New developed software tool for assessment and calculation of emissions for different asphalt pavement rehabilitation methods

Václav Snížek[1, a], Jan Valentin[1, b], Michael Engels[2, c]

[1] *Department of Road Structures, Czech Technical University in Prague, Faculty of Civil Engineering, Praha, Czech Republic*

[2] *Wirtgen GmbH, Windhagen, Germany*

[a] vaclav.snizek@fsv.cvut.cz
[b] jan.valentin@fsv.cvut.cz
[c] michael.engels@wirtgen.de

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ABSTRACT

Construction industry similarly to any other industry, is forced to face recent trends and necessary environmentally friendly solutions, like for example emphasizing emission reduction. On the other hand, modern methods, especially coming from the IT sector, are often not easy adoptable for this industrial area. As part of ongoing research activities started within the European CoRePaSol project and continuously followed in Centre for Effective and Sustainable Transport Infrastructure in the Czech Republic to focus was oriented on the issue of energy demand and emission production calculation for pavement recycling techniques. Together with these assessments a new software tool was developed, which is in detail oriented on the determination of environmental burden in terms of emissions if different pavement rehabilitation techniques are used. There were already lots of studies on greenhouse gas emissions presented, but most of them focus mainly on CO2, not reflecting other emissions. The importance of this paper is in the detailed identification and understanding and description of other greenhouse gas emissions like NOx, HC, CO, fine particles matter and also CO2. The study contains an application of the assessment software (calculator) for a real job site, presenting possible pavement rehabilitation methods including their technological variants and a subsequent decision for a preferred solution. Included are traditional rehabilitation methods (mill&fill, including RAP material with different portion) as well as both cold and hot in-place recycling techniques. This paper aims to show the truth of environmental impact of available rehabilitation methods, as well as to present the developed software application.

Keywords: Carbon, Life cycle assessment, Reclaimed asphalt pavement (RAP) Recycling, Software

1. INTRODUCTION

Pavement recycling technologies represent a modern approach mainly for pavement reconstruction. Besides the traditional Mill & Fill method (cold milling of the required part of the asphalt pavement and replacing the milled structure by new structural layers), hot and cold recycling methods performed usually in-situ are used as well. The particular methods have their given technological specification which differs particularly by way of application, as well as material and construction machinery used for these recycling techniques. As a consequence, the methods are not always mutually substitutable and universally applicable. Their applicability and suitability are determined by experts on the basis of technical standards or regulations, practical experience concerning the local conditions of the project and respect to the technical tradition.
The completion of each technological type of recycling has a certain environmental impact. If we focus on greenhouse gas emissions, this particularly concerns CO_2, NO_x, volatile hydrocarbons, CO and solid particles. Such harmful substances are released into the atmosphere during each of the partial pavement reconstruction processes – starting with the production / refinement / extraction or processing of the construction materials applied (bituminous binders, hydraulic binders, aggregate and others). It is the activity associated with securing the material that is subsequently incorporated in the construction project that is the most critical emission burden for the environment. Besides the aforementioned activities, harmful substances are also emitted when the reconstruction is completed – construction machinery operation - demolition work, material crushing and screening, subbase levelling, material and mix transport or laying, [1].

2. OPTIREC CALCULATOR

The new calculation tools, OptiRec CR and OptiRec MF, developed within the framework of the activities of the Czech Technical University in Prague in cooperation with Wirtgen GmbH allow to the user to obtain an important comparison of the technological options for asphalt pavement rehabilitation selected on the basis of the environmental impact, time or economic demands of pavement reconstruction by various recycling approaches. The tool does, nevertheless, not compare the technical equality between cold recycling with asphalt overlay and the mill&fill approach using only hot asphalt mix, i.e. the structural effect of both techniques will not always necessarily be the same. This is not the aim of the calculator. Both tools are innovative in their approach to the evaluation of technological variants and universality of settings, quantity of construction machinery included in the database, with the option of choosing any proprietary machinery set, [2]. Material data about energy demandingness used by OptiRec are taken from existing inventories which are internationally available. This includes also data about hot mix asphalt including the energy demand of a mixing plant. Machinery related data related to fuel consumption and engine effectiveness are based on information from the producers. The software was so far designed using MS Visual Basic where the material and machinery data are combined with various LCA formulas.

2.1. OptiRec CR (Cold Recycling)

The OptiRec CR software application handles primarily pavement reconstructions by detaching and mixing, applying cold recycling approaches, most frequently in-situ. There are primarily the technological options as listed below for the individual methods:

1) Detaching and mixing the material of the existing structure of the selected layers (e.g. re-shaping)
2) Recycling with the application of hydraulic binders (R) – cement or cement suspension
3) Cold recycling (CR) in various forms using bituminous binder or a combination with hydraulic binder
   a. bitumen emulsion
   b. bitumen emulsion and cement (lime)
   c. bitumen emulsion and cement suspension
   d. foamed bitumen
   e. foamed bitumen and cement (lime)
   f. foamed bitumen and cement suspension.

In comparison to the traditional reconstruction technology, cold recycling technologies have a number of advantages and some limits. In the case of cold recycling in situ, these are as follows, [5]:

+ the reconstruction method with lowest energy requirements;
+ minimized time demands of the reconstruction;
+ small quantities of material transported from and to the site if compared to the mill & fill method;
+ minimized need for new virgin materials;
- challenging use on roads with a high quantity of street inlets and other entry points to engineering utilities;
- need to use special machinery (recycler) in the machinery set.

Figure 1: Cold in-situ recycling – foamed bitumen, cement suspension (typice known set of machinery) [3]

In relation to the aforementioned technological options, the construction machinery performs activities further specified in Table 1.

Table 1: Activities performed during asphalt pavement reconstruction – recycling technologies [4]

Activity*	Machinery	Material processed
Detaching (milling) the deteriorated pavement surface and mixing it with new materials and binders if in-situ approach is used	Recycler	Damaged asphalt surface layer, part of base layers, hydraulic or bitumen binders, recycled mix
Compacting the recycled mix	Roller	Recycled mix, granular material
Levelling the recycling mix into the required slopes	Grader	Base layers, granular material, recycled mix
Homogeneous distribution of hydraulic binders on the pavement surface (if applied)	Bitumen sprayer truck	Hydraulic binder
Preparation of cement suspension from a cement mixture with water (if applied)	Cement suspension mixer	Hydraulic binder
Water delivery and supply for mix preparation	Water tank	Water
Asphalt mix delivery and supply for mix preparation	Truck with trailer (bitumen tank)	Bitumen emulsion
Bituminous binder delivery and supply for bitumen foam preparation	Truck with trailer (bitumen tank)	Bitumen
* With respect to the relatively small quantity of the material transported to the site, the transportation of material (binders and water) to the site is not included in the software application calculation.		

2.2. OptiRec MF (Mill & Fill)

The MF software version primarily handles reconstructions of flexible pavements by the traditional Mill and Fill technology. It is currently the standard and most common solution of pavement rehabilitation in the form of milling of the required layers of a flexible pavement (most often the surfacing) and replacement thereof by new structural layers. The method is effective but quite demanding of material resources in particular. As a consequence of cost savings in the field of reconstructions and the requirement for environment-friendly methods, alternative and equally effective solutions are being sought, like e.g. the aforementioned cold recycling, or hot recycling in situ or a combination of the methods available.

Summary of advantages and disadvantages for traditional rehabilitation methods for flexible or semi-rigid asphalt pavements, [5]:

+ universally applicable anywhere;
+ possible use for municipal roads (streets) in urban areas;
+ many decades of experience;
+ relatively low requirements for machinery during completion;
- high requirements for material resources – large quantities and demanding logistic transfers (aggregate, bitumen);
- economically more demanding.

Table 2: Activities for asphalt pavement reconstruction – traditional mill and fill method, [4]

Activity	Machinery	Material processed
Removal of dirt from the pavement surface	Sweeper	Dirtiness on the road
Cold milling of deteriorated pavement surfacing	Cold milling machine	Deteriorated asphalt surfacing, partly also base layers
Transport of materials between the construction site and dumping site, quarry or production plant	Truck / if necessary with trailer	Reclaimed asphalt material, new asphalt mix, aggregates
Uniform spreading of bituminous tack coat on the surface of a asphalt layer	Bitumen sprayer truck	Bitumen emulsion
Paving of asphalt layers	Paver	Asphalt mixes
Compaction of asphalt layers	Roller	Asphalt mixes

3. PRACTICAL APPLICATION OF THE SOFTWARE TOOL (EXAMPLE)

A road requiring reconstruction of the asphalt surfacing by one of the technological options, either cold recycling or traditional mill & fill method with a new asphalt layer, was chosen for a suitable explanation how the OptiRec tool works and what might be its advantages. This chapter aims to utilise the OptiRec applications in order to assess the selected reconstruction options. The options will be compared on the basis of the total CO_2 generated during the production of the materials incorporated in the project (asphalt mixes, hydraulic binders and bituminous binders) and CO_2 produced by the machinery during the work completion as such. Apart from CO_2, other emissions of greenhouse gases (particularly NOx, volatile hydrocarbons, CO, solid airborne particles) will be assessed as well. For the purposes of demonstrating the calculation tool results, a project with the following input parameters was chosen (see Table 3).

Table 3: Basic project pavement data

Type of road	Asphalt pavement (interurban)
Length of the section	1 000 m
Width of the rehabilitated road	10 m
Rehabilitation depth	120 mm (mill&fill)
	245 mm (cold recycling)

The road intended for reconstruction is a hypothetic example of a road with a minor traffic load / intensity (mainly by heavy loaded vehicles). The end of the pavement surfacing life is indicated by defects like e.g. deep cracking in the asphalt layers, deep pavement deterioration etc.. The pavement surfacing consists of asphalt concrete of total thickness 120 mm. The base layer consists of a layer of mechanically compacted aggregate on a protective layer made of crushed gravel. The total thickness of the pavement structure is 350 mm.

Table 4: Equivalent CO_2 for particular input materials and mixes, [6, 7]

Cold recycled mix component	Density (t/m^3)	CO_2 (kg/t)	Data source
Water	1.00	0.0003	IVL
Cement CEM II 32.5 R	1.25	980	IVL
Bitumen emulsion (C60B7)	1.00	221	Eurobitume
ACsurf 11	2.36	40*	Benninghofen, OptiRec
ACbin 16	2.34	37.9*	Benninghofen, OptiRec
ACbase 16	2.32	34.9*	Benninghofen, OptiRec
* Values for the assumed option of natural gas mixing plant heating.			

Table 5: Basic data of fuel (production and consumption) [6, 7]

Substance	Density (t/m^3)	CO_2 (kg/l)	Data source
Diesel – refining	0.84	0.26	Afteroilev
Diesel – consumption	0.84	2.66	Czech Ministry of Environment

3.1. Mill & Fill (Mill & Replace)

Within the framework of the traditional asphalt pavement reconstruction method, the whole thickness of both surfacing asphalt layers is supposed to be milled away, whereas selective milling is not used. The base layer of the compacted aggregate is retained. A prerequisite for this is sufficient bearing capacity and evenness of the area. The extracted material will be transported to a landfill or a mixing plant (the distance of 30 km was chosen). Subsequently, a typical paver will pave two new structural asphalt layers ACbin 16 and ACsurf 11. The original vertical alignment of the pavement will be retained mainly because of possible bridge structures. With respect to the nature of the reconstruction technology, the OptiRec MF will be applied.

Sequence of the reconstruction steps:
1) Milling 120 mm of the surfacing (wearing and binder course)
2) Transportation of the extracted material to a landfill / mixing plant (30 km distance)
3) Transport of ACbin mix from the mixing plant to the site (30 km distance)
4) Paving the ACbin mix, with a thickness of 80 mm
5) Tack coat by applying a cationic bitumen emulsion
6) Transport of ACsurf mix from the mixing plant to the site (30 km distance)
7) Paving the ACsurf mix to the thickness of 40 mm

Together with the information on dimension parameters and pavement composition, the list of the steps is used as underlying information for working with the OptiRec tool.

Table 6: Traditional option for pavement rehabilitation – pavement design

Original pavement design	Activities during the rehabilitation works	New pavement design after the rehabilitation works
40 mm – ACsurf 11 80 mm – ACbin 16 150 mm – mechanically bond granular material 200 mm – Ga (31.5mm)	Cold milling and later paving Cold milling and later paving - -	40 mm - ACsurf 11 80 mm – ACbin 16 150 mm – mechanically bond granular material 200 mm – Ga (31.5 mm)

A traditional reconstruction of the pavement asphalt surfacing can be divided into two basic steps – cold milling and new asphalt mix paving and compaction. Both steps are performed by a set of machines consisting primarily of standard machinery used in road construction (sweeper truck, tipper truck, paver, rollers etc.). During the milling, the crucial type of used machinery is the cold milling machine, which if special equipment is attached, can be used partly as a recycler (e.g. during cold recycling). The asphalt mix is laid to the necessary thickness by an asphalt paver supplied with hot asphalt mix, transported straight from the mixing plant. The following table 7 indicates the average fuel consumption and emissions of particular building machinery used in this type of rehabilitation. All values have been calculated by the OptiRec MF software.

Table 7: Average fuel consumption of the machinery used in the project (l/m^2)

Used machinery	Fuel	Fuel consumption (l/m^2)	CO_2 (t/m^2)
<u>Milling:</u>			
Sweeper truck	diesel	0.0027	7.750E-06
Cold milling machine	diesel	0.0811	2.366E-04
Tipper truck 1	diesel	0.5632	1.644E-03
<u>Paving and compaction:</u>			
Tipper truck 2	diesel	0.5638	1.644E-03
Bitumen sprayer truck	diesel	0.0021	6.200E-06
Asphalt paver	diesel	0.0365	1.064E-04
Tandem roller 1	diesel	0.0112	3.270E-05
Tandem roller 2	diesel	0.0112	3.270E-05
Static roller	diesel	0.0101	2.957E-05

The fuel consumption of machinery set in a hypothetical project is indicated both for individual machines and as a overall sum for the entire project. The quantity of CO_2 generated is indicated identically (table 8). A graphic expression of the values in the table is given in figure 2.

Table 8: Total released CO_2 emissions and fuel consumption on a hypothetical project

Used machinery	Consumption (l)*	Released emissions CO_2 (t)
Milling:		
Sweeper truck	26.44	0.0775
Cold milling machine	810.53	2.3668
Tipper truck 1	5 631.76	16.4447
Paving and compaction:		
Tipper truck 2	5 638.15	16.4634
Bitumen sprayer truck	21.23	0.0620
Asphalt paver	364.64	1.0647
Tandem roller 1	112.00	0.3270
Tandem roller 2	112.00	0.3270
Static roller	101.25	0.2957
TOTAL	**12 818**	**37.4288**

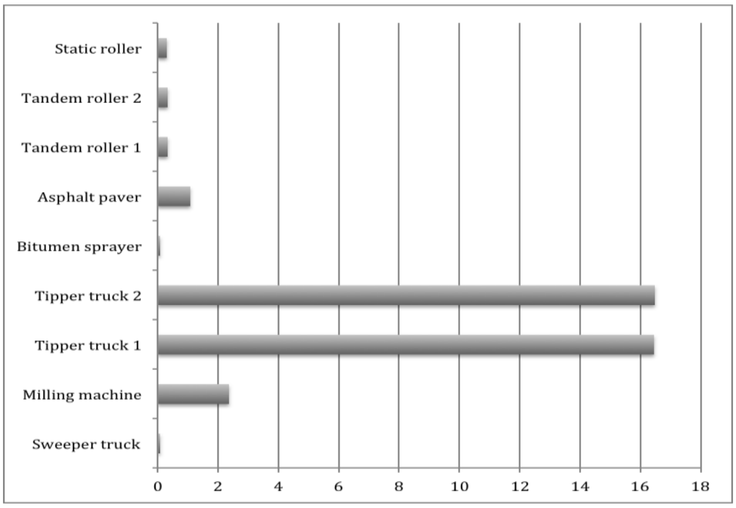

Figure 2: Total release of CO_2 emissions produced by the used machinery (t)

Table 9: Total CO_2 emission related to the materials used in the hypothetical project (t)

Type of used asphalt material	CO_2 (t)
Paved mix:	
ACsurf 11	37.82
Bitumen emulsion	2,210
ACbin 16	71.23
Bitumen emulsion	2,210

Table 10: Total released emissions on a hypothetical project

Used machinery	CO_2 (t)	NOx + HC (t)	CO (t)	PM (t)
Milling:				
Sweeper truck	0.0775	2.7937	1.0306	0.0491
Cold milling machine	2.3668	2.4343	14.3342	0.1024
Tipper truck 1	16.4447	8.6488	24.7286	0.1649
Paving and compaction:				
Tipper truck 2	16.4634	8.6586	24.7566	0.1650
Bitumen sprayer truck	0.0620	2.2350	0.8245	0.0393
Asphalt paver	1.0647	3.2987	5.2292	0.0373
Tandem roller 1	0.3270	2.8552	2.4409	0.1395
Tandem roller 2	0.3270	2.8552	2.4409	0.1395
Static roller	0.2957	1.2875	2.0089	0.0143
TOTAL	**37.4288**	**35.0673**	**77.7944**	**0.8513**

3.2 Cold recycling – option with bitumen emulsion and cement

In the case of pavement rehabilitation by cold recycling technology, the chosen technical option is applying cationic emulsion with residual bitumen content of 2.5 % and additional use of 1 % cement. In-situ recycling up to the thickness of 220 mm will be performed by a recycler and only the asphalt wearing course must be milled off. The new asphalt layer ACbin 11 of a total thickness 50 mm will be paved on the top of the cold recycled and compacted layer.

Sequence of steps:

1) Milling off 50 mm of the surfacing (wearing course)
2) Transportation of the extracted material to a land fill / mixing plant (30 km distance)
3) In-situ cold recycling - 220 mm (binder course + part of the base course) – use of 2.5 % by mass of bitumen emulsion (expressed by means of residual bitumen) and 1 % by mass of cement
4) Tack coat by cationic bitumen emulsion
5) Transport of ACsurf 11 from the mixing plant to the site (30 km distance)
6) Laying ACsurf 11, 50 mm

Table 11: Cold recycling option for pavement rehabilitation – pavement design

Original pavement design	Activities during the rehabilitation works	New pavement design after the rehabilitation works
40 mm - ACsurf 11	Cold milling, paving	50 mm - ACsurf 11
80 mm – ACbin 16	Cold recycling (in-situ)	220 mm – cold recycled mix
150 mm – mechanically bond granular material	Cold recycling (in-situ)	200 mm – Ga (31.5 mm)
200 mm – Ga (31.5 mm)	-	

With respect to the recycling and paving works, this example employs OptiRec CR (recycling works) and, subsequently, OptiRec MF (milling the wearing course and subsequent paving of this layer again).

Table 12: The content of binders and water in cold recycled mixtures

Component	Content in the mix (% by mass)
Bitumen emulsion (C60B7)	3.5 (2.5 % residual binder)
Cement CEM II 32.5 R	1.0
Water	3.0

Table 13: Average fuel consumption of the machinery used in the project (l/m^2)

Used machinery	Fuel	Fuel consumption (l/m^2)	CO_2 (t/m^2)
Milling:			
Sweeper truck	diesel	0.0027	7.750E-06
Cold milling machine	diesel	0.0811	2.366E-04
Tipper truck 1	diesel	0.5632	6.852E-04
Recycling:	diesel	0.0026	7.721E-06
Binder spreader (cement)	diesel	0.0064	1.879E-05
Water tanker	diesel	0.0072	2.106E-05
Bitumen tanker	diesel	0.1365	3.986E-04
Recycler (WR 250)	diesel	0.0093	2.703E-05
Compactor	diesel	0.0146	4.262E-05
Grader	diesel	0.0093	2.703E-05
Tandem roller 1	diesel	0.0084	2.460E-05
Static roller 1			
Paving and compaction:	diesel	0.2361	6.892E-04
Tipper truck 2	diesel	0.0005	1.550E-06
Bitumen sprayer	diesel	0.0182	5.524E-05
Asphalt Paver	diesel	0.0056	1.635E-05
Tandem roller 2	diesel	0.0056	1.635E-05
Tandem roller 3	diesel	0.0051	1.478E-05
Static roller 2			

Average fuel consumption and CO_2 emission production for particular machines used for the project is summarized in table 13. The follow-up table 14 then shows together with figure 4 total values for each machine related to the whole project.

Table 14: Total released CO_2 emissions and fuel consumption on a hypothetical project

Used machinery	Consumption (l)*	Released emissions CO_2 (t)
Milling:		
Sweeper truck	26.53	0.0775
Cold milling machine	810.53	2.3668
Tipper truck 1	2346.57	6.8520
Recycling:		
Binder spreader (cement)	26.44	0.0772
Water tanker	64.37	0.1880
Bitumen tanker	72.37	0.2107
Recycler (WR 250)	1 365.26	3.9866
Compactor	92.58	0.2706
Grader	145.97	0.4262
Tandem roller 1	92.58	0.2703
Static roller 1	84.25	0.2460
Paving and compaction:		
Tipper truck 2	2 360.55	6.8928
Bitumen sprayer truck	5.31	0.0155
Asphalt paver	182.32	0.5324
Tandem roller 2	56.00	0.1635
Tandem roller 3	56.00	0.1635
Static roller 2	50.63	0.1478
TOTAL	**7838.26**	**22.8874**

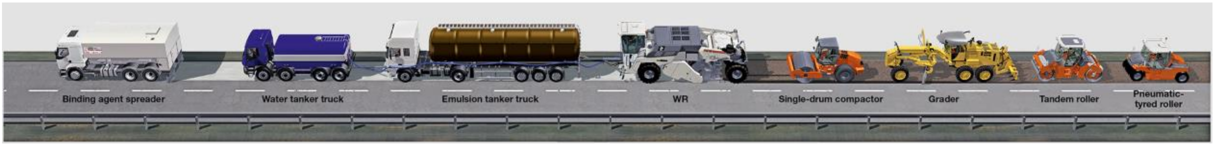

Figure 3: Cold recycling – set of used machinery (example), [3]

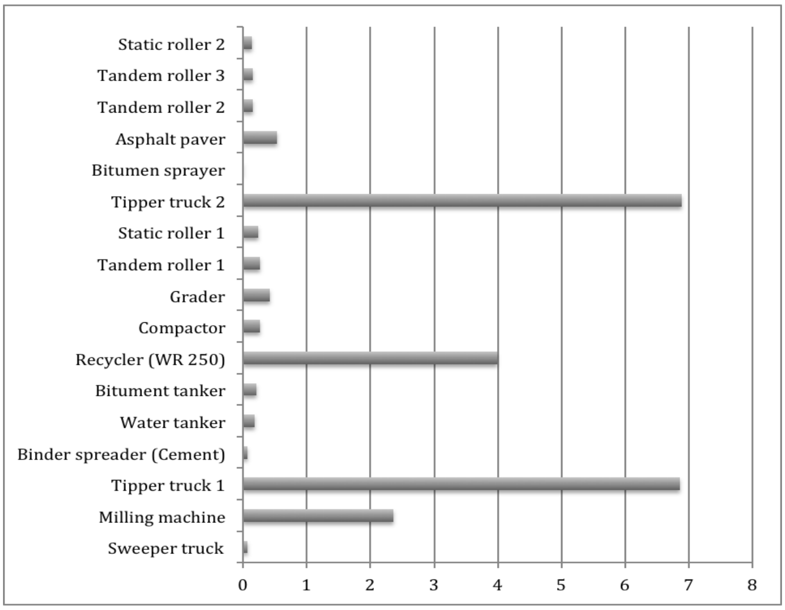

Figure 4: Total release of CO_2 emissions produced by the used machinery (t)

Table 15: Total CO_2 emission related to the materials used in the hypothetical project (t)

Component for cold recycled mix	Content in the mix (% by mass)	CO_2 (t)
Cold recycling:		
[1] Water	3.0	0.05
[2] Cement CEM II 32.5 R	1.0	104.15
[4] Bitumen emulsion (60 %)	3.5	28.64
Asphalt paving:		
ACsurf 11	-	47.28
Bitumen emulsion	-	2.21
Data source: 1-IVL;2-Athena & IVL; 3-Eurobitume; 4-Eurobitume		

Table 16: Total released emissions on a hypothetical project – cold recycling technology

Used machinery	CO_2 (t)	NOx + HC (t)	CO (t)	PM (t)
Milling:				
Sweeper truck	0.0775	2.7937	1.0306	0.0491
Cold milling machine	2.3668	2.4343	14.3342	0.1024
Tipper truck 1	6.8520	3.6037	10.3036	0.0687
Recycling:				
Binder spreader (cement)	0.0772	0.1785	0.5105	0.0034
Water tanker	0.1880	15.5517	5.7370	0.2732
Bitumen tanker	0.2107	1.5388	4.3077	0.0287
Recycler (WR 250)	3.9866	39.0390	19.3894	1.1080
Compactor	0.2706	3.9253	3.4082	0.1948
Grader	0.4262	4.1899	3.6778	0.2102
Tandem roller 1	0.2703	2.3877	2.0687	0.1182
Static roller 1	0.2460	1.0685	1.6900	0.0121
Paving and compaction:				
Tipper truck	6.8928	3.6251	10.3650	0.0691
Bitumen sprayer truck	0.0155	0.5587	0.2061	0.0098
Asphalt Paver	0.5324	1.6494	2.6146	0.0187
Tandem roller 2	0.1635	1.4276	1.2204	0.0687
Tandem roller 3	0.1635	1.4276	1.2204	0.0697
Static roller 2	0.1478	0.6439	1.0044	0.0072
TOTAL	**22.8874**	**86.0434**	**83.0886**	**2.4120**

3.3 Summary

The table below contains an overview of applicable technical options with a focus on CO_2 production. The table also contains the presumed quantities produced per square metre of the project completed by the technology in question. This means the total quantity of CO_2 generated (released) in relation to the production of the materials incorporated as well as the emissions resulting from the operation of construction machinery during the reconstruction.

Table 17: Technical rehabilitation options – focus on production (release) of CO_2

Used technology for rehabilitation	CO_2 (kg/m^2)	Total CO_2 (t)
MF – traditional approach of pavement rehabilitation	0.015	153.12
CR – cold recycling with bitumen emulsion and pre-spread cement	0.017	173.13
Source: Calculations are based on data from producers of machinery as well as from the European emission standards.		

Table 18: Technical rehabilitation options – focus on individual production (release) of CO_2

Used technology for rehabilitation	CO_2 (t) material	CO_2 (t) machinery
MF – traditional approach of pavement rehabilitation	115.69	37.43
CR – cold recycling with bitumen emulsion and pre-spread cement	150.25	22.89

Not only CO_2 counts to harmful greenhouse gas emissions released during production of building materials, their use, transport and fitting in structures. Another risk to the environment can be identified mainly with other greenhouse gases like NO_x, volatile hydrocarbons, CO or solid particle matters. This comprehensive information about the burden of the environment together with economic and material related demand is given by the software solutions OptiRec.

Table 19: Technological options and the overall emission comparison

Used technology for rehabilitation	CO_2 (t) total	NO_x + HC (t) total	CO (t) total	PM (t) total
MF – traditional approach of pavement rehabilitation	153.12	35.09	77.84	0.85
CR – cold recycling with bitumen emulsion and pre-spread cement	173.13	86.05	83.11	2.41

4. CONCLUSION

The computing tool for assessment of energy consumption and emission release of different solutions of asphalt pavement rehabilitation represents an effective instrument for evaluating technological options of pavement reconstruction. The evaluation of individual options is presented by the values of emitted harmful substances (CO_2, NO_x, volatile hydrocarbons, CO and solid airborne particles). Users also receive information about the economic requirements, resource requirements (materials, machinery), fuel consumption, time demands and unit indicators.

The basic prerequisites for using the OptiRec software application are sufficient input parameters about the project to be calculated, as well as at least basic knowledge and overview concerning pavement structures or the overall road construction.

The tool with open access to its architecture is used, inter alia, to support environmentally friendlier approach to construction and non-renewable resource management. It supports recycling technologies that reuse materials once incorporated and improved by quality enhancement.

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