Reinforcement methods designed to increase the residual life expectation of rigid pavements

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Abstract. The lifespan of a road structure can be evaluated only based on a traffic forecast. After a road is open to traffic, degradations are starting to develop, even at light and moderate traffic levels. Thus, at a specific time moment during the structure’s lifespan, the residual life expectation of a road can be determined as a function of the degradation state and the forecasted traffic. The degradation state can be evaluated either by using the approximated characteristics of the road construction materials or, based on the real material properties that are experimentally determined on core samples. If the residual life is estimated based on up-to-date traffic forecasts and real road materials properties, the common reinforcement methods used to prologue the lifespan of the structure can be optimized and adapted to the specific conditions of each type of pavement.

1. Introduction
The European road network consists of approximately 5.5 million km of which the majority are managed under local and regional road departments [1]. In this context, the annual maintenance spending in the European road infrastructures is about 30 billion euro. Also, according to the latest prognosis of the European Union Road Federation, in the upcoming future is expected that up to 90% of road works will involve the maintenance of the existing network and only 10% of investments will be used for construction of new roads [2].

If the residual life expectation of a road structure is estimated based on standard material characteristics and generic traffic forecasts (method referred to as the simplified approach), the road administrators can apply only common reinforcement methods to prolong the structure lifespan [3]. These methods are designed such that to be applied regardless the type and the intensity of the degradation state. Thus, in many cases, the common reinforcement methods are related to a deficit of efficiency. In addition, the lack of appropriate and timely maintenance induces an increase in the cost of both future reinforcement and vehicle operating costs. On the other hand, if the residual life expectation is estimated based on the real mechanical and elastic properties of the pavement materials and up to date traffic forecast (method referred to as the accurate approach), the reinforcement methods can be adapted to the overall characteristics of the road structure. Also, since only the necessary works are performed, the energy consumption and the greenhouse gas emission can be significantly reduced.

The residual life of a road, \( D_v \) (equation 1) represents the number of years for which the existing structure can sustain the forecasted traffic. In case of rigid pavements, the capacity to sustain the traffic is defined as the number of standard axles loads \( N_{adm} \) at which the road concrete layer can resist without developing excessive degradations, divided by the average annual traffic.
$D_v = \frac{N_{adm}}{N_{c,\text{yearly}}}$

where: $N_{c,\text{yearly}}$ – the average annual traffic, in millions of standard axles; is determined by dividing the traffic volume to the number of years corresponding to the period that is analysed.

This work consists in a case study related to a county road localised in the North – East part of Romania. For this pavement structure, the residual life expectation was computed using both approaches, the simplified and the accurate one and thus, two distinct reinforcement techniques were proposed, a common one and an optimised one.

2. The simplified approach

2.1. Tensile strength of concrete pavement

In the simplified approach, only the mechanical characteristics of the pavement materials are determined and the elastic properties are taken as provided in the guide norms. The mean tensile strength was experimentally determined by performing the split test on 5 cylindrical core samples which were extracted from different regions of the road (figure 1, table 1) [4].

![Cylindrical concrete core sample](image1)

![Failure mode](image2)

Figure 1. Tensile test of concrete pavement.

The tensile strength by splitting was computed using equation 2 [4].

$$R_B = 0.9 \cdot f_d \cdot R_{B,\text{med}}$$

where:

- $0.9$ – partial factor for reducing the tensile strength of concrete (is chosen according to the severity of the degradation state);
- $f_d$ - partial factor for reducing the tensile strength of concrete (is chosen according to the pavement degradation index);
- $R_{B,\text{med}}$ - average value of tensile strength by splitting, in MPa.

The characteristic tensile strength by splitting was computed using equation 3 [4].

$$R_{BC,\text{car}} = R_{\text{med}} - t_a \cdot s$$

where:

- $t_a$ – coefficient that account for the number of samples for which the results may vary with more than 15% from to mean results;
- $R_{\text{med}}$ – average value of the tensile strength;
- $R_{\text{med}} = \sum R_i / n$;
- $n$ - number of samples, $n = 5$;
- $R_i$ – tensile strength determined for sample $i$;
Table 1. Tensile strength of concrete pavement.

| Sample number | h (cm) | $h^2$ (cm$^2$) | Φ (cm) | $R_i$ (MPa) | $R_i^2$ (MPa) |
|---------------|--------|----------------|--------|-------------|--------------|
| 1             | 17.50  | 306.25         | 9.30   | 2.82        | 7.95         |
| 2             | 17.80  | 316.84         | 9.40   | 3.14        | 9.86         |
| 3             | 17.30  | 299.29         | 9.30   | 3.76        | 14.14        |
| 4             | 15.00  | 225.00         | 9.30   | 4.16        | 17.31        |
| 5             | 18.00  | 324.00         | 9.40   | 3.27        | 10.69        |

$R_A = 2.78 \text{ MPa}$

$R_{BC, car} = 2.75 \text{ MPa}$

2.2. Modulus of elasticity of the concrete pavement
In the Romanian Norm NP 111-04 there are given rough estimations for the modulus of elasticity of concrete pavements, based on the average value of the tensile strength [5]. For the concrete pavement that was studied in this work, the approximative modulus of elasticity, $E_{est}$ is 24000 MPa and the corresponding Poisson coefficient, $\mu$ is 0.15.

2.3. Numerical analysis of the road structure
The road structure lays on a foundation soil of type P5. The characteristics of P5 soils, according to the provisions given in the Romanian Norm NP 111-04 are listed in table 2 [5]. The hydrological regime (type 2b) was established based on the soil type and on the climate type of the Nord – East part of Romania, where the road is located [5].

Table 2. Characteristics of the foundation soil.

| Soil category | Soil type | Classification | Plasticity index $I_p$ | Clay (%) | Dust (%) | Sand (%) |
|---------------|-----------|----------------|------------------------|----------|----------|----------|
| Cohesive      | P5        | clay, dusty clay, sandy clay, clay, dusty sandy | Over 15 | 30…100 | 0…70 | 0…70 |

The numerical analysis of the pavement structure was performed using the Calderom 2000 software [6]. The latter is based on a rational computing method designed for the evaluation of the resilient stresses and strains in roadways pavements. Since the Calderom 2000 software is based on a rational computing method, it is possible to analyze a road pavement structure in two distinct approaches. The first one consists in a classical design of the structure, taken into consideration the given traffic and the corresponding service life.

The second approach is to analyze an existing road pavement structure by estimating the evolution of the degradation state over time in terms of cumulative probability of failure. For the pavement structure that was analyzed in this study it was applied the second approach. The road structure was modelled as a classical multi-layer elastic linear body. The properties of the road materials and the geometrical configuration of the layers are listed in table 3. The outcomes of the numerical analysis in terms of variation of stresses and strains over the structure’s depth are listed in table 4.
Table 3. The properties of the road materials and the geometrical configuration of the layers.

| No. | Layer                          | Thickness (cm) | Modulus of elasticity (MPa) | µ   |
|-----|--------------------------------|----------------|-----------------------------|-----|
| 1   | Road concrete Bce4             | 16             | 24000                       | 0.15|
| 2   | Ballast (foundation and capping layers) | 30         | 169                         | 0.27|
| 3   | Existing bedding soil          | ∞              | 65                          | 0.42|

Table 4. Stress and strain variation over the pavement depth.

| Z (cm) | σr (MPa) | εr (μstrain) | εz (μstrain) |
|--------|----------|--------------|--------------|
| -16.00 | .210E+01 | .746E+02     | -.281E+02    |
| 16.00  | .113E-02 | .746E+02     | -.262E+03    |
| -46.00 | .159E-01 | .975E+02     | -.158E+03    |
| 46.00  | -.217E-02| .975E+02     | -.250E+03    |

As mentioned before, the capacity to sustain the traffic is determined based on the number of standard axles loads, \( N_{adm} \) at which the road concrete layer can resist without developing excessive degradations divided by the forecasted traffic. The concrete pavement which was analyzed in this work has the Bce 4 indicative. According to the provisions given in the Romanian Norm NP111-04, the corresponding exponent of Bce 4 is \( b = -1/15 \). The latter is a selective parameter based on which the equation for determining \( N_{adm} \) is chosen (equation 4) [5].

\[
\log N_{adm} = 15 (\log R_{BC, car} - \log \sigma_r, base) - 6.30325
\]

where: \( \sigma_r, base \) – the tensile stress at the base of the road concrete layer.

The residual life period was determined using equation 1. The obtained value \( (29 \times 10^5 \text{ years}) \) indicates that the analysed pavement structure can sustain the forecasted traffic for less than one year. Thus, in order to prolongate the lifespan of the structure and satisfy the safe and comfort requirements, the road pavement should be reinforced with an additional layer.

2.4. Numerical analysis of the reinforced road structure

The common method of reinforcement for the concrete pavements consists in an overlay structure compose of a top layer of 4 cm of asphalt concrete and a binding layer of 8 cm of asphalt concrete. The new road structure was modelled using the approach described in the previous section. The properties of the road materials and the geometrical configuration of the layers are listed in table 5. The outcomes of the numerical analysis in terms of variation of stresses and strains over the structure’s depth are listed in table 6.

Table 5. The properties of the road materials and the geometrical configuration of the layers.

| No. | Layer                          | Thickness (cm) | Modulus of elasticity (MPa) | µ   |
|-----|--------------------------------|----------------|-----------------------------|-----|
| 1   | Top layer – asphalt concrete   | 4              | 4200                        | 0.35|
| 2   | Binding layer – asphalt concrete | 8            | 3600                        | 0.35|
| 3   | Road concrete Bce4            | 16             | 24000                       | 0.15|
| 4   | Ballast (foundation and capping layers) | 30         | 169                         | 0.27|
| 5   | Existing bedding soil         | ∞              | 65                          | 0.42|
Table 6. Stress and strain variation over the pavement depth.

| Z (cm) | $\sigma_r$ (MPa) | $\varepsilon_r$ (µstrain) | $\varepsilon_z$ (µstrain) |
|-------|------------------|---------------------------|---------------------------|
| -12.00 | -4.23E+00        | -2.46E+02                 | -6.06E+02                 |
| 12.00  | -8.35E+00        | -2.46E+02                 | -1.10E+02                 |
| -28.00 | 1.29E+01         | 0.46E+02                  | -1.72E+02                 |
| 28.00  | 1.28E-02         | 0.46E+02                  | -1.54E+03                 |
| -58.00 | 9.48E-02         | 0.60E+02                  | -1.01E+03                 |
| 58.00  | -1.89E-02        | 0.60E+02                  | -1.58E+03                 |

3. The accurate approach

3.1. Modulus of elasticity of the concrete pavement
In the accurate approach, both the mechanical and the elastic characteristics of the pavement materials are experimentally determined. For this purpose, 5 additional cylindrical core samples were extracted,profiled at the ends, instrumented with 2 micro-meter callipers with dial indicator and subjected to a series of compressive stress cycles up to approximately 40% of the ultimate compressive strength [7]. The modulus of elasticity of the concrete samples ($E_c$) was determined as the average slope of the stress-strain responses captured during the cyclic loading (table 7).

Table 7. Modulus of elasticity of concrete pavement.

| Sample number | h (cm) | $h^2$ (cm$^2$) | $\Phi$ (cm) | $R_i$ (MPa) | $E_c$ (MPa) |
|---------------|-------|---------------|-------------|-------------|-------------|
| 1             | 16.70 | 278.89        | 9.40        | 2.82        | 33543.5     |
| 2             | 16.70 | 278.89        | 9.30        | 3.14        | 28394.8     |
| 3             | 15.93 | 253.65        | 9.30        | 3.76        | 43209.4     |
| 4             | 16.23 | 263.41        | 9.30        | 4.16        | 35493.4     |
| 5             | 16.39 | 268.63        | 9.40        | 3.27        | 35160       |

$E_{c, av} = 35160$ MPa

3.2. Numerical analysis of the road structure
The numerical analysis of the pavement structure was performed using the same approach as in section 2.3. The properties of the road materials and the geometrical configuration of the layers are listed in table 8. The outcomes of the numerical analysis in terms of variation of stresses and strains over the structure’s depth are listed in table 9.

Table 8. The properties of the road materials and the geometrical configuration of the layers.

| No. | Layer                                  | Thickness (cm) | Modulus of elasticity (MPa) | $\mu$ |
|-----|----------------------------------------|----------------|-----------------------------|------|
| 1   | Road concrete Bce6                     | 16             | 35160                       | 0.15 |
| 2   | Ballast (foundation and capping layers)| 30             | 169                         | 0.27 |
| 3   | Existing bedding soil                  | $\infty$      | 65                          | 0.42 |
Table 9. Stress and strain variation over the pavement depth.

| Z (cm) | $\sigma_r$ (MPa) | $\varepsilon_r$ (µstrain) | $\varepsilon_z$ (µstrain) |
|--------|-----------------|---------------------------|---------------------------|
| 0      | -.242E+01       | -.559E+02                 | .289E+01                  |
| -16.00 | .229E+01        | .554E+02                  | -.205E+02                 |
| 16.00  | .453E-03        | .554E+02                  | -.200E+03                 |
| -46.00 | .123E-01        | .767E+02                  | -.127E+03                 |
| 46.00  | -.127E-02       | .767E+02                  | -.201E+03                 |

By taking into consideration the experimentally determined tensile strength and modulus of elasticity it results that the concrete pavement which was analyzed in this work has the Bce 6 indicative. According to the provisions given in the Romanian Norm NP111-04, the corresponding exponent of Bce 6 is $b = -1/16$ [5].

Therefore, by knowing the real concrete indicative and applying the accurate method the real residual life period of the road structure was determined ($10^4$ years).

3.3. Numerical analysis of the reinforced road structure

Since both the mechanical and elastic properties of the asphalt concrete are known, the reinforcing method can be optimized. Usually, the optimizing process consists in a gradual diminishing of the depths of the common reinforcing layers up to the limit where the tensile stresses at the bottom of the concrete layer reaches the admissible tensile strength.

The difference between the real modulus of elasticity of the concrete pavement ($E_c = 35160$ MPa) and the estimated one ($E_{est} = 24000$ MPa) is close to 50%. Thus, in the first part, it was checked if the top layer of the common reinforcement can be reduced from the beginning at 50%. In this case, the reinforcing layers consists in 4 cm asphalt concrete top layer and 4 cm asphalt concrete binding layer. The new road structure was modelled using the same approach that was described in the previous sections. The properties of the road materials and the geometrical configuration of the layers are listed in table 10. The outcomes of the numerical analysis in terms of variation of stresses and strains over the structure’s depth are listed in table 11.

The maximum tensile stress at the base of the road concrete layer (total depth = -24 cm) is 1.75 MPa, less than 1.77 MPa (admissible tensile strength, computed according to the provisions given in [3]). Thus, the optimization of the common reinforcing method (which consists in 50% diminishing of the top layer depth) is suitable for the characteristics of the analyzed road structure.

Table 10. The properties of the road materials and the geometrical configuration of the layers.

| No. | Layer                                      | Thickness (cm) | Modulus of elasticity (MPa) | $\mu$ |
|-----|-------------------------------------------|----------------|-----------------------------|-------|
| 1   | Top layer – asphalt concrete               | 4              | 4200                        | 0.35  |
| 2   | Binding layer – asphalt concrete           | 4              | 3600                        | 0.35  |
| 3   | Road concrete Bce4                        | 16             | 35160                       | 0.15  |
| 4   | Ballast (foundation and capping layers)   | 30             | 169                         | 0.27  |
| 5   | Existing bedding soil                      | $\infty$       | 65                          | 0.42  |
Table 11. Stress and strain variation over the pavement depth.

| Z (cm) | σr (MPa)  | ɛr (µstrain) | ɛz (µstrain) |
|--------|-----------|---------------|--------------|
| -8.00  | -486E+00  | -325E+02      | -634E+02     |
| 8.00   | -144E+01  | -325E+02      | -385E+01     |
| -24.00 | 175E+01   | 425E+02       | -157E+02     |
| 24.00  | 542E-03   | 425E+02       | -150E+03     |
| -54.00 | 939E-02   | 599E+02       | -102E+02     |
| 54.00  | 204E-02   | 599E+02       | -160E+03     |

All the numerical analyses that were presented in this paper were performed using Calderom 2000 software. The latter is a well-known tool that enable the rational design of a pavement structure, which is part of the Romanian county or national road network [8]. For road structures that are different compared to the common pavement systems, which are used in Romania, this software may provide inaccurate results. This fact is due to several limitations, from which the most significant one is related to the impossibility of modelling the interface condition for adjacent layers. Thus, it should be noted that the results that were presented in this paper refers strictly to a specific road pavement structure and, if changes in the structural compositions are to be done, different assumptions should be defined and, in some cases, a specific software should be used.

This work is part of an extensive research project, related to the methods designed to prolongue the road structures lifespans and to the modern rehabilitation and recycling methods of pavement layers. More information regarded to the experimental programs that were performed in the frame of this research project can be consulted in a recently published paper [9].

4. Conclusions

The evaluation of the road resilient life expectation is one of the core parts that characterize the transport network reliability. In Romania, the rigid road pavements are constantly exposed to large traffic volumes, high temperature changes and aggressive influence of deicing agents during winter period, which decrease the durability of concrete.

At a particular level of degradation, the residual life expectation can be determined by applying either the simplified method or the accurate evaluation method. In the second case, both the mechanical and elastic properties of the concrete pavement are experimentally determined. Also, up-to-date traffic forecasted are used, which are based on stochastic behavioral models and risk models designed for estimating the travel choice behavior over time. In this work, both methods of evaluating the residual life expectation were applied for a county road with rigid pavement structure.

The reinforcing layers that were designed based on the accurate method implies less materials and work compared to the ones designed based on the common reinforcing method. In particular, the top layer depth is half than the same layer that is indicated in the common reinforcing method. Beside the diminishing of the intervention costs, by applying the accurate method, only the necessary works are performed and thus, the energy consumption and greenhouse gas emission can be significantly reduced. Also, it can be concluded that the road reinforcing solutions that are designed based on the accurate method are results-oriented and can improve the efficiency of the transportation industry.

References

[1] Di Graziano A, Marchetta V and Cafiso S 2020 Structural health monitoring of asphalt pavements using smart sensor networks: A comprehensive review Journal of traffic and transportation engineering 7(5) 639-51
[2] European Union Road Federation (ERF) 2014 Road Asset Management-an ERF Position Paper
for Maintaining and Improving a Sustainable and Efficient Road Network European Union Road Federation, Bruxelles

[3] Florida Department of Transportation, Office of Design 2019 Rigid pavement design manual Pavement Management Section

[4] SR EN 12390-6/2010 Testing hardened concrete. Part 6: Stress resistance by splitting test pieces

[5] NP 111-04 Normative for the calculation of the base layers made of cement concrete for road structures

[6] http://www.cnadnr.ro/ro/comunicare/publicatii/proiectare (accessed at 06.01.2021)

[7] SR EN 12390-13/2014 Testing hardened concrete. Part 13: Determination of the secant modulus of elasticity in compression

[8] PD 177-2001 Normativ pentru dimensionarea sistemelor rutiere supple și semirigide (Metoda analitică), (in Romanian)

[9] Ungureanu D, Țăranu N, Hoha D, Zghibarcea Ş, Isopescu D N, Boboc V, Oprișan G, Scutaru M C, Boboc A and Hudişteanu I 2020 Accelerated testing of a recycled road structure made with reclaimed asphalt pavement material Construction and Building Materials 262 120658