Environmental impact of bituminous mixtures produced with reclaimed asphalt pavement and rejuvenator

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Abstract. The paper focuses on the investigation of the potential environmental impact related to the production of several types of bituminous mixtures containing different dosages of Reclaimed Asphalt Pavement (RAP) and Rejuvenator (Rej). All materials used in the presented study are specific and generally used for pavements in Romania. The RAP material was considered as an inert material and it was used in three dosages (25%, 50% and 75%). For the bituminous mixture produced with 50% RAP material, a rejuvenator consisting in a mixture of vegetal oils was used in three dosages of 0.2%, 0.4% and 0.6% by mass of RAP material. A total of seven types of bituminous mixtures were considered including one ‘conventional’ mixture produced with virgin materials and used as reference. The Environmental Impact Assessment was estimated for the production process of the analysed bituminous mixtures, by using Eco-indicator 99 method within SimaPro software. The results prove that the addition of RAP material leads to a net decrease of the energy use and environmental impact. Besides, when rejuvenators are used in this process, they can affect the energy balance and reduce the difference in environmental impact.

1. Introduction

Over the last decades, many research efforts were spent to find better solutions to increase the amounts of recovered/recycled and renewable materials used in the road construction industry.

Roads, as all the other types of constructions require during their lifetime or at the end of it, several interventions such as rehabilitation, modernization, resurfacing, reconstruction, etc in order to ensure the safety and comfort of the traffic participants. The Reclaimed Asphalt Pavement (RAP) refers to the term used for the material obtained by milling or by full-depth removal of the old asphalt pavement. The RAP material is considered 100% recyclable and its use in the production of new asphalt mixtures leads to important benefits as cost reduction or conservation of energy, virgin aggregates and binders, etc. [1], [2].

During recent years, many countries have developed various policies based on the sustainability in the road domain, based on the recovery, the reuse, the recycle of materials in order to produce new eco-friendly materials.

According to the Annual Technical Report from 2018 in USA the asphalt industry is considered ‘the most diligent recycler’, where more than 99% of RAP material is being reused and 82.2 million tons of RAP material are used in new bituminous mixtures [3]. However, the reuse of RAP in the production of
new bituminous mixtures is not very popular in Romania as there is no reporting data regarding the reuse of such materials.

In the production process of a bituminous mixture containing RAP material, fresh aggregates must be used depending on the amount of the RAP material and its characteristics in order to obtain a continuous grading curve of the final mix. The mix also needs a fresh binder - usually a softer binder is needed - in order to ensure the optimal binder content of the final mix. Regarding the production of an eco-friendlier bituminous mixture containing high amounts of RAP material, many studies showed the potential of renewable materials such as vegetal oils to regenerate the hard-aged RAP binder and finally to improve the mix characteristics [4], [5], [6], [7].

Usually, the renewable materials are called rejuvenators. Several studies were focused on the investigation of fresh and RAP binders behaviour mixed with different types of rejuvenators by evaluating the conventional, rheological and other properties which proved the capability of these products to rejuvenate the RAP binder and to provide a blend with similar characteristics of fresh binders [8], [9], [10], [11].

A lot of research was devoted to highlight the environmental impacts of a road pavement by performing life cycle assessments (LCA) and Green-House Gas (GHG) [12], [13], [14]. The Environmental Impact Assessment (EIA) represents the process from which information are given about the effects of the implementation of a project, a production, a construction process etc. has on the environment, leading to a final decision, by evaluating their impacts, to stop or to adjust the initial project, process, etc. In [15], [16], [17] is shown that the use of RAP materials and rejuvenators in the production of new bituminous mixtures leads to smaller impacts on the environment and also to a cost efficiency.

The objective of this paper is to investigate the potential environmental impact related to the production of several types of bituminous mixtures containing different amounts of Reclaimed Asphalt Pavement (RAP) and Rejuvenator (Rej). One ‘conventional’ bituminous mixture (produced with virgin materials) used as reference was also considered in the study. The Environmental Impact Assessment was estimated for the production process of the bituminous mixtures while all the other processes were assumed to be similar. The Eco-indicator 99 method within SimaPro software was used.

2. Materials

All materials (figure 1) used in this work were chosen with respect to the specifications from the Romanian Norms in order to produce bituminous mixtures with the maximum aggregate size of 16 mm.

The materials used in this study are:

- quarry crushed aggregates (0-4; 4-8 and 8-16);
- natural sand 0-4;
- limestone filler;
- RAP material (divided into two lots: 0-8; 8-22.4);
- fresh 50/70 binder;
- rejuvenator (oil of vegetal origin).

The crushed aggregates (0-4, 4/8 and 8-16) have the same provenance and according to the specification of the producer the rock nature is dacite (intermediate in composition between andesite and rhyolite).

In this study the RAP material was obtained from milling the bituminous surface layer of an old deteriorate road pavement from Timis county, Romania. It must be pointed that this RAP material meets the requirements specified in the European Norms, regarding the characteristics of the material before and after the binder extraction (characteristics of the RAP aggregates and of the RAP binder). The RAP material was divided into two lots: 0-8 and 8-22.4 and stored near to an asphalt mix plant.

As fresh binder a 50/70 penetration grade binder was used, and a mixture of vegetal oils was used as a rejuvenator.

A total of seven types of bituminous mixtures (figure 1), including one ‘conventional’ bituminous mixture produced with virgin materials (used as reference), were considered.
Proportions of the base components as shown in figure 1 were calculated in order to produce bituminous mixtures with a total binder content of 5.6% (without the rejuvenator) containing 0%, 25%, 50% and 75% RAP material and different dosages of rejuvenator. A summary table regarding the proportions for all bituminous mixtures is reported in table 1.

![Figure 1. Characteristics of materials used to produce the analysed bituminous mixtures.](image)

**Table 1.** Proportions in percent (%) of base materials within the considered bituminous mixtures.

| Bituminous mixtures | Crushed aggregates | Proportions in percent (%) | RAP material | Rejuv. |
|---------------------|--------------------|----------------------------|--------------|--------|
|                     | 8-16       | 4-8          | 0-4         | Natural sand 0-4 | Filler | Agg. from RAP 8-22.4 | Agg. from RAP 0-8 | RAP binder | Fresh binder | Rejuvenator |
| D.0.R.0              | 23.60      | 20.77        | 40.59       | 2.83           | 6.61   | -                       | -               | -         | 5.60         | -           |
| D.25.R.0             | 16.10      | 12.94        | 35.87       | 0.87           | 4.62   | 18.00                   | 6.00            | 1.00       | 4.60         | -           |
| D.50.R.0             | 8.02       | 7.98         | 28.13       | 2.27           | 2.26   | 36.00                   | 12.00           | 2.00       | 3.60         | -           |
| D.75.R.0             | -          | -            | 21.93       | -              | 0.47   | 54.00                   | 18.00           | 3.00       | 2.60         | -           |
| D.50.R.0.2           | 8.02       | 7.97         | 28.1        | -              | 2.26   | 35.95                   | 12.00           | 2.00       | 3.60         | 0.10        |
| D.50.R.0.4           | 8.01       | 7.96         | 28.08       | -              | 2.26   | 35.92                   | 11.97           | 2.00       | 3.60         | 0.20        |
| D.50.R.0.6           | 8.00       | 7.96         | 28.05       | -              | 2.26   | 35.88                   | 11.95           | 2.00       | 3.60         | 0.30        |

As shown in figure 1 and table 1, for the bituminous mixture produced with 50% RAP material, a rejuvenator consisting in a mixture of vegetal oils was used in three dosages of 0.2%, 0.4% and 0.6% by mass of RAP material. The rejuvenator was used in order to restore the mechanical properties of aged RAP binder [10], [11] and to improve the blending between the RAP material and the virgin materials.

All bituminous mixtures considered in this study were tested in the laboratory by investigating their thermomechanical behaviour (more details in Section 3).

All bituminous mixtures were named according to the dosage (D) of RAP material (0, 25, 50 and 75) and the dosage of the rejuvenator (R) by the mass of RAP material (0, 0.2, 0.4 and 0.6).

It must be specified that all bituminous mixtures have the following common characteristics:

- continuous 16 mm grading curve (figure 2);
• 5.60% total binder content by weight of the final mix not including here the rejuvenator;
• the RAP material used for each mix has the same proportion: 25% RAP 0-8 + 75% RAP 8-22.4.

The binder content of this RAP material mix, measured trough extraction and recovery is 4%.

Figure 2 shows the grading curve used for the considered mixtures together with the minimum and maximum limitations specified in the Romanian Norm AND 605.

3. Laboratory investigation
As mentioned in Section 2, all seven bituminous mixtures considered in this study were analysed in the laboratory by performing the following tests:
• Marshall tests, parameters analysed: stability, flow and ratio between stability and flow;
• determination of density, water absorption and void contents (hydrostatic method);
• indirect tension tests at 10°C, 15°C, 20°C and 25°C, parameter analysed: resilient modulus;
• uniaxial cyclic compression tests with confinement at 50°C, 300 kPa, parameter analysed: permanent deformation resistance (dynamic creep) and the creep rate at 10000 impulses;
• complex modulus tests – two-point bending test on trapezoidal specimens.

In order to highlight the influence of the RAP material and the effect of the rejuvenator used in different dosages, as an example, figure 3 and figure 4 show the results obtained from the Marshall test and the indirect tension test at 20°C.

Marshall tests were performed according to SR EN 12697-34, on cylindrical samples produced in the laboratory by using the Marshall compaction method with 50 blows/part. The indirect tension tests were performed according to SR EN 12697-26, on cylindrical samples produced with the gyratory press at 80 gyrations.

Three samples were tested for each type of bituminous mixture/each test. The average values are reported in figure 3 (3a – Marshall stability, S; 3b – Marshall flow, F; 3c – ratio between stability and flow, S/F) and figure 4 together with the limits imposed by the Romanian Norm AND 605 for a bituminous mixture with a 16 mm maximum aggregate size.

As expected, the increase of the RAP material within the new bituminous mixtures leads to an increase of the stability, S/F ratio and resilient modulus at 20°C and to a decrease of the flow. It can be observed that for the bituminous mixtures produced with more than 25% RAP (D.50.R.0 and D.75.R.0) the stability is higher than the maximum limit. In this case, a rejuvenator should be used in order to decrease the stiffness of the mix.

On the other side, it must be observed that the mechanical behaviour of the mix produced with 25% RAP is close to the one of the conventional bituminous mixture. A small increase of the stability, flow, S/F ratio and resilient modulus at 20°C for this mix was observed. Therefore, the use of less than 25% of the considered RAP material in the production of a new bituminous mixture leads to a final mix that is still within the limits imposed by the Romanian Norm for a bituminous mixture with a 16 mm maximum aggregate size.
For the bituminous mixtures produced with 50% RAP and rejuvenator, a decrease of the stability and resilient modulus at 20°C with the increase of the rejuvenator content, was observed. On the other side, the increase of the rejuvenator content corresponds to an increase of the flow and S/F ratio.

Figure 3. Marshall test results: (a) Marshall stability; (b) Marshall flow; (c) Ratio S/F.

Figure 4. Resilient modulus at 20°C test results.

Moreover, the mix produced with 50% RAP and 0.4% Rej by mass of the RAP material, presents a similar behaviour as the conventional one. This tendency confirms the conclusions from [10], [11] where it was shown that the corresponding binder blend of D.50.R.0.4 presents similar conventional and rheological properties to those of the used fresh 50/70. Practically the rejuvenating effect of the rejuvenator is counterbalancing the effect of the aged RAP binder within this binder blend.

It must be specified that similar tendencies were observed for all the other parameters for the studied bituminous mixtures. By investigating the thermomechanical properties of the bituminous mixtures considered in table 1, it was observed that:

- a percentage smaller than 25% RAP do not have an important impact on the mechanical behaviour of the final mix. Acceptable differences compared to conventional mix were observed and the properties of the final mix are still within the limits imposed by the norms in use;
- the mix produced by using 50% RAP and 0.4% Rej (by mass of the RAP material) presents similar characteristic to the conventional one.
4. Procedure
The Environmental Impact Assessment (EIA) was estimated for the production process of the analysed bituminous mixtures by using Eco-indicator 99 method within SimaPro software.

According to the method, the steps followed in the assessment are:

- establish the purpose of the calculation and define the system boundaries of the analysed process;
- collect or associate the input values (resources and emissions) for each material, production process, transport process, energy and disposal scenario;
- quantify the inventory - materials and processes;
- evaluate the total impact;
- interpret the obtained results.

In the Eco-indicator 99 [18] method the term environment is defined on the basis of three types of damage: the human health, the ecosystem quality and the resources. Each of these represents the sum of quantified emissions of several sub-sequent impact categories.

The output values of this analysis are Eco-points which are quantified values that express the total environmental impact of the defined production process of asphalt mixtures. The eco-point unit (Pt) is representative for 1/1000 of the yearly environmental load of one average European inhabitant [18].

The purpose of the environmental impact study is to investigate the potential environmental impact related to the production of one ton (1 T) of several types of bituminous mixtures containing different dosages of RAP and rejuvenator as described in Section 2. The system boundaries considered in this analysis is shown in figure 5. All the other operations or processes were excluded from the analysis.

![Image of System boundaries](image-url)

**Figure 5. System boundaries.**

In the extraction and production of the raw materials for crushed aggregates, natural sand, filler, binder and RAP material all processes from the extraction of the rock up to the last processing stage (each process with its emissions), including also the transport within the quarry, were considered.

The RAP material was obtained from the milling process of an old existing pavement. Thus, in the EIA the RAP material was considered as stored near to the asphalt mix plant and it was divided into two lots: 0-8 and 8-22.4 mm. Moreover, the analysis was performed by considering that the RAP is an inert material. No processes, emissions or energy use were associated to the production of this material. This scenario for the RAP material was proposed by taking into consideration that the milling, transport or other processes are part of the LCA of original mix and thus out of the actual system boundaries.

For the transportation of all materials integrated in the analysis, table 2 shows the road distances from each quarry, refinery, etc. to the asphalt mix plant considered as located in Timisoara. This process includes the emissions generated during the transport and from the extraction/production process of fuel. The unit used for this process is tkm as it represents the transport of one tone of material over one kilometre.

**Table 2. Transport distances to the asphalt mix plant.**

| Material           | Transport distance to asphalt mix plant, (km) |
|--------------------|---------------------------------------------|
| Crushed aggregates | 260                                         |
| Natural sand       | 70                                          |
| Limestone filler   | 210                                         |
| Fresh 50/70 binder | 300                                         |
| Rejuvenator        | 305                                         |
| RAP material       | -                                           |
In the production of bituminous mixtures, the following processes were considered:

- heating process of the fresh aggregates: energy use – natural gas;
- heating process of the RAP material: energy use – diesel;
- heating process of the fresh binder: energy use – natural gas;
- mixing process: energy use – natural gas.

It must be specified that the rejuvenator is added to the fresh binder tank when all materials are heated and ready for the mixing process.

Table 3 sums the amounts of resources (in kg) and processes (transport in tkm, energy in MJ) used to produce one ton of each type of bituminous mixture as defined in table 1.

**Table 3. Amounts of resources and processes used to produce 1 T of each bituminous mixture.**

| Bituminous mixtures | Materials, kg | Transport, tkm | Energy, MJ |
|---------------------|---------------|----------------|------------|
|                     | Fresh agg.    | RAP            | Fresh binder | Rejuvenator | Natural gas | Diesel |
| D.0.R.0             | 944.0         | -              | 56.0        | -           | 98.9        | 280    |
| D.25.R.0            | 704.0         | 250            | 46.0        | -           | 90.3        | 222    |
| D.50.R.0            | 464.0         | 500            | 36.0        | -           | 75.1        | 165    |
| D.75.R.0            | 224.0         | 750            | 26.0        | -           | 65.5        | 108    |
| D.50.R.0.2          | 463.5         | 499.5          | 36.0        | 1.0         | 75.4        | 165    |
| D.50.R.0.4          | 463.1         | 499.0          | 35.9        | 2.0         | 75.7        | 165    |
| D.50.R.0.6          | 462.6         | 498.5          | 35.9        | 3.0         | 76.0        | 165    |
| D.50.R.0.2          | 463.5         | 499.5          | 36.0        | 1.0         | 75.4        | 165    |
| D.50.R.0.4          | 463.1         | 499.0          | 35.9        | 2.0         | 75.7        | 165    |
| D.50.R.0.6          | 462.6         | 498.5          | 35.9        | 3.0         | 76.0        | 165    |

Figure 6 shows the LC flow. The life cycle of the final product was considered from the early stages, including production and acquisition of the raw materials, and the production process of bituminous mixtures while the end-of-life (EOL) phase considered the recycling and the final disposal of material. With regard to the EOL, it was considered a scenario in which after the construction and the service life of the road, the surface layer will be milled and the resulting material will be transported, sorted and reused (disassembly) in the production of other new bituminous mixtures as another RAP material. Thus, in a new LCA, the RAP material is ready-to-use, as it is considered in the current analysis.

**Figure 6. Life cycle of the final product.**

5. **Environmental impact - results**

The environmental impact of the production process of bituminous mixtures containing RAP material in various percentages: 0%, 25%, 50% and 75% RAP and rejuvenator: 50% RAP material, three dosages of 0.2%, 0.4% and 0.6% rejuvenator by mass of RAP, was investigated.

Figure 7 and figure 8 show the impact for the production phase per impact categories of all bituminous mixtures produced with different amounts of RAP, without rejuvenator: D.0.R.0, D.25.R.0, D.50.R.0 and respectively D.75.R.0. Similar plots (figure 9 and figure 10) were built as a comparison between the conventional bituminous mixture (D.0.R.0) and the mixtures produced with 50% RAP and different amounts of rejuvenator: D.50.R.0, D.50.R.0.2, D.50.R.0.4, D.50.R.0.6.
In figure 7 and figure 9 respectively, the three main impact categories were summed from the impacts given on impacts as follows: ecosystem quality (climate change, radiations, ozone layer, ecotoxicity and acidification), resources (land use, minerals and fossil fuels) and human health (carcinogens, respiratory organics and respiratory inorganics).

It can be observed in figure 7 that the major impact is for the fossil fuels due to the use of resources. A major decrease is observed with the increase of RAP. For all the other categories the impact is smaller than one eco-point. However, higher values of impact were recorded for inorganic respiratory emissions and climate change.

![Figure 7. Environmental impact production phase – bituminous mixtures without rejuvenator (weighting) – values per impact category.](image)

![Figure 8. Environmental impact production phase - bituminous mixtures without rejuvenator (single score).](image)

![Figure 9. Environmental impact production phase (weighting) - comparison between the conventional bituminous mixture and the bituminous mixtures produced with 50% RAP and different amounts of rejuvenator.](image)

![Figure 10. Environmental impact production phase (single score) – comparison between the conventional bituminous mixture and the bituminous mixtures produced with 50% RAP and different amounts of rejuvenator.](image)

In figure 8 and figure 10 respectively, the environmental impact of the production phase of each considered bituminous mixture is shown as a global single score. As expected, the production of the conventional bituminous mixture has the highest environmental impact. On the other side, the increase of RAP material within bituminous mixtures corresponds to a decrease of the environmental impact.

It was shown in Section 3 that when less than 25% of the considered RAP is used in the production of a new bituminous mixture, the characteristics of the final mix are within the limits specified in the Romanian Norms for a bituminous mixture with a 16 mm maximum aggregate size. Therefore, the
environmental impact for this solution (D.25.R.0) is near to 9 eco-points, with a decrease of 1.8 eco-points than the conventional one.

When high amounts of RAP are used in the production of a new bituminous mixture, depending on the properties of this material, rejuvenators should be used. The solution with 75% RAP (D.75.R.0) was considered here only to highlight the environmental impact potential of this 100% recyclable material. In this case, a substantial decrease of the environmental impact as more than half of the conventional solution could be obtained.

Table 4 indicates the global score for each mix design analysed in this study and the scores obtained per impact category. The results prove that the addition of RAP material leads to a net decrease of the energy use and environmental impact.

Figure 9 indicates that the increase of the rejuvenator content corresponds to a small increase of the impact for the fossil fuels. It can be observed that the same tendency appears for the human health, where the impact is less than one eco-point (higher values of impact were recorded for inorganic respiratory emissions and climate change). A considerable impact was observed for the land use, due to the fact that the rejuvenator considered in this study is a mix of vegetal oils.

Regarding the production process of bituminous mixtures containing 50% RAP and different amounts of rejuvenator, an increase of the environmental impact (Figure 10) was observed with the increase of the rejuvenator content. However, this does not represent a major increase in impact, approximately 0.50 eco-points increase per 0.1% rejuvenator content by the total mass of the final bituminous mixture.

From the results obtained in the laboratory (as described in Section 3) it was observed that the characteristics of the D.50.R.0.4 bituminous mixture is similar to the one of the conventional bituminous mixture. The environmental impact for this solution (D.50.R.0.4) is near to 8 eco-points, with a decrease of 2.8 eco-points than the conventional one. It can be concluded that when rejuvenators are used in this process, they can affect the energy balance and reduce the difference in environmental impact.

6. Conclusions

The objective of this paper was to investigate the potential environmental impact related to the production of one ton of several types of bituminous mixtures containing different amounts of Reclaimed Asphalt Pavement (RAP) and Rejuvenator (Rej). All materials considered in this study are specific and generally used for pavements in Romania.

Three bituminous mixtures containing 25%, 50% and 75% of RAP were considered and for the bituminous mixture produced with 50% RAP a rejuvenator consisting in a mixture of vegetal oils was used in three dosages of 0.2%, 0.4% and 0.6% by mass of RAP material. One conventional bituminous mixture produced with virgin materials, was used as reference. A total of seven types of bituminous mixtures were considered in this study. The environmental impact was investigated for the production process of the analysed bituminous mixtures (all the other processes were assumed to be similar by using Eco-indicator 99 method within SimaPro software.)
The following conclusions can be drawn:

- the production process of the conventional bituminous mixture leads to the highest environmental impact;
- the increase of RAP material within bituminous mixtures corresponds to a decrease of the environmental impact due to the reuse of materials;
- when less than 25% of the considered RAP is used in the production of a new bituminous mixture, the characteristics of the final mix are within the limits for a bituminous mixture with a 16 mm maximum aggregate size. Therefore, the environmental impact for this solution (D.25.R.0) is near to 9 eco-points, with a decrease of 1.8 eco-points than the conventional one;
- an increase (approximately 0.50 eco-points increase per 0.1% rejuvenator content by the total mass of the final bituminous mixture) of the environmental impact was observed with the increase of the rejuvenator content;
- based on the experimental work and on the results presented in other studies [10-11], the mix design D.50.R.0.4 presents a similar thermomechanical behaviour to the one of the conventional bituminous mixture. The environmental impact for the production of D.50.R.0.4 is close to 8 eco-points with a decrease of 2.8 eco-points than the conventional one;
- although not feasible for use, the mix design with 75% RAP (D.75.R.0) can lead to a substantial decrease of the environmental impact (more than half);
- the addition of RAP material leads to a net decrease of the energy use and environmental impact;
- when rejuvenators are used in this process, they can affect the energy balance and reduce the difference in environmental impact.

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