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Evaluation of Subgrade Resilient Modulus using CBR Test Data to Facilitate Mechanistic-Empirical Pavement Design (MEPD)

B.H.T. Ariyarathne and U.P. Nawagamuwa

Abstract: Sri Lankan road pavement design has relied on empirical design guidelines, and it is now transforming to a more modern approach known as the Mechanistic-Empirical Pavement Design (MEPD) method, aligning with global best practices. One crucial input parameter in this new methodology is the Resilient Modulus (RM) of unbound materials. Determination of RM and establishment of typical values is essential to implement the MEPD. This study has devoted significant attention to the RM evaluation process and developing predictive models for determiningRM from CBR values. Furthermore, typical RMvalues for locally available soil types have been established. In addition to that, ageospatial database has been established with information on soil properties and RMvalues throughout Sri Lanka. This database is a valuable resource for M-E road pavement design, providing quick reference data to conceptual designs and Level 3-MEPD.

Keywords: Resilient Modulus, MEPD, Light Weight Deflectometer, CBR

1. Introduction

The traditional pavement design methodology in Sri Lanka relies on empirical guidelines derived from Overseas Road Note 31 [1] and American Association of State Highway and Transportation Officials (AASHTO) design guides [2]. However, this empirical approach presents limitations, particularly in utilizing indirect material properties like the CBR, resulting in inaccuracies in pavement design due to neglecting the influence of environmental factors and axle loads. To address these challenges, the Road Development Authority (RDA) has initiated a transformation towards the Mechanistic-Empirical Pavement Design (MEPD), aligning with the global trend.

RDA introduced the RDAPDS software for MEPD in Sri Lanka, initially using Level 3 reliability level and planning to transition to Level 2 and Level 1. Criteria for each level are specified in the RDAM-E Pavement Design Guide [3]. Within the MEPD system, Resilient Modulus (RM) is a vital input parameter for unbound material. Level 1 necessitates extensive laboratory testing, Level 2 relies on predictive models, and Level 3 accepts typical values [4].

However, determining RM values in Sri Lanka presents challenges due to equipment unavailability, the absence of a soil database, and limited research on pavement layer modulus for local materials. This study aims to address these challenges through the following objectives:

1. **Development of a Predictive Model**: The goal is to create a predictive model for RM assessment using CBR test results.
2. **Establishment of Typical RM Values:** Focuses on establishing typical RM values for local subgrade materials in Sri Lanka.
3. **Development of a Database**: Aims to create an extensive soil database with RM values forthe MEPD process.

Various analytical methods, including multiple linear and non-linear regression analyses, were employed to achieve these objectives. Excel and MATLAB software was utilized to develop predictive models, while ArcGIS was used to establish a geodatabase. The software facilitated the creation and management of this geodatabase, enabling the integration of location-based data with associated test information.

Eng. B.H.T. Ariyarathne, AMIE (SL), B.Sc. Eng. (Hons) (Moratuwa), DIPPCA, Engineer in Road Development Authority of Sri Lanka,
Email:thiranka@gmail.com
https://orcid.org/0000-0001-9217-1453
Eng.(Prof.) U.P. Nawagamuwa, CEng, FIE(SL), B.Sc.Eng. Hons(Moratuwa), MEng(AIT), DrEng(YNU), Professor, Department of Civil Engineering, University of Moratuwa, Sri Lanka
Email:udeni@uom.lk
https://orcid.org/0000-0002-7088-0694

2. Literature Review

2.1 Mechanical–Empirical Pavement Design and its Implementation

The Federal Highway Administration (FHWA) in the United States began looking into incorporating mechanical principles in road pavement design in the 1950s when the MEPD approach started. At the time, traditional empirical design methods were widely used, but they were known to be unreliable and often resulted in pavements that did not perform to the expected level. The FHWA first published MEPD guidelines in 2002 [5].

The MEPD method gained widespread adoption as a standard pavement design approach by numerous countries and organizations worldwide in the subsequent years. MEPD has gained widespread acceptance in engineering and is now regarded as the state-of-the-art method for road projects. Its implementation results in better-performing pavements with longer lifespans and lower maintenance costs. Many countries are currently working on updating and refining the MEPDGuidelines.

Implementation Process in Sri Lanka

RDAoversees the design, construction, and maintenance of the country's leading road network. Implementing the MEPD method in Sri Lanka began in 2014, initially attempting to use commercially available software for MEPD work. However, in 2018, with the help of the Asian Development Bank, RDA began developing and implementing its Mechanical-Empirical-based design approach by developing a software "RDAPDS" [3] with the assistance of the Korean Institute of Civil Engineering and Building Technology (KICT).

2.2 Subgrade Characterization in MEPD

The subgrade soil is one of the main components of the pavement. It supports the pavement structure, and its characteristics are critical in determining its performance.

Sub-grade characterization in MEPD involves determining the properties related to the loading and environmental conditions. The RM of the soil, indicating its stiffness under loading, is a critical input parameter for the MEPD process.

In the MEPD process, there are three design levels, with Level 1 being the most precise and Level 3 being the least accurate. The required accuracy of input parameters depends on the selected level.

Resilient Modulus of Subgrade Soil

The RM is the ratio of recurrent deviator axial stress to recoverable axial strain, and it is used to characterize the response of a material to stress.

For the Level 1 design, it is necessary to conduct laboratory testing to determine the RM values for input parameters, and for the Level 2 design, utilization of established relationships to ascertain RM values is allowed. Furthermore, for the Level 3 design, typical RM values could be used [4].

The Cyclic Triaxial Test is a commonly used method to evaluate the Resilient Modulus of soil in the laboratory [6].

In-situ measurement of the RM of unbound layers could be evaluated using a lightweight deflectometer (LWD), which uses a dynamic load to induce a deflection in the pavement. Subsequently, the RM value will be determined [7].

2.3 LWD andits Application for Modulus Determination

The LWD (Figure 1) is a portable device designed to measure the RM of unbound layers in situ. It uses a dynamic load to induce a deflection in the pavement, which is then utilized to determine the RM of the material.

The maximum deflection(d_0) of the plate is measured by the geophone, located at the center of the plate. A force transducer, placed within the housing, is responsible for quantifying the exerted force (P). The Boussinesq equation is used to calculate the in-situRM of pavement layers, as given in Equation (1).

$$RM = \frac{2K_s(1-v^2)}{Ar_o} \quad \text{... (1)}$$

where

K_s = Stiffness of the material

A = Stress Distribution Factor (3/4 π)

π = 22/7

υ = Poisson's ratio of material

r_0 = Plate Radius

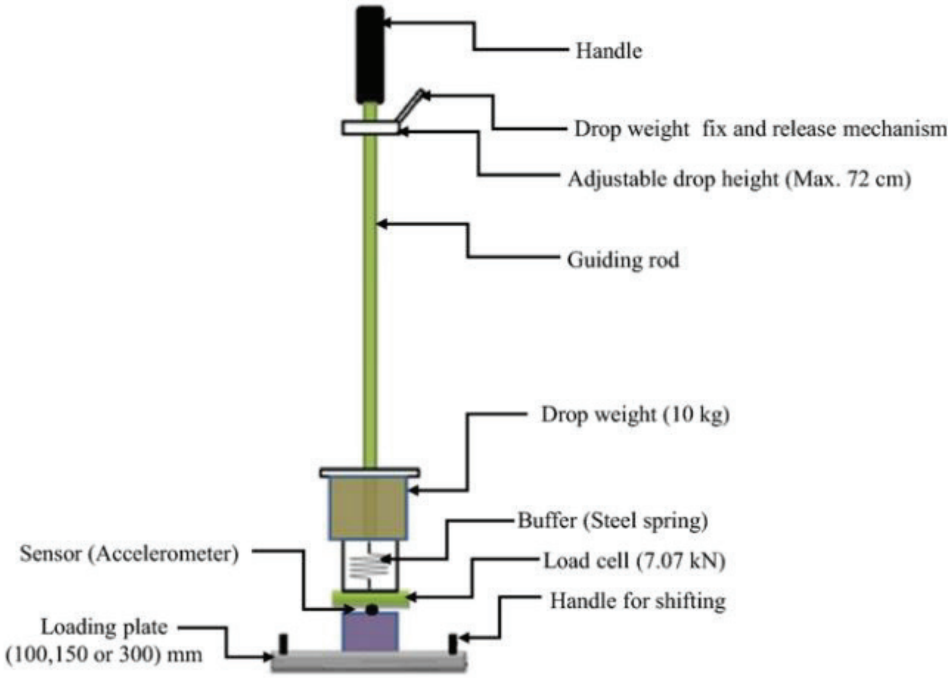

Figure 1 –Lightweight Deflectometer and its Components

LWD Test on Compaction Mould

DeterminingRM in the laboratory using cyclic triaxial testing is complex and time-consuming. To find alternative methods, various researchers have explored new approaches and technologies.

Schwartzet et al. [8] conducted a comprehensive study and established a new approach for determining RM in the laboratory as an alternative method. This method employed LWD on the compaction mould to ascertain the RM.

The RM of the soil can be determined by applying the theory of elasticity to a cylinder with constrained lateral deflection. The analysis was based on the assumption that the soil exhibits elastic behaviour, that deformation occurred exclusively within the soil and not in the underlying platform, and that the impact load was approximated as being quasi-static in nature [8]. The RM values were calculated using Equation(2).

$$RM = \left(1 - \frac{2\upsilon^2}{1-\upsilon}\right)\frac{4H}{\pi D^2}k \ldots \text{(2)}$$

where

υ = Poisson's ratio
H = Mould Height
D = Plate Diameter
k = Stiffness

2.4 RM from Cyclic Triaxial Testing versus RM from LWD Testing on Mould

In the study conducted by Schwartzet al. [8], the laboratory RM test results (Cyclic triaxial test) were compared with the LWD results conducted on the Proctor Compaction mould. The study findings revealed a strong correlation between the Laboratory RM and the modulus obtained from LWD tests when the deviator stress equalled the confining stress [8].

Later, this method was adopted by other researchers in their studies.

A study by Kimet et al. [9] aimed to ascertain the modulus under various moisture conditions byutilizing LWD testing on Proctor moulds. Multiple trials were undertaken to investigate the influence of wall friction on modulus values. It was observed that friction between the inner wall and within the fill material significantly impacted deflection. It states that the impact of friction on deflection can be reduced by applying lubrication to the inner wall, as per the study findings.

Another research study, as referenced in Kuttah [10], was undertaken to evaluate the performance of laboratory LWD tests on moulds containing sandy soil as the subgrade material. The study specifically investigated the influence of the number of drops on the RM value under different moisture contents.

According to the findings, increasing the number of LWD drops led to greater dynamic deformation modulus and a tighter fit to the equivalent robust modulus recorded in RMT testing.

This method was more practical since fewer LWD drops were needed to achieve near-elastic behaviour in sandy soils compacted at low moisture contents. Additionally, laboratory LWD tests on compaction moulds with lateral confinement and end-boundary conditions contributed to reaching resilient behaviour faster than field LWD testing conditions with lower soil confinement.

Moreover, the study quoted the following statement: "This procedure enables the predicting of the resilient modulus values from LWD tests on any design material and required testing conditions." Therefore, the study suggested using an LWD test to determine the resilient Modulus of tested soils directly and quickly.

A study conducted by Jibonetet al. [11] analyzed the moisture-modulus relationship and the relationship between RM and LWD modulus($E_{LWD,Mould}$) on soil by testing eight soil types at three different moisture contents ($0.9M_o$, M_0, $1.2M_o$). Based on these findings, the following relationship with RM and $E_{LWD,Mould}$ was established with $R^2 = 0.82$.

$$\mathrm{RM} = 0.97 \times E_{LWD,Mould} \qquad \text{... (3)}$$

2.5 Determination of Resilient Modulus from Predicting Models

Laboratory triaxial testing provides accurate and reliable RM values, but evaluating material properties is time-consuming and costly. Therefore, predictive models have instead been developed to estimate the RM of soil from other parameters. Predictive models are recommended for Level 2 of the MEPD [5].

Prediction of Modulus from CBR value

Numerous equations have been employed in the research literature to determine the RM from CBR values.

In 1962, Heukelom et al. [12] found the famous Heukelom and Klomp relationship:

$$\mathrm{RM}(MPa) = 10.34 * CBR \text{... (4)}$$

This equation was developed using dynamic impedance tests and Rayleigh waves in the Netherlands and UK. This relationship was derived from wave propagation tests at low strain levels and dynamic deflection tests. The equation has been used for fine-grained soils when the CBR is less than or equal to 10%.

Green et al. [13], cited by the U.S. Army Corps of Engineers, proposed Equation (5) based on their comparison of in-situ CBR measurements and vibration wave propagation measurements on experimental roads with subgrade layers formed from fine-grained soil.

$$\mathrm{RM}(MPa) = 37.3 * CBR^{0.71} \text{... (5)}$$

The South African Council for Scientific and Industrial Research (CSIR) applied Equation (6) of the form $\mathrm{RM} = \mathrm{k} * \mathrm{CBR}^{\mathrm{a}}$ to estimate the Resilient Modulus of materials, by adjusting the k factor based on the soil types. Eventually, Equation (6) was proposed and is applicable for CBR values ≤20% (Paterson et al. [14]).

$$\mathrm{RM}(MPa) = 20.7 * CBR^{0.65} \qquad \text{... (6)}$$

Transportation and Road Research Laboratory (TRRL) proposed Equation (7) based on the study conducted by Powel et al. [15]. It was based on in situ CBR tests and Rayleigh wave propagation tests, and it is applicable for CBR values varying from 1 to 12%.

$$\mathrm{RM}\ (MPa) = 17.6 * CBR^{0.64} \qquad \text{...(7)}$$

3. Methodology

To accomplish the objectives of this research, a series of tasks were executed. Specifically, the following activities were carried out:

- Collection of previous results of soil tests conducted at different places in Sri Lanka.
- Conducted laboratory testing to determine subgrade soil's fundamental properties and RM values.
- Systematic analysis to develop relationships with the RM value.

3.1 Soil Data Collection Procedure

Soil data was gathered from the RDA Provincial Laboratories and the Central Laboratory. Data was collected from tests conducted over the past two years. Testing data such as Maximum Dry Density (MDD), OptimumMoisture Content (OMC), Atterberg Limits, Soil Type, and CBR were collectedwith corresponding GIS coordinates.

3.2 Laboratory Testing Procedure

Subgrade materials were collected from 28 locations, an approximate quantity of 50 kilograms, to conduct laboratory testing. These materials underwent comprehensive testing to determine their fundamental properties. The tests encompassed sieve analysis, determination of Atterberg limits, MDD, OMC, and Soil Classification according to BS 1377 [16].

Moreover, a specialized test method, as developed by Schwartz et al. [8], was employed to determine the RM values of the soil.

3.3 Development of a Modulus Predicting Model

Figure 2 entails the systematic examination and development of an appropriate predictive model to evaluate the resilient modulus for Sri Lankan soil.

4. Results & Analysis

4.1. Subgrade Material Properties

The twenty-eight samples utilized in the study consist of 97% coarse-grained sandy soil, with the remaining 3% representing fine-grained soil. A summary of the tested soils, along with the corresponding test results for each soil type, is summarized in Table 1.

Table 1 –Summary of the Test Results

Soil Type	No. of Samples	CBR Range	RM Range
SC	14	6 - 27	55 -175
SC-SM	10	8 - 36	103 - 199
SM	02	7 -15	81 -141
CL	01	7	51
SP-SM	01	9	80

According to the results, the CBR values of tested soil ranged from 6 to 36. Subsequently, an RM test was conducted using an LWD on the compaction mould, and Equation (3) was applied to convert the LWD modulus values into RM values. The obtained results indicate a range of RM values from 55 to 199.

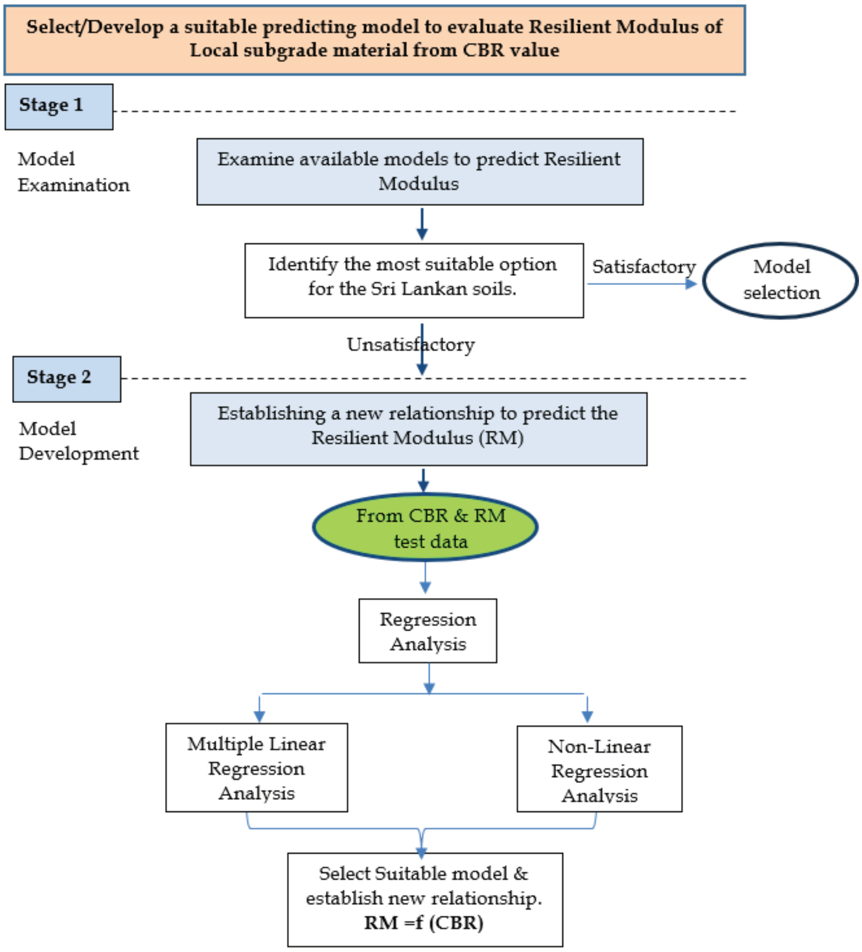

Figure 2 – Systematic Examination and Development Procedure

4.2 Evaluation & Development of Resilient Modulus Predicting Model

Examination of Existing Models for Local Soil (Stage 1)

In the first stage of the research, an examination of existing models listed in Section 2.5 was conducted to assess their suitability for local soil and plotted in Figure 3. RM values obtained through LWD testing on local soil samples were plotted on the same graph.

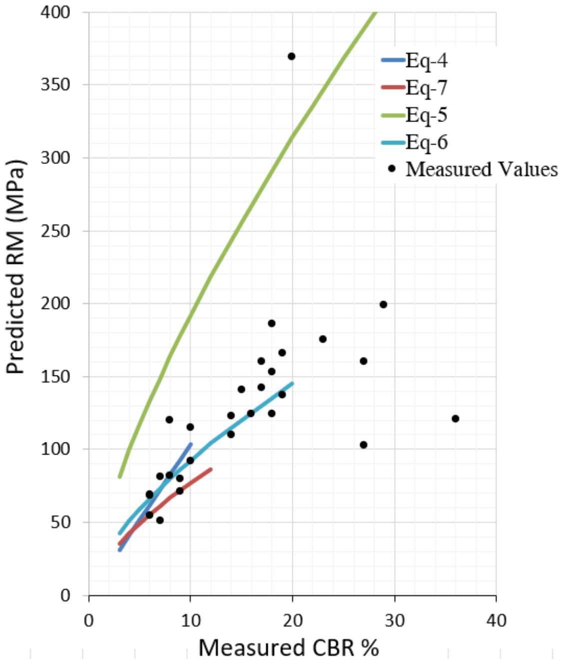

Figure 3 - Comparison of RM Predictive Models

A comparative analysis of each model's suitability for local soil was undertaken, employing the Route Mean Square Error (RMSE) values. Specifically, Equation (4) yielded an RMSE value of 34.9, Equation (5) exhibited 30.37, Equation (6) showed 22.17, and Equation (7) demonstrated 17.32. Additionally, the visualization of these models alongside the measured RM values in Figure 3 revealed a scattered distribution that did not strongly align with the established Equations (Equation 4 to Equation 7).

Many of the existing equations were formulated based on soils from the selected region, characterized by low CBR values (CBR <20%) and fine-grained soils, so they may not be well-suited for local soil conditions. Consequently, recognizing the need for a tailored approach, it was beneficial to develop a new equation specifically catering to the unique characteristics of the local soil.

Development of New Relationship for Local Soil (Stage 2)

Measured modulus values were used to develop a new relationship. As described in the methodology, both Multiple-Linear Regression Analysis and Non-linear Regression Analysis techniques were performedto formulate the equation.

Equation (9), derived from Multiple-Linear regression analysis with an R^2 of 0.89 and a Standard Error of 18.97 using Excel software, indicates a highly favourable outcome of the study.

$$\mathrm{RM} = 37.96 + 5.814 * CBR \qquad \ldots\ldots (8)$$

The above equation (Equation8) is y = mx + c. However, most MEPD software, including RDAPDS, typically requires equations in the form of RM = a * CBR^ b. MATLAB software was used to generate a customized equation by implementing nonlinear regression analysis to accommodate this requirement.Equation (9) is the result of the regression analysis conducted using the MATLAB software.

$$\mathrm{RM} = 21.14 * \mathrm{CBR}^{0.6656} \qquad \ldots\ldots (9)$$

The model demonstrates a strong goodness of fit with an R-squared value of 0.828, an adjusted R-squared of 0.821, and an RMSE of 13.08. Figure 4showsthe measured RM values plotted against predicted values using Equation (9).

These statistical and visual findings collectively underscore the model's robustness and ability to capture the complex relationship between predictor and response variables.The equation was developed using data that encompassed 97% coarse-grained sandy soil. As a result, the model's accuracy is robustly validated for coarse-grained soil, particularly prevalent in Sri Lanka, given that most of the training data pertains to this soil type. However, further validation is essential to evaluate its performance on fine-grained soil.

4.3 Analysis of Soil Data

Over 9,500 individual data points were collected for this analysis. Table 2 summarizes the distribution of subgrade soil types and their corresponding percentages across Sri Lanka.

Figure 5 serves as a visual counterpart to the data in the preceding table, enhancing the overall understanding of the information.

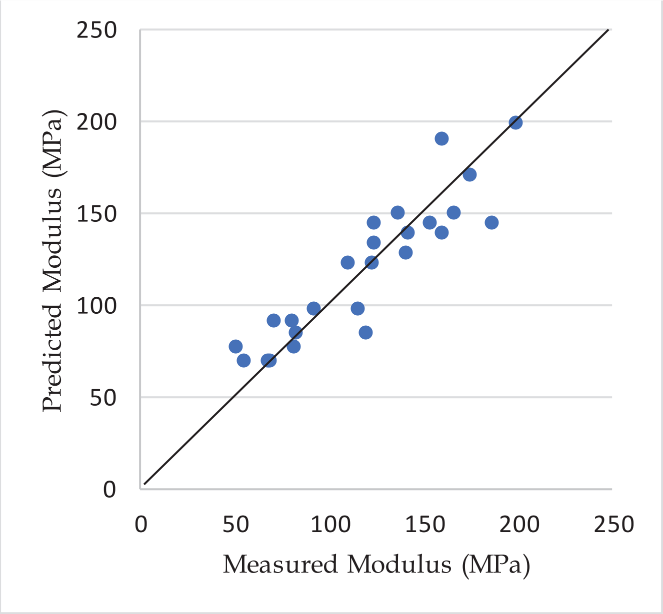

Figure 4 - Measured RM vs. Predicted RM

Table 2 -Distribution of Soil Types in Sri Lanka
(analyzed based on approximately 9,500 data points collected during this study)

Coarse-Grained Soil (50% or more retained on No. 200 sieve)	97.00%	**Gravel (G)**	3.84%	**GW**	0.00%
				GP	0.03%
				GW-GM, GP-GM, GW-GC, GP-GC	0.13%
				GM	0.96%
				GM-GC	0.11%
				GC	2.61%
		Sand (S)	93.16%	**SW**	1.21%
				SP	2.03%
				SW-SM, SP-SM, SW-SC, SP-SC	5.80%
				SM	41.20%
				SM-SC	4.04%
				SC	38.89%
Fine-Grained (More than 50% passes the No.200 sieve)	3.00%	**Low LL** (LL<50)	2.13%	**OL**	0.06%
				ML	0.50%
				ML-CL	0.04%
				CL	1.53%
		High LL (LL>50)	0.87%	**OH**	0.17%
				MH	0.37%
				CH	0.33%

Note: - All these classifications were based on the Unified Soil Classification System (USCS) [17]

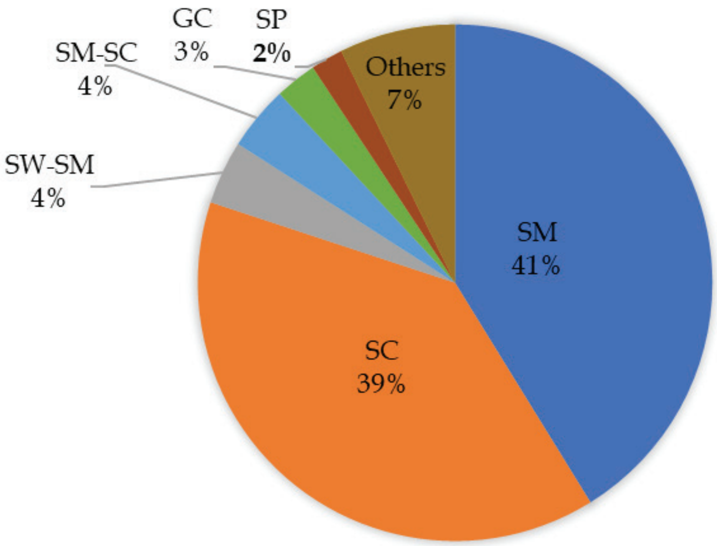

Figure 5 - Major Subgrade Soil Types as a Percentage

According to the above analysis, 97% of subgrade soils in Sri Lanka fallinto the coarse-grain category, while fine-grain soils account only for 3%.

Soil-wise, Silty Sand (SM) and Clayey Sand (SC) are the most prevalent soil types in Sri Lanka, accounting for 41% and 39%, respectively. Other subcategories, such as SW-SM, SC-SM, and GC, are in limited quantities.

4.4 Establishing Typical RM Values for Local Soil Types

This research placed significant emphasis on establishing typical RM values tailored to the specific characteristics of local soil types. Equation (9), developed in this study, was utilized to convert CBR values into RM values of sandy soil types to achieve this.

First, typical ranges for CBR values are established; the Interquartile Range (IQR) is employed for that purpose. The IQR is defined as the range of values that encompasses the middle 50% of a dataset, specifically those falling between the 25th and 75th percentiles. By utilizing the IQR, measure the spread of the central portion of the data, mitigating the influence of potential outliers.

The procedure involves arranging the CBR values in ascending order and identifying the 25th and 75th percentiles. The 25th percentile delineates the lower boundary of the central 50% of the data, while the 75th percentile marks the upper boundary.

The numerical difference between these two percentiles constitutes the IQR. The corresponding typical RM values were then estimated using the newly developed equation.

These study findings are briefly summarized in Table 3 for sandy soil types found in Sri Lanka. These values apply to Level 3 Mechanistic-Empirical (M-E) based pavement designs and can also be employed in provisional designs to estimate costs.

Table 3 - Typical CBR &RM values for sandy soil available in Sri Lanka

Soil Type	Typical CBR (%) Range	Typical RM Range (MPa)
SW	6 - 10	70 - 98
SP	4 - 12	53 - 111
SW-SM, SP-SM, SW-SC, SP-SC	4 – 12	53 - 111
SM	6 – 14	70 - 122
SM-SC	12 - 18	111 - 145
SC	6 - 14	70 - 122

4.5 Development of a Soil Database for MEPD

Establishing a comprehensive Soil Database to facilitate the MEPD involved a systematic approach to collecting subgrade soil test data along road traces. Each sampling location was geocordinated and subsequently mapped onto the Sri Lanka map using ArcGIS software, as depicted in Figure 6. At the time of writing this article, the data collection process had been completed for several provinces, such as Western, Eastern, Northern, and Uva provinces. Ongoing efforts are focused on extending coverage to encompass the entire country.

Detailed information, including soil classification, Atterberg limits, and CBR values, was meticulously recorded for each data location. Additionally, RM values were incorporated by applying Equation 10 to convert CBR values.

Upon finalizing the data collection for the entire country, this study will progress to developing a soil map based on RM values. This map will be a valuable resource for pavement designers, enabling them to accurately determine RM values for their Level 3 MEPD design projects.

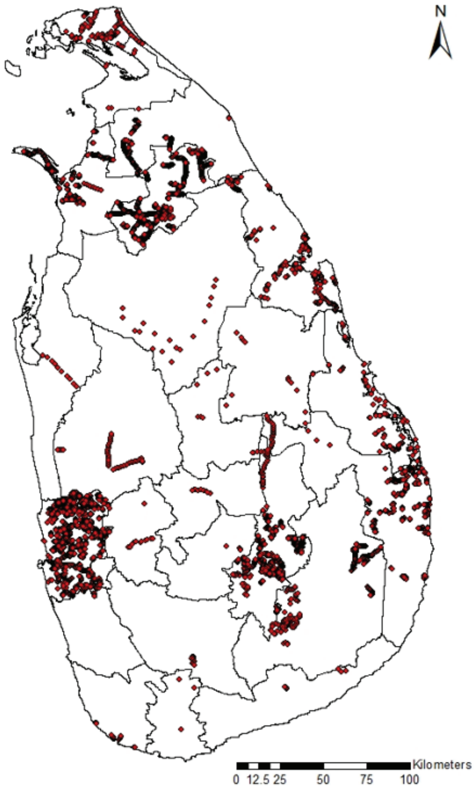

Figure 6 - Geographical locations of data points (Subgrade Locations)

5. Conclusions

Several key recommendations for Mechanistic-Empirical Pavement Design have been outlined based on the findings and insights derived from this study.

With this analysis, it is recommended to incorporate Equation (10) developed in this study,

$$RM = 2\,1.14 * CBR^{0.6656} \quad …. (10)$$

specifically for Level 2 MEPD in Sri Lanka. This equation is tailored to locally available coarse-grained sandy soil, which offers a more accurate and context-specific approach compared to other existing relationships that were not developed for the local soil.

For Level 3 MEPD designs and designs for cost estimates, it is advisable to utilize typical resilient modulus values established based on local soil types. More accurate RM values can be selected from the soil map for the areas where soil data is available.

Furthermore, this study exclusively concentrated on coarse-grained soils. To provide a comprehensive understanding of soil behaviour, it is essential to broaden the scope of the investigation to include fine-grained soil types. Researchers are encouraged to direct their focus toward the Resilient Modulus of unbound layers for locally available soils in the context of MEPD and construction works, as guided by the RDA Pavement Design Standards (RDAPDS).

It is further recommended that comprehensive studies be conducted to validate the developed RM vs. CBR relationships, especially once the Cyclic Triaxial Testing facility becomes available in Sri Lanka. Collectively, these measures enhance the accuracy and applicability of MEPD in Sri Lanka.

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