriate compaction practices in order to achieve the required durability, safety, and performance of the pavement under real service conditions.

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Souhrn

Rekreační a turistický potenciál krajiny závisí nejen na jejích přírodních složkách, ale také na funkčnosti a bezpečnosti související silniční infrastruktury, zejména lesních a venkovských komunikací. Tato studie z inženýrského hlediska hodnotí půdy a kamenivo používané ve konstrukčních vrstvách těchto vozovek, přičemž klade zvláštní důraz na jejich deformační a pevnostní vlastnosti, které jsou nezbytné pro správný návrh.

Analýza se zaměřuje na stanovení modulu pružnosti pomocí laboratorních cyklických zátěžových zkoušek, které realisticky simulují provozní a provozní podmínky. Tento parametr je považován za klíčový pro posouzení únosnosti a dlouhodobé stability nespojených zrnitých vrstev. Souběžně s tím jsou analyzovány soudržnost a úhel vnitřního tření získané z přímých smykových zkoušek a začleněny do numerického modelování pomocí metody konečných prvků.

Výsledky zdůrazňují potřebu kombinovaného hodnocení pevnostních a deformačních vlastností s cílem zajistit trvanlivost vozovky, omezit poškození konstrukce a minimalizovat erozivní procesy, čímž přispívají k udržitelnému řízení infrastruktury i krajiny.

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