Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-242

Resilient Modulus Characterization of Unbound Granular Materials through Laboratory Dynamic Cone Penetration test

Siya Rimoy, Gabriel Rugabandana
Department of Transportation and Geotechnical Engineering, University of Dar es Salaam, Tanzania,rimoy@udsm.ac.tz

ABSTRACT: Traditional design methodology for low traffic volume roads (LVRs) relies on a simple input parameter, the laboratory Dynamic Cone Penetrometer test (DCP) DN-value. However, the DCP test does not simulate the mechanical performance of LVRs Unbound Granular Materials (UGMs) layers under cyclic loading from traffic. The resilient modulus (MR) test is one of the most common and reliable experiments for estimating UGMs response to cyclic traffic loads. Determining MR from the standard repeated load triaxial apparatus test is a complicated, time-consuming, and expensive procedure. Alternatively, MR can be obtained through correlations with other UGMs parameters. Correlating MR from California Bearing Ratio (CBR) values or index parameters has been established to conservatively exclude suitable materials for LVRs. It is therefore necessary to develop improved correlations. This has been achieved by correlating MR values for UGMs compacted at 95% of Maximum Dry Density (MDD) with the laboratory DCP-DN values. The outcome shows that UGMs MR values significantly correlate with laboratory DCP-DN values and follow the power equation of MR = 700 DN-0.7 which yields a degree of determination of R2 = 0.99. The relationship has been validated to estimate a reasonably resilient modulus of UGMs which can be used as an input in the mechanistic pavement design.

KEYWORDS: Resilient modulus, Laboratory DCP-DN, Low volume roads, Unbound Granular Materials.

1 INTRODUCTION

The design methodology for flexible pavement for Low traffic Volume Roads (LVRs) is consistently different from those used in high-volume roads (Rolt & Pinard, 2016). LVRs are defined as those expected to carry an average of approximately 300 motor vehicles per day over their design life, with traffic loading of less than about 1.0 million equivalent standard axles (MESA) in one direction(Rolt & Pinard, 2016). Due to limited resources typically available for LVRs, the technology used to characterize the properties of unbound granular materials (UGMs) is often inadequate. As a result, their load-bearing capacity is usually assessed through indirect or empirical methods. In many developing countries, the laboratory DCP-DN test is the most commonly used method to estimate the strength of UGMs on LVRs (Chibwe & Musenero, 2019; Paige-Green & Van Zyl, 2019a; Pinard M I, 2020). While traditional CBR has been used in the estimation of design strength parameters for pavement carrying High Volume Roads (HVRs). The Laboratory DCP-DN design method relies on a simple input parameter of DN-value depending on the Traffic Loading Class (TLC). The procedure for determining the laboratory DCP-DN is like that of the in-situ DCP test; however, the key difference lies in the testing location. The laboratory DCP-DN is conducted within a CBR mould, whereas the in-situ DCP test is performed directly in the field on pavement layers, borrow pits, or to assess subgrade bearing capacity (Paige-Green & Van Zyl, 2019b). The Laboratory DCP-DN test is a straightforward method for selecting construction materials for Low-Volume Roads (LVRs). However, its application within mechanistic-empirical design methods remains limited. Similar to the California Bearing Ratio (CBR) test, the DCP-DN procedure is quasi-static and does not replicate the effects of moving traffic loads on pavement layers. Current research indicates that the resilient modulus of unbound granular materials (UGMs) is the only reliable and appropriate parameter recommended for use in pavement design under the Mechanistic-Empirical Pavement Design Guide (MEPDG) (NCHRP, 2003). The resilient modulus is defined as a ratio of deviator stress to the resilient strain experienced under repeated vehicle loading conditions that aim to simulate traffic loading under repetitive conditions (AASHTO, 1994; Hajj et al., 2018). Conducting Repeated Triaxial Testing to determine the resilient modulus remains a costly and impractical option for Low-Volume Roads (LVRs)(Rugabandana & Rimoy, 2023). The procedure demands specialized equipment and highly trained personnel to ensure accurate and reliable results, limiting its feasibility for routine use in such projects (George & Kumar, 2018). To address this, several researchers as summarized in Table 1 have developed correlations between the resilient modulus of unbound granular materials (UGMs) and in-situ Dynamic Cone Penetrometer (DCP) test results, primarily for heavily trafficked pavements. However, these correlations are generally specific to certain materials, traffic loads, and environmental conditions, making them unsuitable for broader application. Additionally, they were derived under field conditions with uncontrolled moisture content. To enhance the practical implementation of mechanistic-empirical design methods for LVRs in developing countries, this study seeks to establish a correlation between the resilient modulus and laboratory-based DCP-DN results.

Table 1. Various Mr-DN relationship

S/NO	Reference	Relation developed
1	Chai et al. (1987)	Mr = $17.6(\frac{269}{DN})^{0.64}$
2	De Beer (1991)	log Mr =3.04785-1.06166log (DN)
3	Hassan (1996)	Mr = 48.32-14.061log (DN)
4	Chai et al. (1998)	Mr = $2224(DN)^{-0.996}$
5	Jianzhiuetal. (1999)	Mr= $338\ (DN)^{-0.39}$
6	Chen et al. (1999)	Mr= $338\ (DN)^{-0.39}$
7	Pandey et al. (2003)	Mr= $357.8\ (DN)^{-0.6445}$
8	Mukabi (2014)	Mr= $11689\ (DN)^{-0.741}$
9	Mukabi (2014)	Mr = $a_o\,(DN)^{a1}(\gamma d)^{a2}(\frac{LL}{Wc})^{a3}$
10	George and Kumar (2018)	Mr = $16.8 + (\frac{928.24}{DN})$
11	Ravindra Gudishara (2004)	Mr= $415.4\ (DN)^{-0.25}$

The previous studies presented in detailed the factors that affect the resilient modulus of UGMs which includes stress level, moisture content, density, material gradation, aggregate type and shape, number of load cycles, load duration frequency, and load sequence (Alnedawi et al., 2021; Lekarp et al., 2000; Won et al., 2023). Among these factors, moisture content and stress levels are the most important in influencing the resilient modulus of UGMs (Rahman & Erlingsson, 2015; Tamrakar & Nazarian, 2021).

2 MATERIALS AND METHODS

2.1 *Materials*

Twenty-one active borrow sites supplying unbound granular materials (UGMs) for low-volume road construction were identified and sampled from Dar es Salaam and the Coastal region of Tanzania. These borrow pits are currently in use for sourcing construction materials. The locations of the sampled borrow areas are shown in Figure 1. The collected materials were transported to the laboratory for preliminary testing and determination of their resilient modulus.

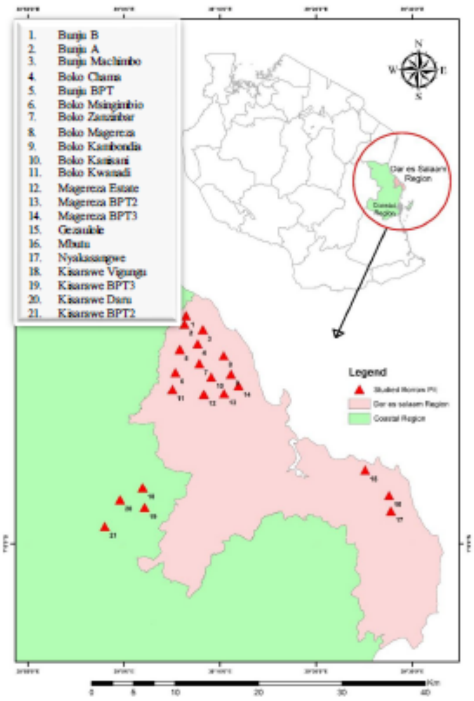

Figure 1. Location of borrowpits

2.2 *Methods*

2.2.1 *Determination of soil indices*

The laboratory-testing program for soil index parameters from the selected study areas included a comprehensive set of tests to evaluate the engineering properties of unbound granular materials (UGMs). These tests comprised the California Bearing Ratio (CBR) and CBR swell to assess load-bearing capacity and potential for expansion; Laboratory Dynamic Cone Penetrometer-Dynamic Number (DCP-DN) for penetration resistance; and Proctor tests to determine the Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), which are essential for compaction control. Additionally, Particle Size Distribution (PSD) analysis was conducted to evaluate soil gradation, while the Specific Gravity of Soil (GS) provided information on the mineral composition of the materials. The Plasticity Index (PI) was used to assess the soil's plasticity characteristics, and the Grading Modulus (GM) was calculated to summarize the overall gradation quality. All tests were performed following the procedures and standards outlined in the Tanzanian Road Works Specifications to ensure consistency and reliability of the results (Ministry of Works (TZ), Central Material Laboratory (TZ), 2000).

2.2.2 *Test for mineralogical composition*

The collected samples were first categorized according to their geographic locations to account for potential regional variations in material properties. From each group, representative samples of unbound granular materials (UGMs) were selected for further analysis of their mineralogical composition. To identify and characterize the types of minerals present within these samples, X-ray Diffraction (XRD) analysis was carried out. This technique measures the diffraction of X-rays as they interact with the crystal structures of minerals, allowing for the identification of specific mineral phases based on their unique diffraction patterns and associated wavelengths.

2.2.3 *Laboratory DCP-DN-values*

The procedure used to determine the Dynamic Cone Penetrometer-Dynamic Number (DCP-DN) value of the material closely followed the methodology typically employed for the standard California Bearing Ratio (CBR) laboratory test, with one key modification. Instead of utilizing the conventional CBR plunger to apply vertical penetration into the compacted soil specimen within the CBR mold, a Dynamic Cone Penetrometer (DCP) was employed to perform the penetration. In this adapted method, the soil sample was first compacted in a standard CBR mold at its Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) using Proctor compaction energy, in accordance with the relevant specifications (Fernandes, 2016; MWTC, 2016; Rolt & Pinard, 2016). Following compaction, the DCP apparatus consisting of a steel cone attached to a rod and a sliding hammer was positioned vertically over the mold. The cone was then driven into the compacted soil by repeated free-fall blows of the hammer, and the penetration depth was recorded after each blow. This process continued until a sufficient depth of penetration was achieved, allowing for the calculation of the DCP-DN value, typically expressed in millimeters per blow. This setup and procedure are illustrated in Figure 2, which shows the laboratory arrangement used for DCP-DN testing.

Figure 2. Laboratory DCP-DN set up

2.2.4 *Determination of resilient modulus*

At the TANROADS Central Materials Laboratory, an advanced automated testing system the Universal Testing Machine model UTM-130 is available and was utilized for determining the resilient modulus of unbound granular materials. This high-capacity device is specifically designed to perform Repeated Load Triaxial (RLT) tests, which are essential for evaluating the stress-dependent resilient behavior of pavement materials under simulated traffic loading conditions. For this study, the UTM-130 was employed to conduct resilient modulus testing in full compliance with the procedures outlined in the AASHTO T307 standard (AASHTO, 2017). Specimen preparation involved compacting cylindrical samples (152X305mm) of the test material to specified dimensions and target densities corresponding to their respective Optimum Moisture Content (OMC) and Maximum Dry Density (MDD), as determined from prior compaction tests. The resilient modulus testing followed the procedure outlined in the AASHTO T307 test method (AASHTO, 2017). Each material was weighed according to its MDD and OMC values. The materials were then compacted into five (5) equal layers in a 152mm diameter and 305mm high mold with a 4.54kg hammer from 457mm drop height. The testing sequence for base and subbase materials began with 1,000 cycles during the conditioning phase. This initial cycling was intended to eliminate plastic strains prior to measuring the resilient modulus. Following conditioning, 100 cycles were applied for each of the 15 test sequences. The resilient modulus corresponding to each specific stress path was determined by averaging the final five data points.

3 RESULTS AND DISCUSSION

3.1 *Mineralogical components*

The mineralogical analysis conducted using X-ray Diffraction (XRD) revealed that the unbound granular materials (UGMs) obtained from borrow pits located in Dar es Salaam predominantly contain calcite ($CaCO_3$) and magnesium calcite ($MgCaCO_3$) as the major mineral constituents. In contrast, samples collected from borrow pits in the Kisarawe area, within the Coastal region, were found to be rich in kaolin minerals, primarily kaolinite with the chemical composition $Al_2H_4O_9Si_2$. These findings indicate that the mineralogical composition of UGMs varies significantly depending on their geographic source, which in turn affects their engineering properties. The experimental results from this study demonstrated a clear relationship between mineral content and soil index properties. Specifically, an increase in the concentration of calcium carbonate ($CaCO_3$) and magnesium oxide (MgO) associated with the presence of calcite and magnesium calcite was observed to contribute to a decrease in the Liquid Limit (LL), Plastic Limit (PL), and Plasticity Index (PI) of the UGMs. This suggests that carbonate-rich materials tend to exhibit lower plasticity, which has important implications for their behavior and suitability in pavement applications, particularly in low-volume road construction.

3.2 *Soil index parameters*

The soil index and strength parameters obtained from laboratory testing were utilized as the basis for the classification of unbound granular materials (UGMs), following the guidelines provided in both the American Association of State Highway and Transportation Officials (AASHTO) classification system and the Tanzania Pavement Design Manual (TPDM). These parameters provided essential insights into the suitability of the materials for use in pavement layers, particularly for low-volume road applications.

The particle size distribution of the UGMs evaluated in this study. UGMs classified as G25 exhibited fine contents between 9% and 12%. Notably, the highest fine contents up to 25% were observed in UGMs categorized as G15 and G7. Previous research suggests that the optimal fine content for UGMs ranges between 5% and 12%, as this range tends to offer a balance between compaction, stability, and performance (Chen et al., 2019; Osouli et al., 2018). When fine content exceeds this optimal range, the materials become more sensitive to moisture variations (Chen et al., 2020). Increased moisture can reduce the M_R, thereby decreasing the stiffness and structural capacity of the pavement layer. This indicates the importance of limiting fine content to ensure the optimal performance of UGMs.

The California Bearing Ratio (CBR) values of the tested UGM samples were found to range between 7% and 30%, which is within the acceptable range for materials typically used in the construction of low-volume roads in Tanzania. These values confirm the appropriateness of the sampled materials for such applications, in line with national standards. Further analysis revealed a notable correlation between mineralogical composition and strength properties. UGMs containing a higher proportion of calcite ($CaCO_3$) exhibited relatively higher CBR values, indicating greater load-bearing capacity. This suggests that calcite-rich materials contribute positively to the mechanical strength of the soil. Conversely, samples with a higher content of kaolin minerals (such as kaolinite) were observed to have elevated Optimum Moisture Content (OMC) values when compared to samples with higher calcite content. This implies that kaolin-rich materials tend to retain more moisture, which may influence compaction behavior and strength development. Overall, the results highlight the importance of mineralogical composition in influencing both the strength and moisture-related properties of UGMs, which is critical for their effective classification and utilization in pavement design.

3.3 *Resilient modulus and laboratory DCP-DN values*

Laboratory testing of unbound granular materials (UGMs) sourced from 21 active borrow pits was conducted to evaluate their mechanical behavior under both Optimum Moisture Content (OMC) and soaked conditions. Two key tests were performed on each sample: the Laboratory Dynamic Cone Penetrometer-Dynamic Number (DCP-DN) test and the resilient modulus (Mr) test. These tests aimed to assess the penetration resistance and elastic response of the materials, respectively both of which are critical for determining their suitability for use in low-volume road construction. Under OMC conditions, the DCP-DN values ranged between 4 mm/blow and 20 mm/blow, indicating relatively firm material behavior in their optimal moisture state. When subjected to soaked conditions simulating the effects of moisture saturation typically experienced during wet seasons or poor drainage scenarios the DCP-DN values increased, ranging from 8 mm/blow to 62 mm/blow. Despite this increase, all values remained within the acceptable limit of 4-65 mm/blow as specified in the Tanzania Low Volume Roads Guideline, confirming the general suitability of the materials under both dry and wet conditions. Correspondingly, the resilient modulus (Mr) values for the tested UGMs ranged from 89 MPa to 262 MPa, reflecting a wide variation in the elastic stiffness of the materials. These values were evaluated against standard ranges for natural gravel materials commonly used in pavement construction. The results indicate that many of the sampled materials fall within the expected performance range, providing further confidence in their application for pavement layers in low-volume road networks. This dual-condition testing approach highlights the significance of moisture sensitivity in UGM performance and reinforces the importance of considering both dry and soaked behaviours in pavement material evaluation.

3.4 *Development of Mr-DN relationship*

A statistically significant relationship between the resilient modulus (Mr) and laboratory Dynamic Cone Penetrometer-Dynamic Number (DCP-DN) values was established, with Mr treated as the dependent variable and DN as the independent variable. Analysis was conducted at a 95% confidence level. As illustrated in Figure 3, there is a clear inverse relationship where Mr decreases as DN increases, indicating that the soil's strength diminishes with higher DCP penetration resistance values. This strong negative correlation confirms that laboratory DCP-DN values can reliably predict the resilient modulus of unbound granular materials (UGMs). The significance of the model was supported by Analysis of Variance (ANOVA) results, which yielded a p-value of 8.20×10^{-9} substantially below the conventional significance threshold of 0.05 indicating that the regression model is highly statistically significant. Furthermore, the coefficient of determination (R^2) was found to be 0.99, demonstrating an excellent fit between the predicted and observed Mr values and confirming the model's high predictive accuracy. The resulting regression equation, which quantifies this relationship, is presented below.

Predicted $Mr = 700\ DN^{-0.7}$

Where;

Mr = resilient modulus of UGMs (MPa)

DN = Penetration rate mm/blow (at OMC)

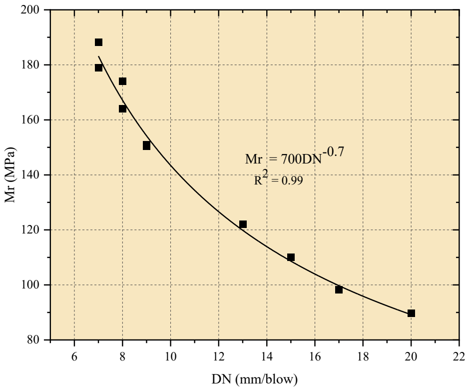

Figure 3. Relationship between Mr-DN

3.5 *Validation of developed correlation*

The correlation model developed for unbound granular materials (UGMs) was rigorously validated using eleven independent data sets collected from various borrow pits within the study area. These validation samples were carefully selected to represent geological formations similar to those used in the initial model development, ensuring consistency in the material characteristics. Figure 4 illustrates the comparison between the predicted resilient modulus (Mr) values derived from the model and the actual laboratory-measured Mr values. The data points closely follow the line of best fit, with a coefficient of determination (R^2) of 0.99, indicating an excellent agreement between predicted and observed values. Additionally, the comparison yielded a coefficient of variation (CoV) of 0.1, further demonstrating the high precision and reliability of the developed correlation. This low CoV confirms that the model provides an accurate and consistent prediction of the resilient modulus from the Dynamic Cone Penetration index (DCP-DN) values for natural UGMs.

Moreover, when comparing the developed model to established correlations from previous studies by Chai et al. (1987), Chen et al. (1999), and Jianzhiu et al. (1999), it was observed that these earlier models also show strong correspondence with the current study's results. The CoV for these comparative models approached zero, and the mean ratio of predicted to actual Mr values was close to 1.0, indicating similarly high accuracy. Figure 5 presents a comparative analysis that highlights the compatibility of the current model with these well-known correlations, which were originally developed for predicting the resilient modulus of subgrade soils.Based on these validation results and comparisons, it can be confidently concluded that the developed correlation model is robust and reliable at a 95% confidence level for predicting the resilient modulus of UGMs within the geological context of the study area.

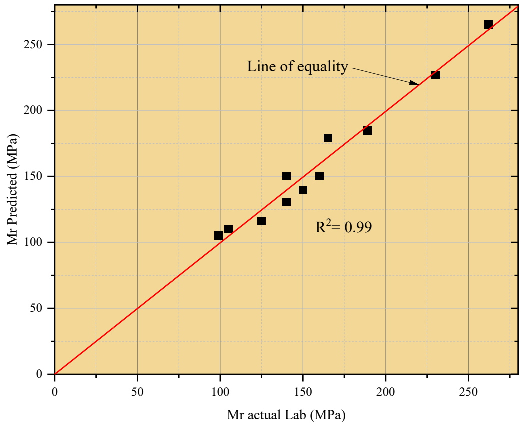

Figure 4. Predicted Mr Vs actual lab Mr

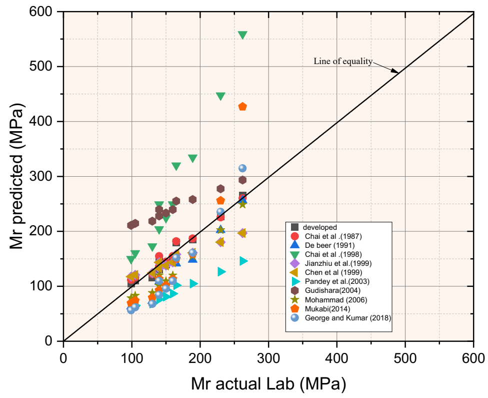

Figure 5. Comparison of developed model with existing model

4 CONCLUSION

This study presents a thorough investigation into the resilient modulus (Mr) of unbound granular materials (UGMs) commonly used in the construction of low-volume roads (LVRs), with an emphasis on developing a predictive model for Mr based on laboratory Dynamic Cone Penetrometer (DCP) test results. A total of twenty-one UGM samples were collected from different regions across the country and subjected to a series of laboratory tests under controlled moisture conditions representative of field environments. The results of the study indicate that existing Mr-DCP-DN correlation models particularly those originally developed for field-based assessments are not directly applicable to the mechanistic-empirical pavement design of LVRs. These models fail to account for the specific material behavior and environmental conditions relevant to low-volume road applications in the local context. Based on the findings of this research, the following conclusions have been drawn:

- The correlation between the Mr values and the laboratory DCP for UGMs compacted at 95% MDD followed a power model of $Mr = 700DN^{0.7}$ with a coefficient of determination value of 0.99.

- The mineralogical composition of unbound granular materials (UGMs) has a significant impact on both their resilient modulus and laboratory DCP-DN values. Specifically, samples with a higher content of calcite were observed to exhibit greater resilient modulus values, indicating increased stiffness, while simultaneously showing lower DCP-DN values, reflecting higher resistance to penetration. This correlation underscores the influence of mineralogy on the mechanical behavior of UGMs.
- The resilient modulus of unbound granular materials (UGMs) is significantly influenced by both their moisture content and maximum dry density. An increase in moisture content leads to a reduction in the resilient modulus, indicating a decrease in the material's stiffness and load-bearing capacity under repeated loading. This reduction is attributed to the weakening of particle interlocking and the development of pore water pressures, which reduce shear strength. Conversely, an increase in maximum dry density typically achieved through proper compaction results in a corresponding increase in the resilient modulus. Higher dry density enhances particle contact and structural integrity within the material matrix, thereby improving its resistance to deformation. These trends observed in the study highlight the critical role of moisture and compaction control in optimizing the performance of UGMs in pavement layers.
- A strong agreement was observed between the resilient modulus (Mr) values predicted using the proposed correlation model and those obtained through direct laboratory measurements. The model demonstrated a high level of accuracy, evidenced by a coefficient of determination (R^2) of 0.99, indicating that 99% of the variability in the measured Mr values could be explained by the model. This excellent correlation confirms the predictive capability of the developed equation. The results further establish that the resilient modulus of natural unbound granular materials (UGMs) is strongly and inversely correlated with the Dynamic Cone Penetration index (DCP-DN). As DCP-DN values increase, indicating reduced material resistance, the Mr values decrease accordingly, reflecting a lower stiffness of the material. This relationship reinforces the effectiveness of using laboratory DCP-DN results as a reliable predictor for estimating Mr in pavement design applications, only for low-volume roads.

5 ACKNOWLEDGMENTS

Support received from TANROADS Central Materials Laboratory is greatly acknowledged.

6 REFERENCES

AASHTO. (1994). T P46 - 94: Resilient Modulus ofUnbound Materials (LTPP Protocol P46).

AASHTO. (2017). T 307-99: Standard Method of Testing for Determining the Resilient Modulus of Soils and Aggregate Materials (Issue 20127).

Alnedawi, A., Kafle, B., Ullah, S., & Kerr, W. (2021). Investigation of non-standard unbound granular materials under cyclic loads: experimental and regression analyses. International Journal of Pavement Engineering, 0(0), 1–13. https://doi.org/10.1080/10298436.2021.1877291

Chen, W. B., Feng, W. Q., & Yin, J. H. (2020). Effects of water content on resilient modulus of a granular material with high fines content. Construction and Building Materials, 236, 117542. https://doi.org/10.1016/j.conbuildmat.2019.117542

Chen, W. B., Feng, W. Q., Yin, J. H., Borana, L., & Chen, R. P. (2019). Characterization of permanent axial strain of granular materials subjected to cyclic loading based on shakedown theory. Construction and Building Materials, 198, 751–761. https://doi.org/10.1016/j.conbuildmat.2018.12.012

Chibwe, J., & Musenero, L. (2019). Comparative Analysis of the Dynamic Cone Penetrometer-Cone Penetration Rate Design Approach against Other Methods Used for Upgrading of Low Volume Roads: Case of Uganda and Zambia. Transportation Research Record: Journal of the Transportation Research Board, 2673(12), 811–820. https://doi.org/10.1177/0361198119853570

Fernandes, A. C. M. (2016). Low-Volume Roads Pavements Civil Engineering Supervisors : Key words. Pavimentos Para Estradas de Baixo Tráfego.

George, V., & Kumar, A. (2018). Studies on modulus of resilience using cyclic tri-axial test and correlations to PFWD, DCP, and CBR. International Journal of Pavement Engineering, 19(11), 976–985. https://doi.org/10.1080/10298436.2016.1230428

Hajj, E. Y., Thavathurairaja, J., Stolte, S., Sebaaly, P. E., Piratheepan, M., Motamed, R., & Center, W. R. S. (2018). Resilient Modulus Prediction Models of Unbound Materials for Nevada. SOLARIS Consortium, No. P224-14-803.

Lekarp, F., Isacsson, U., & Dawson, A. (2000). State of the Art: Resilience Response of Unbound Aggregates. 3(February), 66–75.

Ministry of Works (TZ), Central Material Laboratory (TZ), N. P. R. A. (Npra). (2000). Standard Specification for Road Works Standard Specification for Road Works. Isbn 9987-8891-2-3, 1–317.

MWTC. (2016). Low Volume Roads Manual. 13–25.

NCHRP. (2003). Harmonized test methods for laboratory determination of resilient modulus for flexible pavement design, Final Report Volume I: unbound granular material.

Osouli, A., Tutumluer, E., & Vaughn, B. (2018). Plasticity Requirements of Aggregates Used in Pavement Base and Subbase Courses. https://doi.org/10.36501/0197-9191/18-018

Paige-Green, P., & Van Zyl, G. D. (2019a). A Review of the DCP-DN Pavement Design Method for Low Volume Sealed Roads: Development and Applications. Journal of Transportation Technologies, 09(04), 397–422. https://doi.org/10.4236/jtts.2019.94025

Paige-Green, P., & Van Zyl, G. D. (2019b). A Review of the DCP-DN Pavement Design Method for Low Volume Sealed Roads: Development and Applications. Journal of Transportation Technologies, 09(04), 397–422. https://doi.org/10.4236/jtts.2019.94025

Pinard M I, H. J. I. A. (2020). Pavement Design of Low Volume Roads using the DCP-DN Method. September.

Rahman, M. S., & Erlingsson, S. (2015). Predicting permanent deformation behaviour of unbound granular materials. International Journal of Pavement Engineering, 16(7), 587–601. https://doi.org/10.1080/10298436.2014.943209

Rolt, J., & Pinard, M. I. (2016). Designing low-volume roads using the dynamic cone penetrometer. Proceedings of the Institution of Civil Engineers: Transport, 169(3), 163–172. https://doi.org/10.1680/jtran.14.00059

Rugabandana, G., & Rimoy, S. (2023). Resilient Modulus Characterization of Unbound Granular Materials Through Laboratory Dynamic Cone Penetration Test. International Journal of Pavement Research and Technology. https://doi.org/10.1007/s42947-023-00318-7

Tamrakar, P., & Nazarian, S. (2021). Moisture effects on moduli of pavement bases. International Journal of Pavement Engineering, 22(11), 1410–1422. https://doi.org/10.1080/10298436.2019.1696460

Won, J., Tutumluer, E., & Byun, Y. H. (2023). Predicting permanent strain accumulation of unbound aggregates using machine learning algorithms. Transportation Geotechnics, 42. https://doi.org/10.1016/j.trgeo.2023.101060