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CASE STUDY ON THE EFFECT OF RECYCLED ASPHALT LAYER PARAMETERS ON THE BEARING CAPACITY OF THE PAVEMENT

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Abstract. Numerous ways to use recycled asphalt (RA) in the road base course will provide both environmental and economic benefits, allowing to recycle and utilise this initially waste material in road or pavement reconstruction projects. However, the properties and parameters of RA necessary for the application of reclaimed asphalt pavement (RAP) in a new pavement structure in most cases are not detectable in the design stage, which complicates design and construction process. The purpose of this paper is to study possibilities for evaluating the performance and parameters of RA, as well as to review the possibilities, methods and applications for RA testing. Data for this case study were obtained from recently completed road structures in the form of FWD measurements, together with lab explored parameters of drilled pavement cores. Based on that data, the relationships between the main pavement structural parameters, such as modulus on the surface of the pavement, compressive strength of RA core segment, thickness of bound layers and back

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calculated modulus were examined. On the way to exploring different analytical approaches, two approximation models were developed and compared, using the obtained data: by directly approximating the obtained data and after processing them with artificial neural network (ANN).

Keywords: artificial neural network (ANN), base damage index (BDI), compressive strength, FWD, pavement testing, reclaimed asphalt pavement (RAP), recycled asphalt, resilient modulus.

Introduction

The incremental distress and damage accumulation in a road pavement under certain traffic load, material properties of bound and unbound pavement structural layers and subgrade, climatic and geotechnical constraints are well known phenomena, which condition the growing need for repair and reconstruction of existing road structures using increasing amounts of new materials. Since Latvia does not possess its own oil deposits and enough rock suitable for asphalt production, most of the basic asphalt components must be imported. Thus, it is very important to recycle the used road pavement materials making emphasis on RA.

At the same time, due to the tightening environmental requirements for the industry and as a way to reduce the environmental impact of bituminous pavements, there is a growing demand for more effective possibilities and motivation to reuse bituminous material from the reconstructed pavements. Some new technologies were introduced in the bituminous road pavement sector earlier, which nowadays, apart from the economic benefits, are considered to have also environmental benefits. These so-called “green” technologies need to be analysed in detail in order to make an informed decision on the environmental impact. The environmental impact of a certain product is dependent on various preconditions, e.g. local aspects, valid regulations, and application and performance in practice. As it is concluded by Anthonissen, Van den Bergh, & Braet (2016), the use of RAP in new asphalt mixtures yields significant environmental advantages due to the saving of virgin materials and reduced transportation distances of raw material.

Thus, due to increased construction costs and rising environmental awareness, there is a definite need for structured research on the possibilities, properties and technologies for the use of RAP in road pavement construction. RAP is considered a good alternative for the road base course from technical, economic and environmental points of view. In order to use RAP in road pavement, its granular structure usually needs to be improved by adding virgin aggregate and stabilized with the binder – either cement, lime, or bitumen. At the same time, proper design procedures and calculations should be provided. At the moment, there are limited possibilities to predict and design the properties of prepared RAP due to high material anisotropy, lack of knowledge about its structural behaviour and field performance data about experience of RAP implementation, as well as about conditions and parameters of the existing pavement. Typically, there is no sufficient information available about design parameters and procedures for stabilizing of RA material. The purpose of this study is to fill in the gap in experience of designing and using RA in road pavement structures.

In Latvia, several projects have already been implemented, where cement stabilized RA was used as a base layer laid above the remaining road structure. In this study, the bearing capacity parameters and other information about the pavement structure with the stabilized RA road base layers were acquired and analysed to search for new approaches and principles to evaluate and design RAP-based road structure solutions.

1. Literature review

So far, many researchers have studied the trends in concrete properties using previously published research data in an attempt to establish a relationship between compressive strength and modulus of elasticity of concrete materials, including recycled materials.

Silva, De Brito, & Dhir (2016) described the effect of incorporating recycled aggregates on the modulus of elasticity of concrete pointing considering the contributing factors, such as replacement level, size and origin, as well as mixing procedures, exposure of the resulting concrete to different environmental conditions, use of chemical admixtures and additions, and development of the modulus of elasticity over time. The statistical analysis was conducted in order to explain the loss of modulus of elasticity based on the quality and replacement level of recycled aggregates. The paper suggests a relationship between the modulus of elasticity and compressive strength.

Some authors tried to use ANN as a validation tool comparing the results calculated using traditional pavement design approaches with the results obtained by the trained ANN algorithm. Abo-Hashema (2009) tried to simplify mechanical-empiric design procedures by replacing them with the trained ANN model. The researcher concludes that ANN technique can be used to determine the pavement overlay thickness with high accuracy based on M–E procedure.

Trtnik, Kavčič, & Turk (2009) show that ANN can be successfully used in modelling and predicting concrete strength relationships, it can be also used to easily estimate the compressive strength of concrete by using only the ultrasonic pulse velocity value and some mix parameters of concrete.

Tabaković, Gibney, McNally, & Gilchrist (2010) find that the base course containing up to 30% RAP displayed improved fatigue resistance relative to the control mix manufactured from virgin materials.

Bleakley & Cosentino (2013) studied the properties of cold recycled RAP solutions, as well as RA blends that were generated in situ from full–depth reclamation (FDR). It was established that M_R values of the untreated cold recycled RAP blends and the untreated FDR RAP blends ranged from 120 MPa to 502 MPa and 171 MPa to 578 MPa, respectively, and M_R values of the cement–treated FDR RAP blends were significantly higher than the untreated FDR RAP blends, they also had lower permanent strains.

The previous researches unanimously suggest that there is a decrease in the modulus of elasticity as the RA usage level in RAP increases, provided that every other parameter related to the mix design is constant. This loss is directly associated with the lower elastic modulus of RA, which consequently governs the modulus of elasticity of the resulting material. According to Noguchi & Nemati (2007), in the case of regular concrete there is a nonlinear correlation between elastic modulus and compressive strength. This would be a sufficient reason to expect that a similar relationship applies to the lean concrete and RA. It is also stated that there is no significant difference between the parameters considered, if they are measured using cores of different diameters (100 mm and 150 mm). As to the concrete, similar properties have been previously recorded for stabilized soil (Lee, Kim, Yoon, & Lee, 2014). The parameters of concrete produced using RA have also been studied by Huang, Shu, & Burdette (2006), however there is no direct comparison with the strength parameters and the amount of binder is closer to the concrete consistency (15–20%). The compressive strength values set there are between 15 MPa and 30 MPa and the modulus of elasticity – between 10 GPa and 30 GPa, which is a relatively high strength material. In other similar studies, only predominantly high-strength RAP materials have been discussed. All of the above-mentioned studies have been performed on laboratory prepared samples. They are usually 100 mm or 150 mm in diameter with h = 300 mm. Information on the studies with samples of other height dimensions was not considered.

2. Methodology and measurements

2.1. Method

The data for analysis of the bearing capacity of RAP containing pavement were acquired on the recently completed reconstructed road sections. The road sections studied are part of the national main road network – they are located on roads A1, A3, A7, A8, A9, and A12. Traffic intensity in these sections is similar, therefore, it is reasonable to assume that the designed road pavement structures also have similar load-bearing parameters. This assumption is used to estimate the measured RA layer parameters.

Since road sections under research have been recently completed, all design data, including actual geotechnical and hydrological conditions, as well as the road works documentation has been available. In order to detect actual thickness of each pavement layer, test cores from whole depth of pavement structure at each section under research were taken and measured.

FWD testing was performed along each road section. Since each side of the road structure in all tested sections was built using separate technological processes, FWD test points were spread out equally on both sides along each section, with 50 m interval between them. FWD tests were conducted twice on each test point – in early autumn and spring in order to acquire data in possibly extensive range of hydrological conditions that are expected to affect the bearing capacity of the pavement. In such a way, more than a thousand FWD measurements, each attached to the respective pavement structure (core) containing RA and to the corresponding geotechnical data, were acquired. FWD measurement data under the load center (d_1) and at the distance of 30 cm, 60 cm, 90 cm, 120 cm, 150 cm and 180 cm (d_2 to d_7, respectively) from load center were used for analysis. Modulus of elasticity on surface (E_1) and in depth of pavement structure (E_2 to E_7, respectively) then were back calculated using the measured deflections:

$$E(1) = \frac{2x\left(1-\nu^2\right)\sigma_0 a}{\mathrm{d}r}, \quad \text{if } r = 0; \tag{1}$$

$$E(r) = \frac{\left(1-\nu^2\right)\sigma_0 a^2}{r\mathrm{d}r(r)}, \quad \text{if } r > 2a \tag{2}$$

where E(r) – modulus of elasticity at depth r; ν – Poisson's ratio ($\nu = 0.35$); σ_0 – stress under load, MPa; a – diameter of the load area, cm; r – distance from the load center, cm; dr(r) – measured deflection at distance r.

FWD data were obtained twice at the same test points – in November and in April, in order to identify the worst condition depending on water content in the subgrade. Because the weather conditions during FWD tests were different, the results were adjusted to pavement temperature according to Chen, Bilyeu, Lin, & Murphy (2000):

$$d = d_T \left[10^{(68-T)} \right], \tag{3}$$

where d – adjusted deflection to the reference temperature of 20 °C (68 °F), in; d_T – deflection measured at temperature T (°F), in;

$$\alpha = 3.67 \cdot 10^{-4} \cdot t^{1.4635} \text{ (for wheel paths)},$$

where t – thickness of the AC layer, in; T – mid-depth temperature (°F) of the AC layer at the time of FWD testing.

The RA layer core segments were tested in compression tests. Tests were performed in accordance with EN 13286–43:2013 L "Unbound and hydraulically bound mixtures – Part 43: Test method for the determination of the modulus of elasticity of hydraulically bound mixtures", with universal testing apparatus Instron 8202 (250 kN load frame) in unconfined compression test. Both modulus of elasticity E_{RA} and compression resistance σ_{RA} were obtained from the drilled RA samples.

The design value of resilient or elastic modulus E_{RA} on the stabilized RA layer as well as base damage index[1] (BDI) was derived based on the obtained FWD data. Additionally, the quality and consistency of construction works were analysed by examining information from FWD measurements, cores and design data.

It must be noted that during drilling of RA samples from road pavement, the core structure was damaged to a great extent. Condition of the RA samples in this study varied in a large range – from dense to lose. The weakest core samples (about 10%) were damaged seriously and were no longer usable for testing. Other ones were damaged partially – more or less, mostly depending on binder content in the mixture. With regard of this circumstance, the following conclusion may be made: a more appropriate evaluation methods must be developed or adapted for RAP structures, knowing that RA can also be a loose material. Test procedures that were developed for regular concrete or asphalt in most cases are not suitable for RA mixtures. Even if the core is suitable for testing, invisible damages that occur during sample drilling can lead to significant underestimated factors in test results.

[1] Base Damage Index: $BDI = d_2 - d_3$.

It should be also borne in mind that the height of the drilled core specimens usually varies and it is virtually impossible to obtain the dimensions required by the standardized test description, designed to work with the samples prepared in the laboratory.

2.2. Analysis

Based on the data obtained during the study, most of the obvious relations were singled out and evaluated. As the BDI is defined as a parameter, which reflects the bearing properties of the pavement structure, it was examined by relaying it in a direct way with all important RAP parameters in this study:

- compressive strength of RAP material σ;
- back calculated modulus of elasticity on the pavement surface E_1;
- modulus of elasticity of RA measured from the drilled cores E_{RA};
- thickness of RA layer h_{RA}, which is set during the design process according to the related structure and design parameters. It is assumed that design modulus of RA material is 500 MPa, as it is set in the design guide, and the designed pavement structures, including RA layer with thickness h_{RA}, all demonstrate similar bearing capacity.

The obtained relationships are shown in graphs in Figures 1, 2, 3 and 4. As it may be seen from Figures 1 and 3, the relationships between BDI and strength parameters of RA shows no or weak correlation.

The relationship between the modulus on the pavement surface E_1 and *BDI* is strong (Figure 2), however, that was to be expected, because *BDI* and E_1 are in indirect functional dependence. Closer investigation may lead to the observation that the dependence is not linear, as might have been expected.

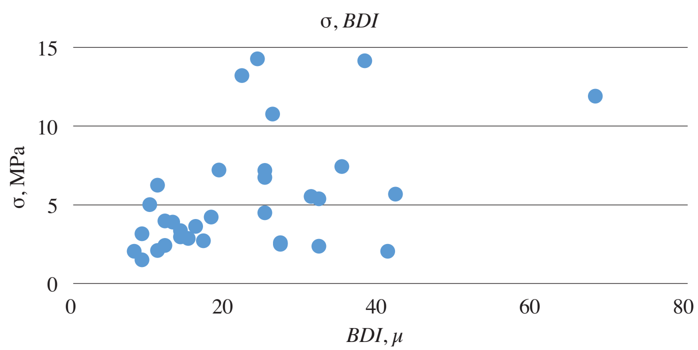

Figure 1. Relationship between *BDI* and compressive strength of RA

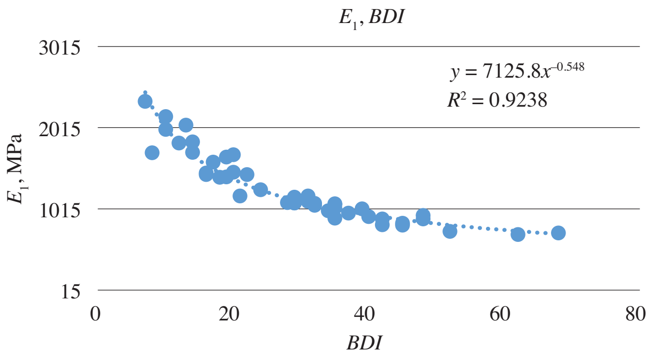

Figure 2. Relationship between *BDI* and back calculated from deflection d_1

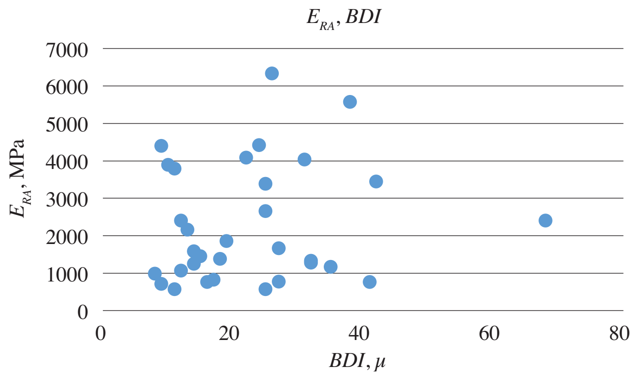

Figure 3. Relationship between modulus of elasticity of *RA* and *BDI*

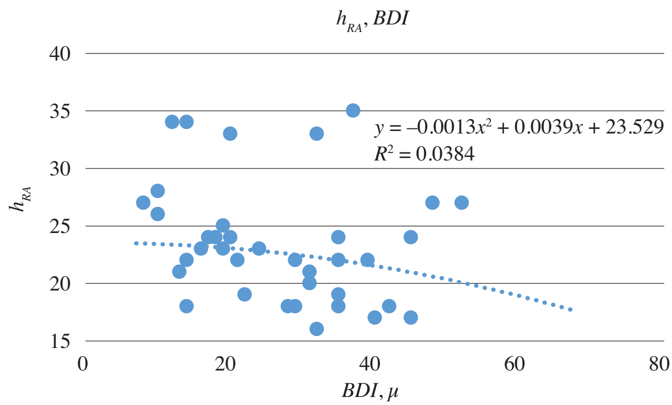

Figure 4. Relationship between thickness of *RA* layer and *BDI*

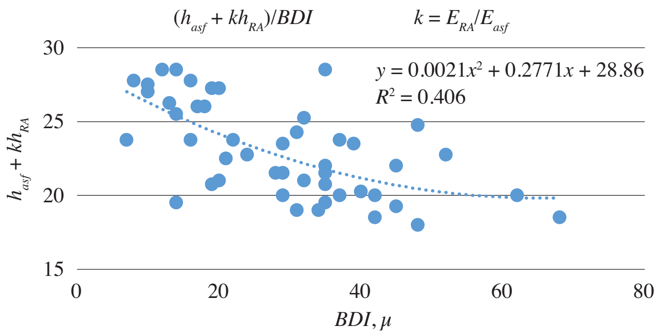

Figure 5. Relationship between function h_{asf} + 0.2h_{RA} and *BDI*

To understand the reason for the relatively high dispersion and poor correlation, adjacent factors were considered – the total thickness of the bound layers of the pavement structure: $h_{asf} + h_{RA}$. Again, there was no fixed significant correlation between the strength parameters of the measured RAP material and total pavement bearing capacity and BDI measured by FWD. The strongest correlation was found between the function of the bound layer thicknesses: $f(h) = h_{asf} + kh_{RA}$, where $k = E_{RA}/E_{asf}$, and *BDI*, reaching regression factor $R^2 = 0.4$ (Figure 5). Similar to the previous relationships, the last one also was weak. The shape of the relationship $(h_{asf} + kh_{RA})/BDI$ is similar to the shape of the relationship E_1/BDI (Figure 2). This leads to an idea of using those relationships for design calculations. From graphs E_1/BDI (Figure 2) and $(h_{asf} + kh_{RA})/BDI$ (Figure 5) it may be observed that if the total thickness of bound layers rises, it results in a rather rapid increase of the bearing capacity of the pavement structure. If the reference point (desired strength) is taken, for example, $BDI = 35$ (see graph E_1/BDI in

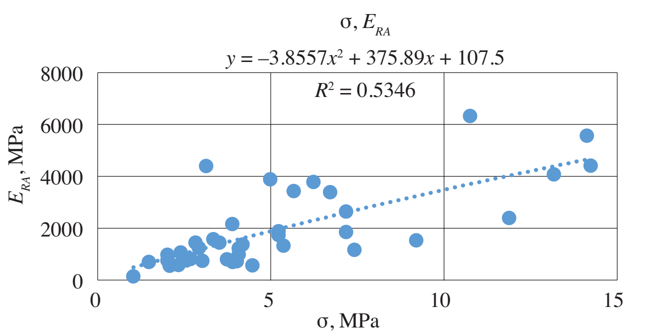

Figure 6. Relationship between compressive strength and modulus of elasticity of *RA*

Figure 2), which corresponds to approximately E_1 = 1000 MPa, then this corresponds to the total thickness of bound layers ~ 22 cm (Figure 5), if k = 0.2. The reduction is made by applying a coefficient of 5 to the thickness of the recycled layer, which approximate the calculation of the value of the elastic modulus of the material (2500/500). Thus, if the target value of E_1 is set to 1000 MPa and the thickness of the asphalt layer – 18 cm, the thickness of the RA layer should be $5 \cdot 4 = 20$ cm.

It can also be concluded considering the weakness of correlations in Figures 1, 3, 4 and 5 that the approved pavement design procedure still allows for inappropriate estimation and interpretation of design parameters and procedure itself, which leads to dubious, inconclusive results.

In order to check if there is any relationship between elastic modulus and compressive strength of RAP material, the main strength characteristics of RAP sample cores – compression resistance (σ) and elastic modulus (E_{RA}) were compared and a weak correlation was established, reaching regression factor R^2 = 0.5 (Figure 6). Moreover, this graph points to a similarity with the same relationship for concrete described above.

Weakness of the obtained relationships can be explained by the underestimated impact of other pavement structures, asphalt layer properties, as well as distinct heterogeneity and variability of subbase and subgrade properties in the selected test sections. It thus may be concluded that consideration of bound layer strength parameters together with bound layer thickness and FWD measured response alone is not sufficient to get a reasonable view on the road pavement properties. The degree of freedom for such a functionality must be raised. In order to get some clues for the new research directions, it is possible to determine the main trends, which, in its turn, can help in further search for stronger and more reliable relationship that would appear useful for RAP design and evaluation.

For this purpose, the measured data of E_{RA}, compressive strength of RAP material σ, and RA layer thickness h_{RA} was approximated with piecewise cubic interpolant; the model with two degrees of freedom was build. Following the design logic, thickness h_{RA} must be a smooth function of E_{RA} and σ, then multiplication $E_{RA}h_{ora}$ can highlight possible disproportions in the tested structures. As shown in Figure 7, the model now gives a clear idea of the location of the points with such a disproportion. It is now possible to identify and discuss in more detail, for instance, the distinct test point in the middle of the graph with parameters E_{RA} = 1160 MPa, σ = 7.42 MPa and h_{RA} = 26 cm, which is responsible for graph surface deviation. Two of the identified parameters from that test point are at least as twice as large as the others in the population in the same range. The designed pavement structure proved to be significantly weaker for this point (*BDI* = 45) than the other sections studied, considering that the traffic loads, profiles and other conditions are similar. These factors could point to a design failure. The reasons for such a design solution now can be discussed and clarified.

Since the set of points used for building of the model were determined by relatively limited variance in the measured range of the particular dimension, the model contains local clusters of the points, while a large portion of the domain appears to be without data. As the aim was to study the whole or, to the degree possible, the range of parameters expected in practice, an additional solution had to be found to cover the empty range and to level off irregularities.

This can be done by applying ANN. The input data for ANN training were the measured RA strength parameters σ and E, and the target was multiplication of parameters E_{RA} and h_{RA}. In such a way, a new model was obtained. Using the ANN model, it was possible to obtain a regular mesh of data points that cover all the defined base space σ/E. In the same way,

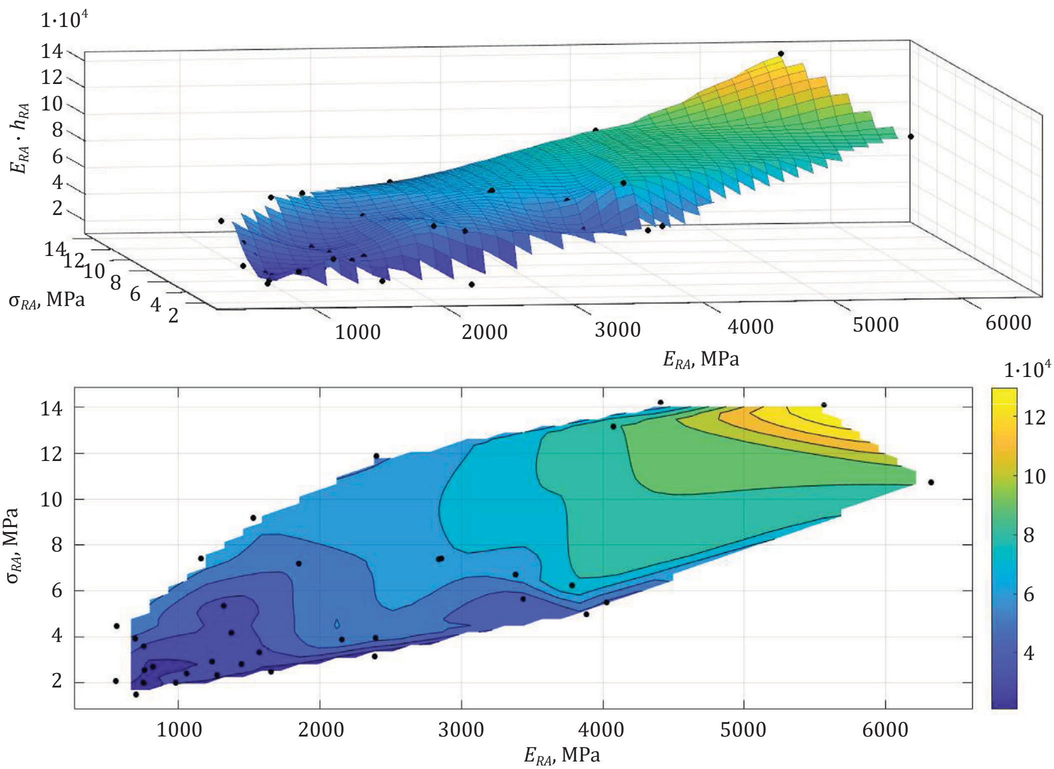

Figure 7. Data approximation using the measured data

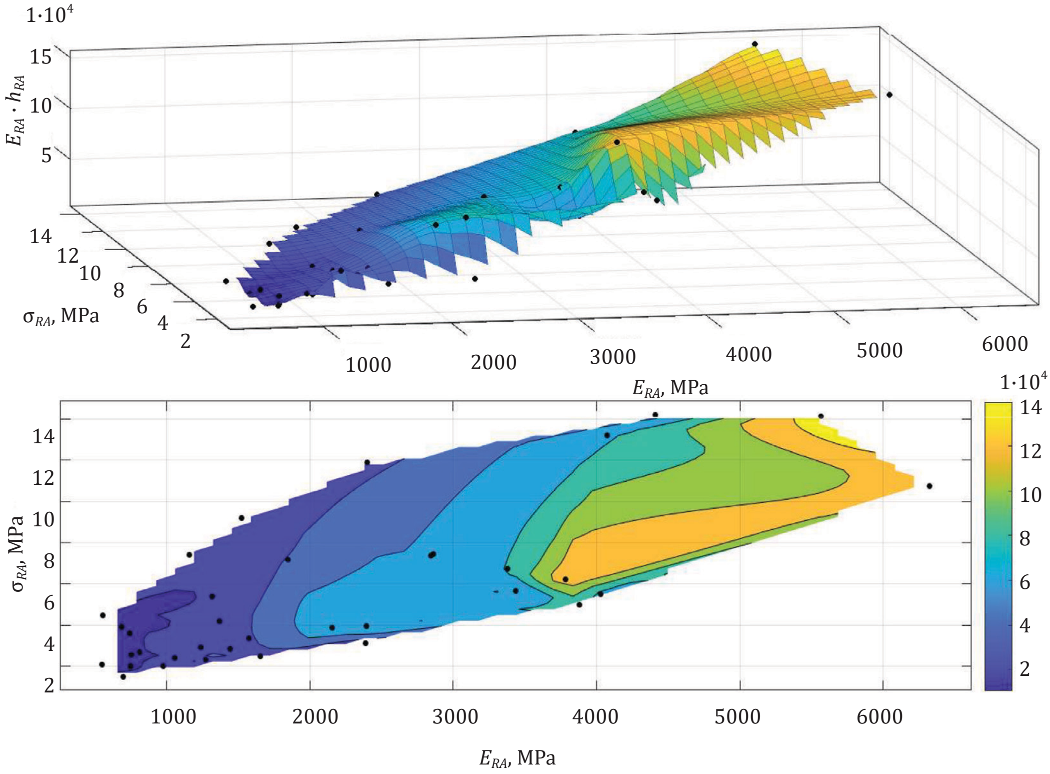

Figure 8. Data approximation using the ANN processed data

ANN can be used to extrapolate the existing data as well. As it can be seen in Figure 8, the new model contains fewer deviations and is smoother. It should be noted here that for the sake of clarity, the starting set of points is used, it is shown in Figure 8. Since this study did not aim to develop some particular relationships and considering the fact that the amount of data was limited, these samples give mostly illustrative idea of possible research strategy and further research directions with a larger data set. For example, from Figure 8. it now follows that the normalized thickness h_{RA} at the test point described above is about 12 cm, if the other parameters remain constant. However, this must be considered in the context of discussion of the reasons for selecting a particular design solution mentioned above.

Conclusions

Finalizing this study some conclusions can be drawn:

It is virtually impossible to obtain the dimensions for RA core samples required by the standardized test description designed to work with concrete samples. Thus, it is necessary to develop or adapt for more appropriate evaluation methods for RAP structures, knowing that RA can also be a loose material. Test procedures that were developed for regular concrete or asphalt in most cases are not suitable for RA mixtures.

Due to distinct heterogeneity and variability of subbase and soil properties, bound layer strength parameters together with thickness and FWD measured response alone are not sufficient factors to get a reasonable view on road pavement properties. The degree of freedom for such a functionality must be raised.

In this case study, the strongest of direct correlations is observed between the function of the bound layer thicknesses $f(h) = h_{asf} + kh_{RA}$ and BDI, reaching regression factor $R^2 = 0.4$ – weak correlation. For practical application, it is necessary to specify it by increasing (at least two times) the number of samples and to specify the effect of bituminous material on the strength parameters.

The models obtained by approximating the real measured data cover only a limited range of parameters. In order to cover a larger range, larger data populations need to be acquired and more complicated approximation is necessary. One of the options is to create artificial data. ANN can be used to extrapolate the existing data as well. For this purpose, in the trained ANN model, the input parameters of a regular set of input data of the necessary range must be selected and respective target data must then be generated.

It can also be concluded considering the weakness of the correlations between the designed and estimated structural data that the approved pavement design procedure still allows for inappropriate estimation and interpretation of design parameters and procedure itself, which can lead to dubious, inconclusive design solutions.

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