

## Article

# Development of an Open-Source R/Shiny Tool for Resilient Modulus Coefficient Interpretation in Pavement Engineering

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## Abstract

The resilient modulus is one of the primary parameters used in mechanistic–empirical pavement design methods and plays a fundamental role in pavement structural analysis and performance prediction. In Brazil, the implementation of the MeDiNa pavement design framework has increased the demand for accessible tools capable of supporting nonlinear modeling and coefficient interpretation. However, many available approaches still rely on proprietary software or spreadsheet-based workflows, limiting reproducibility, accessibility, and usability in teaching and research applications. This study presents the development of an open-source application based on R and Shiny for resilient modulus coefficient interpretation using the composite model adopted in the Brazilian MeDiNa methodology. The proposed application allows spreadsheet-based data importation, automated nonlinear coefficient estimation through nonlinear least-squares regression, graphical visualization of resilient modulus behavior, and generation of interactive three-dimensional response surfaces. Experimental datasets obtained from soil–aggregate mixtures, and published resilient modulus databases were used for validation. The results showed that the application successfully estimated the model coefficients and reproduced the stress-dependent resilient modulus behavior of the analyzed materials. The proposed tool provides an accessible and reproducible computational workflow for resilient modulus interpretation in pavement engineering research, teaching activities, and preliminary laboratory analyses associated with the MeDiNa framework.



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## 1. Introduction

Accurate estimation of the resilient modulus (MR) is a prerequisite for reliable mechanistic–empirical pavement design, since MR values directly govern the predicted structural response of unbound and subgrade layers and, consequently, rutting performance predicted for the pavement structure. Errors or inconsistencies introduced during

coefficient estimation propagate directly into design decisions, potentially leading to under- or over-designed pavement structures. Despite this importance, coefficient estimation and interpretation procedures for MR are still predominantly carried out using non-reproducible spreadsheet routines or closed, proprietary software, which restricts transparency, teaching use, and dissemination among Brazilian pavement laboratories, where the MeDiNa methodology has only recently created broad demand for this type of analysis. The present study addresses this gap by focusing specifically on the laboratory characterization stage of the mechanistic–empirical design process, supporting the determination of MR constitutive coefficients from triaxial test data for the design of new pavement structures. Mechanistic–empirical pavement design methodologies have become increasingly adopted worldwide because they provide a more realistic representation of pavement behavior under traffic loading and environmental conditions than traditional empirical approaches [1–3]. Unlike empirical methods, mechanistic–empirical frameworks incorporate material mechanical properties and constitutive relationships to predict pavement responses such as stresses, strains, rutting, and fatigue cracking, resulting in more reliable structural performance assessments throughout the pavement service life [1,2]. Consequently, laboratory characterization procedures capable of representing the stress-dependent behavior of pavement materials have become essential for modern pavement engineering applications [4,5].

Among the parameters required in mechanistic–empirical pavement design, the MR is considered one of the most critical material properties. It represents the recoverable elastic response of pavement materials subjected to repeated traffic loading and serves as a key input parameter for structural pavement analysis and performance prediction models [6–8]. Previous studies have demonstrated that MR is strongly influenced by stress state, moisture content, soil structure, degree of compaction, and material composition, requiring constitutive models capable of adequately describing its nonlinear and stress-dependent mechanical behavior [4,5,7,9–12]. As a result, accurate MR characterization has become an important step in modern design procedures.

Several constitutive models have been proposed to represent the nonlinear response of pavement materials under cyclic loading. Among the most widely adopted approaches are stress-dependent models that establish relationships between resilient modulus and stress-state variables such as confining stress, deviator stress, bulk stress, and octahedral shear stress [7,13–15]. The pioneering work of Uzan [7] demonstrated the importance of stress-dependent constitutive relationships for granular materials, while subsequent studies expanded these formulations, improved MR testing procedures, and enhanced their applicability to pavement engineering materials [10–12]. The calibration of these models generally requires nonlinear regression procedures to estimate empirical coefficients from repeated-load triaxial test data. and precise estimation and interpretation of these coefficients are essential because they directly influence the predicted mechanical response of pavement layers and, consequently, pavement design outcomes [13,15,16].

MeDiNa (National Pavement Design Method) is the official Brazilian mechanistic–empirical pavement design method, developed by DNIT in partnership with COPPE/UFRJ to replace the previous empirical method based on CBR. The methodology models the pavement structure as a layered elastic system and uses the resilient modulus of each layer as the primary input parameter to calculate critical stresses and strains under traffic loading via mechanistic analysis [8,17,18]. These calculated responses are subsequently used in transfer functions calibrated with Brazilian field data to predict pavement performance over its service life, particularly regarding fatigue cracking in the asphalt surfacing layer and accumulated rutting in the underlying layers. Therefore, accurate characterization of the resilient modulus is a fundamental input for the reliability of MeDiNa’s structural and performance predictions.

In Brazil, the implementation of the MeDiNa pavement design methodology represented an important milestone in the transition from empirical approaches toward mechanistic–empirical concepts [8,17]. The methodology incorporates constitutive models to describe the nonlinear response of pavement materials and requires the determination of model coefficients from laboratory testing. Consequently, MR characterization has become increasingly important for performance prediction under local conditions, particularly in studies involving tropical soils, lateritic materials, and recycled materials [4,5,19,20]. In particular, the growing use of reclaimed asphalt pavement (RAP) has increased the demand for reliable characterization procedures capable of supporting sustainable pavement engineering practices [20].

Although resilient modulus testing has become increasingly common in pavement laboratories, coefficient estimation procedures are still frequently performed using spreadsheets, isolated computational scripts, or proprietary software environments [21–23]. These approaches often require advanced user expertise, reduce reproducibility, and hinder broader dissemination among students, researchers, and pavement practitioners. Furthermore, the estimation of model coefficients and graphical interpretation of resilient modulus behavior are commonly conducted in separate computational environments, resulting in fragmented analytical workflows and increasing the likelihood of operational errors. Recent studies have highlighted the importance of reproducible computational workflows and accessible analytical tools for improving transparency, efficiency, and knowledge dissemination in engineering applications [24,25].

Recent advances in computational engineering have created opportunities to improve reproducibility, transparency, and accessibility in engineering analyses through the adoption of open-source software tools [24–27]. Reproducible computational workflows have become increasingly important in scientific research, enabling greater transparency, verification of results, and dissemination of analytical methodologies [24,25]. The R programming language has emerged as one of the most widely used platforms for statistical computing, data analysis, and scientific reproducibility, while the Shiny framework enables the development of interactive graphical user interfaces that allow users to perform advanced analyses without extensive programming knowledge [26,27]. Combining data importation, nonlinear regression, coefficient estimation, and graphical visualization within a single computational environment can significantly simplify MR interpretation procedures and improve their accessibility to a broader engineering audience.

The development of computational and experimental tools has already demonstrated significant contributions to pavement engineering research. Barra et al. [28], for instance, developed and validated the FADECOM apparatus, an integrated system for evaluating fatigue and stiffness modulus of asphalt mixtures, combining experimental measurements, signal processing algorithms, and computational analysis for pavement design applications. More broadly, recent advances in scientific computing have highlighted the importance of reproducible computational workflows, open-source environments, and automated analytical tools for improving transparency, reliability, and dissemination of engineering methodologies [24–27]. These developments reinforce the growing need for accessible engineering tools capable of supporting laboratory data interpretation, constitutive model calibration, and mechanistic–empirical pavement analyses.

Despite the growing adoption of mechanistic–empirical pavement design methods, there remains a lack of open-source and user-friendly tools specifically developed for MR coefficient interpretation within the MeDiNa framework. Existing approaches are commonly based on spreadsheets, software-specific routines, or computational procedures developed for individual research projects [21–23]. As a result, many available solutions require advanced programming skills or are not readily accessible to students, researchers,

and practicing engineers, limiting their broader use in teaching, research, and routine laboratory applications.

Therefore, this study presents the development of an open-source application based on R and Shiny for resilient modulus coefficient interpretation using the composite model adopted in the Brazilian MeDiNa methodology. The proposed application enables spreadsheet-based data importation, automated nonlinear coefficient estimation through nonlinear least-squares regression, graphical visualization of MR behavior, and generation of interactive three-dimensional response surfaces. Experimental data obtained from soil–aggregate mixtures containing reclaimed asphalt pavement (RAP) and published databases [21–23,29] were used as a validation case study. The proposed tool aims to provide an accessible, reproducible, and transparent computational workflow for MR interpretation in pavement engineering research, teaching activities, and laboratory practice.

## 2. Materials and Methods

This section describes the computational workflow adopted in the proposed application, the experimental database used for validation, the MR constitutive model implemented in the Brazilian MeDiNa framework, the nonlinear regression procedure, and the software architecture developed in R version 4.5.1, using the Shiny framework.

### 2.1. Overview of the Proposed Workflow

The proposed workflow was developed to provide an accessible and reproducible computational environment for MR coefficient interpretation using the composite model adopted in the Brazilian MeDiNa pavement design methodology. The workflow integrates spreadsheet-based data importation, nonlinear regression analysis, automated coefficient estimation, graphical visualization, and generation of three-dimensional response surfaces within a single interactive environment.

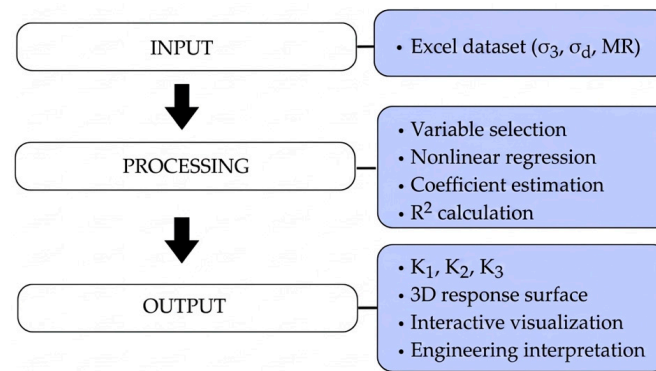
The application architecture follows three main stages: (i) data importation and preprocessing; (ii) nonlinear coefficient estimation through least-squares regression; and (iii) graphical visualization and interpretation of MR behavior. This structure enables users without programming experience to estimate coefficients through a graphical interface while maintaining the transparency and reproducibility associated with open-source computational environments.

Initially, laboratory resilient modulus data are imported into the application through Excel spreadsheets (.xlsx format). After data importation, the user selects the independent and dependent variables associated with the constitutive model. The selected variables are subsequently processed through nonlinear regression procedures to estimate the constitutive coefficients.

After the fitting stage, the application automatically estimates the MR coefficients, calculates the coefficient of determination ( $R^2$ ), and generates graphical outputs representing the stress-dependent resilient behavior of the analyzed material. The generated outputs include three-dimensional response surfaces that allow visual interpretation of MR variation under different stress conditions. Figure 1 presents the general workflow adopted in the proposed application.

### 2.2. Experimental Database

Experimental data used to validate the proposed application were obtained from MR tests performed on soil–aggregate mixtures containing reclaimed asphalt pavement (RAP), as shown in Table 1.



**Figure 1.** General workflow adopted in the proposed application.

**Table 1.** Composition of the evaluation mixtures.

| Mixture | Soil (%) | Gravel (%) | RAP (%) | Max. Dry Unit Weight (g/cm <sup>3</sup> ) | Optimum Moisture Content (%) |
|---------|----------|------------|---------|-------------------------------------------|------------------------------|
| M1      | 30       | 70         | 0       | 2.12                                      | 11.80                        |
| M2      | 30       | 35         | 35      | 2.03                                      | 12.11                        |
| M3      | 30       | 0          | 70      | 1.93                                      | 12.48                        |

The analyzed materials were investigated within the context of mechanistic–empirical pavement engineering applications involving recycled pavement materials.

MR tests were conducted under repeated loading conditions, following the stress sequences and testing procedures prescribed by standard DNIT 134/2018-ME, “Paving–Soils–Determination of resilient modulus–Test method” [30], which also serves as the reference test method adopted in the Brazilian mechanistic-empirical pavement design methodology, MeDiNa.

For each mixture ( $M_1$ ,  $M_2$ ,  $M_3$ ), tests were performed in triplicate for each of the eighteen stress state combinations ( $\sigma_3$ ,  $\sigma_d$ ) prescribed by the standard, resulting in a total of 54 individual test results per mixture. The coefficient of variation among replicates at each stress level was calculated to verify test repeatability, and the mean MR value obtained from the three replicates for each stress combination was used as input data for the nonlinear regression procedure implemented in the application, as illustrated in the INPUT stage of Figure 1.

The laboratory results were organized in spreadsheet format and subsequently imported into the developed application for automated coefficient estimation and graphical interpretation. The use of RAP-containing mixtures as a validation dataset was motivated by the increasing application of recycled materials in sustainable pavement engineering and mechanistic–empirical pavement design approaches.

### 2.3. Resilient Modulus Modeling

The resilient modulus interpretation implemented in the proposed application is based on the constitutive modeling procedures adopted within the Brazilian MeDiNa pavement design methodology. The workflow combines a stress-dependent model with nonlinear regression techniques to estimate model coefficients from laboratory test data. This section presents the constitutive relationship employed in the application and the nonlinear fitting procedure used for coefficient estimation.

#### 2.3.1. Composite Model Adopted in MeDiNa

The coefficient interpretation implemented in the proposed application was based on the composite constitutive model adopted by the Brazilian MeDiNa pavement design method-

ology [15,17]. The model represents resilient modulus as a function of confining stress and deviator stress and is widely employed for the characterization of granular materials, lateritic soils, and soil–aggregate mixtures subjected to repeated traffic loading [4,5,19].

The constitutive relationship is expressed as

$$MR = K_1 \cdot \sigma_3^{K_2} \cdot \sigma_d^{K_3} \quad (1)$$

where MR is the resilient modulus (MPa),  $\sigma_3$  is the confining stress (MPa),  $\sigma_d$  is the deviator stress (MPa), and  $K_1$ ,  $K_2$ , and  $K_3$  are regression coefficients determined experimentally.

The coefficients describe the sensitivity to variations in the stress state and are directly associated with the influence of confining and deviator stresses on material stiffness [13,15,19]. These parameters constitute the primary outputs generated by the proposed application and are subsequently used in mechanistic–empirical pavement design analyses.

### 2.3.2. Nonlinear Regression Procedure

The coefficient estimation procedure was implemented through nonlinear least-squares regression using the `nls()` function available in the R statistical environment, employing the default Gauss-Newton algorithm for iterative optimization. Parameter estimation was performed by minimizing the residual sum of squares between experimentally measured and predicted MR values, with convergence assessed based on the relative change in the residual sum of squares between iterations.

The nonlinear regression model implemented in the application follows the constitutive relationship adopted by the MeDiNa methodology. The fitting procedure requires the specification of initial parameter estimates to facilitate convergence of the nonlinear optimization algorithm. The initial values adopted in the application were:

- $K_1 = 1000$  (initial material stiffness coefficient);
- $K_2 = 0.5$  (initial estimate of the confining stress exponent,  $\sigma_3$ );
- $K_3 = 1.0$  (initial estimate of the deviatoric stress exponent,  $\sigma_d$ ).

These initial values were selected based on coefficient ranges commonly reported in the MR literature [4,5,19,20]. The adopted values were verified through preliminary fitting tests and consistently produced stable convergence of the nonlinear least-squares algorithm for all evaluated datasets.

After convergence, the application automatically extracts the estimated coefficients and calculates the coefficient of determination ( $R^2$ ) based on the correlation between measured and predicted MR values. These predicted values are subsequently used to generate graphical outputs and three-dimensional response surfaces for interpretation of stress-dependent material behavior.

The nonlinear regression procedure was integrated directly into the graphical interface, allowing automated coefficient estimation from spreadsheet-based laboratory datasets without requiring manual programming routines.

To evaluate the robustness of the proposed workflow, the algorithm was applied to datasets obtained from previously published studies involving distinct pavement materials and geomaterials. The estimated coefficients were subsequently used to calculate predicted MR values, which were compared with the corresponding experimental measurements. Model performance was assessed using the coefficient of determination ( $R^2$ ), allowing verification of the adequacy of the implemented fitting procedure across a broad range of datasets.

### 2.4. Software Architecture and Application Development

The proposed application was developed entirely using the R programming language combined with the Shiny framework for implementation of the graphical user interface.

Additional R packages were employed for spreadsheet importation, nonlinear regression procedures, and graphical visualization, including readxl version 1.4.3, plotly 4.12.0, and lattice 0.22-6. After importing a dataset, users select the variables corresponding to MR, confining stress, and deviator stress. The nonlinear regression analysis is then automatically executed, and the estimated coefficients are displayed within the graphical interface.

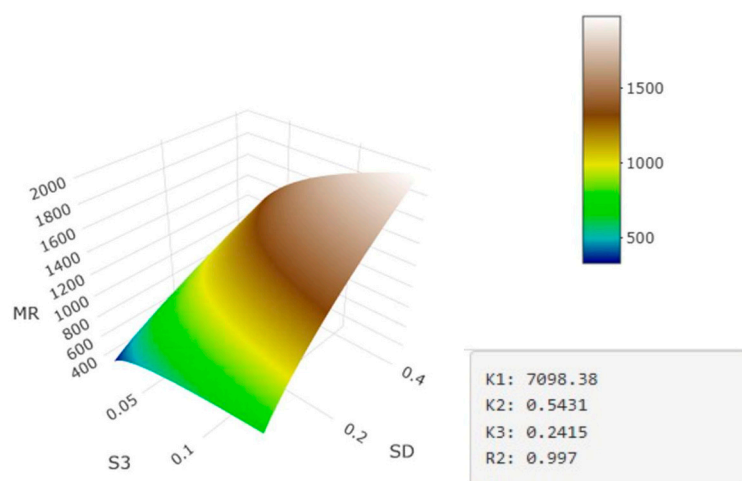
The application enables users to import datasets in Excel format, select dependent and independent variables associated with the constitutive model, execute nonlinear coefficient estimation procedures, obtain resilient modulus coefficients and goodness-of-fit statistics, and visualize three-dimensional resilient modulus response surfaces.

These 3D surfaces are rendered via the Plotly 4.12.0 package, enabling interactive rotation, zooming, and direct inspection of stress-dependent stiffness behavior. This functionality allows users to evaluate the influence of stress variables on MR and facilitates interpretation of constitutive model responses.

Figures 2 and 3 present representative screenshots of the developed application interface and examples of graphical outputs generated during MR interpretation.

### Composite Model

**Figure 2.** Main interface of the developed R/Shiny application.



**Figure 3.** Three-dimensional resilient modulus response surface generated from experimental data using the composite constitutive model.

The three-dimensional surface was generated using the experimental data from Sample 3 in Heidemann et al. (2025) [29], illustrating how the stress state and estimated coefficients ( $K_1$ ,  $K_2$ , and  $K_3$ ) govern the material's resilient response.

The application was designed to provide an accessible and reproducible environment for MR coefficient interpretation without requiring users to directly interact with R

scripts or statistical programming routines. The developed application is publicly available through the ShinyApps platform and can be accessed at <https://elisa-henning.shinyapps.io/Composite/> (accessed on 20 July 2026).

The source code and computational workflow are openly available and may be used for educational, research, and engineering applications.

### 3. Results and Discussion

This section presents the validation and performance evaluation of the proposed R/Shiny application for MR coefficient interpretation. The results focus on the capability of the developed tool to perform automated coefficient estimation, generate graphical representations of resilient modulus behavior, and provide a reproducible computational workflow for mechanistic–empirical pavement engineering applications.

#### 3.1. Application Functionality and Workflow Validation

The developed application successfully performed all stages of the MR interpretation workflow, including spreadsheet importation, nonlinear regression analysis, coefficient estimation, statistical evaluation, and graphical visualization of model responses. The validation datasets, composed of soil–aggregate mixtures containing reclaimed asphalt pavement (RAP) and additional datasets obtained from the literature, were imported and processed without additional preprocessing procedures, demonstrating the flexibility of the implemented workflow.

After variable selection, the nonlinear fitting procedure was automatically executed, and the estimated coefficients were displayed together with the corresponding coefficient of determination ( $R^2$ ). The automated implementation of the nonlinear regression procedure eliminates the need for manual coding and reduces the possibility of user-related operational errors. This feature is particularly relevant for teaching activities, research applications, and routine laboratory analyses, where users may have limited experience with statistical programming environments.

The obtained results demonstrated that the developed application was capable of successfully calibrating the composite MR model for datasets obtained from different studies, producing coefficients of determination ranging from 0.88 to 0.99. These values indicate excellent fitting performance and demonstrate the ability of the implemented nonlinear regression procedure to reproduce the stress-dependent resilient behavior of different pavement materials and geomaterials.

#### 3.2. Graphical Interpretation of Resilient Modulus Behavior

One of the main functionalities of the developed application is the generation of interactive three-dimensional resilient modulus response surfaces. Figure 3 presents an example of the graphical output generated from the fitted constitutive model.

The generated response surface enables direct visualization of the influence of confining stress and deviator stress on predicted values. Such graphical representations facilitate the interpretation of stress-dependent resilient behavior and provide a more intuitive understanding of constitutive model responses compared with conventional tabular outputs.

The interactive visualization environment allows users to rotate, zoom, and inspect the generated surfaces, improving the interpretation of MR trends and model sensitivity to stress-state variables. This functionality is particularly useful in educational environments, where the visualization of nonlinear constitutive behavior may contribute to a better understanding of mechanistic–empirical pavement design concepts.

The generated response surfaces also provide a rapid verification of model consistency and fitting quality. Unexpected trends, unrealistic coefficient estimates, or inconsistent

model responses can be visually identified, providing an additional quality-control mechanism during MR interpretation.

### 3.3. Coefficient Estimation Performance and Practical Applications

The proposed application was developed to automate the estimation of MR coefficients, providing a computational environment capable of generating reliable calibrations of the composite model from laboratory data. To evaluate its predictive performance, the tool was validated using datasets presented by Sagrilo (2020) [22], Maria (2021) [23], and Heidemann et al. (2025) [29], which comprise eighteen stress-state combinations representative of loading conditions adopted in mechanistic–empirical pavement design procedures.

Table 2 presents the observed and predicted MR values, as well as the corresponding prediction errors obtained using the estimated coefficients.

**Table 2.** Observed and predicted MR values and corresponding prediction errors for the validation datasets.

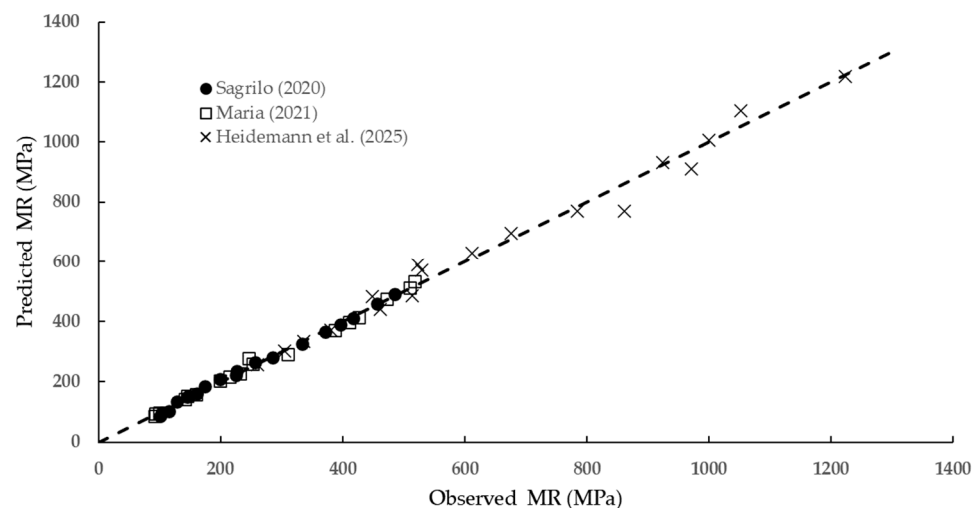
| $\sigma_3$ | $\sigma_d$ | Sagrilo (2020) [22] |                    |           | Maria (2021) [23] |                    |           | Heidemann et al. (2025) [29] |                    |           |
|------------|------------|---------------------|--------------------|-----------|-------------------|--------------------|-----------|------------------------------|--------------------|-----------|
|            |            | Observed MR (MPa)   | Predicted MR (MPa) | Error (%) | Observed MR (MPa) | Predicted MR (MPa) | Error (%) | Observed MR (MPa)            | Predicted MR (MPa) | Error (%) |
| 0.020      | 0.020      | 101.77              | 86.29              | 15.48     | 92.27             | 87.38              | 4.89      | 261.00                       | 255.96             | 5.04      |
| 0.020      | 0.040      | 104.14              | 96.66              | 7.48      | 92.88             | 93.85              | −0.97     | 305.22                       | 302.99             | 2.23      |
| 0.020      | 0.060      | 116.06              | 103.29             | 12.77     | 100.43            | 97.86              | 2.57      | 335.75                       | 334.41             | 1.34      |
| 0.035      | 0.035      | 128.81              | 135.12             | −6.31     | 141.69            | 142.25             | −0.56     | 381.38                       | 371.23             | 10.15     |
| 0.035      | 0.070      | 145.17              | 151.36             | −6.19     | 145.47            | 152.78             | −7.31     | 462.14                       | 439.44             | 22.70     |
| 0.035      | 0.105      | 161.33              | 161.76             | −0.43     | 160.54            | 159.29             | 1.25      | 514.52                       | 485.02             | 29.50     |
| 0.053      | 0.050      | 174.38              | 186.64             | −12.26    | 198.92            | 202.93             | −4.01     | 449.26                       | 482.18             | −32.92    |
| 0.053      | 0.100      | 198.57              | 209.07             | −10.50    | 214.42            | 217.95             | −3.53     | 529.84                       | 570.79             | −40.95    |
| 0.053      | 0.150      | 225.62              | 223.43             | 2.19      | 232.33            | 227.25             | 5.08      | 611.95                       | 629.99             | −18.04    |
| 0.070      | 0.070      | 226.44              | 235.49             | −9.05     | 252.51            | 260.11             | −7.60     | 522.56                       | 588.36             | −65.80    |
| 0.070      | 0.140      | 256.32              | 263.80             | −7.48     | 246.20            | 279.36             | −33.16    | 675.85                       | 696.48             | −20.63    |
| 0.070      | 0.210      | 285.41              | 281.91             | 3.50      | 309.82            | 291.28             | 18.54     | 783.96                       | 768.71             | 15.25     |
| 0.105      | 0.105      | 333.94              | 325.91             | 8.03      | 386.77            | 370.23             | 16.54     | 861.93                       | 770.27             | 91.66     |
| 0.105      | 0.210      | 371.13              | 365.09             | 6.04      | 411.28            | 397.64             | 13.64     | 971.81                       | 911.81             | 60.00     |
| 0.105      | 0.315      | 396.05              | 390.16             | 5.89      | 426.18            | 414.60             | 11.58     | 1000.16                      | 1006.37            | −6.21     |
| 0.140      | 0.140      | 417.21              | 410.42             | 6.79      | 472.49            | 475.62             | −3.13     | 924.44                       | 932.51             | −8.07     |
| 0.140      | 0.280      | 457.12              | 459.76             | −2.64     | 510.72            | 510.83             | −0.11     | 1052.19                      | 1103.86            | −51.67    |
| 0.140      | 0.420      | 485.04              | 491.33             | −6.29     | 517.36            | 532.62             | −15.26    | 1224.09                      | 1218.31            | 5.75      |

The results presented in Table 2 indicate a high level of agreement between experimentally measured values and those estimated by the calibrated model. The prediction errors remained generally low across the evaluated stress states, indicating that the estimated coefficients could reproduce the experimental values with satisfactory accuracy. No systematic bias was observed, suggesting that the implemented fitting procedure adequately captured the stress-dependent behavior of the analyzed materials.

Figure 4 presents the comparison between observed and predicted MR values for all evaluated datasets.

The close agreement between observed and predicted values demonstrates the capability of the proposed workflow to reproduce experimentally observed resilient behavior. The concentration of data points near the one-to-one reference line indicates that the implemented nonlinear regression procedure provided stable and reliable coefficient estimates over a broad range of stress conditions.

To further evaluate the robustness of the proposed workflow, additional MR datasets reported by different authors were analyzed. Table 3 summarizes the estimated coefficients and goodness-of-fit indicators obtained for the evaluated databases.



**Figure 4.** Comparison between observed and predicted resilient modulus values obtained from the datasets of Sagrilo (2020) [22], Maria (2021) [23], and Heidemann et al. (2025) [29]. The dashed line represents the one-to-one relationship.

**Table 3.** Estimated composite model coefficients and goodness-of-fit indicators obtained for resilient modulus datasets reported in the literature.

| Author                       | Sample   | $K_1$   | $K_2$ | $K_3$ | $R^2$ |
|------------------------------|----------|---------|-------|-------|-------|
| Sagrilo (2020) [22]          | CA1      | 2785.00 | 0.64  | 0.18  | 0.99  |
|                              | CA2      | 1644.84 | 0.54  | 0.17  | 0.99  |
|                              | CA3      | 1894.08 | 0.64  | 0.16  | 0.99  |
| Pascoal (2020) [21]          | CA work  | 24.64   | 0.17  | −0.49 | 0.97  |
|                              | 509 work | 25.96   | 0.10  | −0.43 | 0.95  |
|                              | Km3 work | 12.84   | 0.94  | −0.56 | 0.98  |
| Maria (2021) [23]            | M1       | 991.54  | 0.54  | 0.08  | 0.94  |
|                              | M2       | 2217.28 | 0.70  | 0.13  | 0.99  |
|                              | M3       | 2634.68 | 0.77  | 0.10  | 0.99  |
| Heidemann et al. (2025) [29] | M1       | 3443.22 | 0.42  | 0.24  | 0.98  |
|                              | M2       | 6053.84 | 0.49  | 0.29  | 0.99  |
|                              | M3       | 7098.38 | 0.54  | 0.24  | 0.99  |
| This study                   | M1       | 542.20  | 0.25  | 0.00  | 0.92  |
|                              | M2       | 529.74  | 0.33  | −0.15 | 0.88  |
|                              | M3       | 639.88  | 0.42  | −0.17 | 0.92  |

The coefficient of determination values obtained for the analyzed datasets ranged from 0.88 to 0.99, demonstrating excellent fitting performance regardless of material type. These results indicate that the proposed application can successfully calibrate the composite model for soil–aggregate mixtures, recycled materials, granular materials, lateritic soils, and other pavement geomaterials reported in the literature.

The variability observed in the estimated coefficients reflects differences in material composition, stress sensitivity, and mechanical behavior among the analyzed datasets. Such variability is expected and further demonstrates the flexibility of the application to calibrate the composite model for distinct pavement materials without requiring modifications to the computational workflow.

It is worth noting that the RAP-containing mixtures evaluated in this study (M<sub>2</sub> and M<sub>3</sub>, with 35% and 70% RAP content, respectively) produced comparatively lower coefficients of determination (0.88 and 0.92) than most of the non-RAP datasets used for validation (0.94–0.99). This trend is consistent with the recognized heterogeneity of RAP as a pavement material. Residual asphalt films surrounding RAP particles, variability in aggregate–binder interaction, and differences in particle-size distribution may intro-

duce additional dispersion into the mechanical response of RAP-containing blends and consequently affect the goodness of fit of stress-dependent constitutive models. From a generalizability perspective, because the composite model and the nonlinear fitting procedure implemented in the application are independent of material type, the tool remains directly applicable to RAP-containing and other recycled mixtures. However, users should be aware that the reliability of the fitted coefficients for highly heterogeneous recycled materials may be more sensitive to the quality and consistency of the underlying laboratory data than for more homogeneous granular materials or lateritic soils. Nevertheless, the coefficients of determination obtained for the RAP-containing mixtures still indicate satisfactory to very good fitting performance for engineering applications.

From a generalizability standpoint, because the composite model and the nonlinear fitting procedure implemented in the application are material-agnostic, the tool remains directly applicable to RAP-containing and other recycled mixtures. However, users should be aware that the reliability of the fitted coefficients for highly heterogeneous recycled materials may be more sensitive to the quality and consistency of the underlying laboratory data than for more homogeneous granular or lateritic soils.

In addition to the fitting performance, it is also relevant to examine the effect of the granulometric stabilization on the MR itself. The pure soil presented an average MR of 105.7 MPa, whereas the stabilized mixtures resulted in substantially higher values: 269.07 MPa for M1 (an increase of 254% relative to the pure soil), 292.16 MPa for M2 (an increase of 276%), and 291.48 MPa for M3 (an increase of 275%).

These results demonstrate the performance improvement achieved through granulometric stabilization of the soil with crushed stone and RAP, with all three mixtures showing a substantial increase in resilient modulus relative to the unstabilized soil. It is worth noting that the increase in MR is not strictly proportional to RAP content alone (M2 and M3 present comparable increases despite their markedly different RAP proportions, 35% and 70%, respectively), suggesting that the overall gradation achieved by combining soil, gravel, and RAP plays a more decisive role in the resulting stiffness than the RAP content in isolation.

Compared with conventional spreadsheet-based workflows, the proposed application integrates data importation, coefficient estimation, statistical evaluation, and graphical interpretation within a single computational environment. This integration reduces manual processing steps and contributes to greater reproducibility, consistency, and transparency in MR analyses.

The use of open-source technologies provides additional benefits related to accessibility and reproducibility. Because the application was developed using R and Shiny, researchers, students, and practitioners may readily access and apply the computational workflow to different datasets without requiring proprietary software environments.

Although the application was validated using datasets containing RAP mixtures and other pavement materials reported in the literature, the implemented workflow is not restricted to these material types. The proposed framework can be applied to any pavement material compatible with the composite model adopted by the MeDiNa methodology, including granular materials, lateritic soils, and stabilized mixtures.

Overall, the results demonstrate that the proposed application provides an accessible, reproducible, and efficient tool for MR coefficient interpretation, contributing to the dissemination of mechanistic–empirical pavement design concepts and supporting teaching activities, research applications, and preliminary engineering analyses.

## 4. Conclusions

This study presented the development of an open-source application based on the R programming language and the Shiny framework for MR coefficient interpretation using the composite constitutive model adopted by the Brazilian MeDiNa pavement design methodology.

The developed application successfully integrated spreadsheet-based data importation, nonlinear regression analysis, automated coefficient estimation, statistical evaluation, and graphical visualization within a single computational environment. The proposed workflow simplifies MR interpretation procedures, reduces manual processing requirements, and improves the reproducibility of mechanistic–empirical pavement engineering analyses.

Validation performed using datasets obtained from different studies demonstrated the robustness of the implemented nonlinear regression procedure. The application successfully calibrated the composite model for distinct pavement materials and geomaterials, producing coefficients of determination ( $R^2$ ) ranging from 0.88 to 0.99. These results indicate that the proposed workflow is capable of accurately reproducing the stress-dependent resilient behavior of a wide range of materials commonly used in pavement engineering.

The interactive graphical tools incorporated into the application, particularly the three-dimensional response surfaces, provide additional support for understanding constitutive model behavior and interpreting the influence of stress-state variables on the resilient modulus. These features make the application suitable not only for research activities but also for teaching and training purposes in mechanistic–empirical pavement design.

Despite these contributions, some limitations should be acknowledged. The application currently implements only the composite constitutive model adopted by the Brazilian MeDiNa methodology, as this framework was the primary focus of the present study. Other resilient modulus models used internationally, such as those adopted in the MEPDG framework, follow different formulations and were therefore beyond the scope of this work. In addition, the validation was performed using a limited number of datasets and material types, and further evaluation involving a broader range of pavement materials and loading conditions would strengthen the general applicability of the proposed tool. The application is also restricted to the laboratory-based coefficient estimation stage and does not perform structural pavement response analyses. Finally, as with any nonlinear least-squares procedure, the quality and stability of the estimated coefficients depend on the quality of the input data and on appropriate initial parameter estimates. Despite these limitations, the proposed application represents, to the authors' knowledge, one of the first freely available tools specifically developed for resilient modulus coefficient estimation within the Brazilian MeDiNa framework.

Future developments may include the implementation of additional constitutive models, incorporation of permanent deformation analyses, expansion of statistical evaluation tools, and integration with broader mechanistic–empirical pavement design workflows.

**Supplementary Materials:** The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/eng7080374/s1>: Supplementary Material S1: Complete R source code used for the development of the proposed R/Shiny application, including routines for data importation, nonlinear regression analysis, coefficient estimation, and graphical visualization. Supplementary Material S2: Example Excel dataset used for application testing and validation, containing resilient modulus, confining stress, and deviator stress values compatible with the composite model adopted by the MeDiNa methodology.

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A.A.A.d.S.; visualization, H.P.N.; supervision, H.P.N. and E.H.; project administration, H.P.N. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The application developed in this study is publicly available through the ShinyApps platform at <https://elisa-henning.shinyapps.io/Composite/> (accessed on 20 July 2026). The R source code used for application development and an example Excel dataset used for testing and validation are provided as Supplementary Materials S1 and S2. Additional data supporting the findings of this study are available from the corresponding author upon reasonable request.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

|         |                                                                    |
|---------|--------------------------------------------------------------------|
| AASHTO  | American Association of State Highway and Transportation Officials |
| FADECOM | Fatigue and Stiffness Modulus Evaluation Device                    |
| GUI     | Graphical User Interface                                           |
| MeDiNa  | Brazilian National Pavement Design Method                          |
| MR      | Resilient Modulus                                                  |
| NCHRP   | National Cooperative Highway Research Program                      |
| RAP     | Reclaimed Asphalt Pavement                                         |

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