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Innovative 100% RAP cold in-situ recycling of wearing course layers: laboratory and field characterisation and environmental impact assessment

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5 *Dr. Beatrice De Pascale*

6 Department of Civil, Chemical, Environmental and Materials Engineering-University of
7 Bologna, Italy

8 *Dr. Piergiorgio Tataranni*

9 Department of Civil, Chemical, Environmental and Materials Engineering-University of
10 Bologna, Italy

11 *Prof. Claudio Lantieri*

12 Department of Civil, Chemical, Environmental and Materials Engineering-University of
13 Bologna, Italy

14 *Prof. Alessandra Bonoli*

15 Department of Civil, Chemical, Environmental and Materials Engineering-University of
16 Bologna, Italy

17 *Prof. Cesare Sangiorgi*

18 Department of Civil, Chemical, Environmental and Materials Engineering-University of
19 Bologna, Italy

20

21

22 **Abstract:** In the last decade, research is pushing forward the use of innovative techniques and
23 environmentally friendly materials aiming at sustainable development in the construction
24 sector. In the field of road pavement, it is possible to recycle Reclaimed Asphalt Pavement (RAP)
25 material to produce new asphalt mixes. In the present paper, a 100% RAP mixture is proposed
26 through an innovative cold recycling in-situ technique for road pavement maintenance of small
27 damaged sections and repairing distresses. The localized patching is developed through an
28 innovative milling machine that is capable of directly and simultaneously milling and mixing
29 the RAP produced. The innovative machine develops repairs that guarantee the safety and
30 comfort of users. It can intervene locally and the final pavement has performances comparable

1 with those of traditional rehabilitation. For obtaining the final mixture, RAP is combined with
2 cement and a chemical additive, instead of a traditional bituminous binder. The experimental
3 program was divided into a laboratory study of the milled material and a trial field campaign.
4 After the laboratory and in situ phases, the environmental impacts that affect the repaired road
5 sections are also evaluated through Life Cycle Assessment (LCA) tool. Tests from the laboratory
6 and field phase highlighted positive results and downsides that need to be optimized to obtain
7 a good quality intervention. The LCA analysis showed a positive impact in terms of global
8 warming potential. Thanks to the use of the product coming from the milling of the old
9 pavement directly in situ and to the high amount of RAP, it is possible to mitigate the negative
10 environmental impact associated with road pavement maintenance.

11 **Keywords:** RAP, LCA, cold in-place recycling, road pavement maintenance, distress

12

13 **1. Introduction**

14 In recent years, the growing concern for environmental issues has led to the adoption of
15 more sustainable technologies and design approaches. The pavement industry is one of the
16 greatest consumers of natural resources and raw materials and the negative effects in terms of
17 environmental impact are further enhanced by a large production of waste during routine
18 maintenance and rehabilitation works (Pasetto et al., 2017; Tataranni et al., 2018). Thanks to a
19 growing awareness of public opinion on sustainable development, numerous researches have
20 focused on construction operations that can be less detrimental for the environment. Being the
21 maintenance and rehabilitation of existing pavements one of the most urgent problems in the
22 road sector, it is crucial to promote an eco-friendly approach for the development of innovative
23 technologies with reduced environmental impact (Gao et al., 2018). With the limited aggregate
24 and binder availability, together with strict environmental regulations, recycling and use of

1 waste materials have become priority objectives for both administrations and producers
2 (Sangiorgi et al., 2016). Asphalt concrete consists of valuable non-renewable resources, and it
3 can be re-used entirely in new asphalt mixtures and in the rehabilitation of pavements (Tarsi
4 et al., 2020; Valdés et al., 2011). The Reclaimed Asphalt Pavement (RAP) material is usually
5 identified as the aged asphalt concrete coming from existing roads. The possibility of recycling
6 RAP for the production of new road pavements represents a perfect example of circular
7 economy and environmental sustainability. Furthermore, the use of RAP coupled with the cold
8 recycling technology has become a cost-effective technique for the repairing and rehabilitation
9 of road sections (Montañez et al., 2020; Salehi et al., 2021). Different studies have shown that
10 in different countries the common percentage of RAP in the production of HMA has largely
11 exceeded 50% (Meroni et al., 2021; Tarsi et al., 2020; Yang et al., 2021). Considering the cold
12 recycling techniques, instead, the possibility of using RAP increases significantly, reaching
13 100%. The advantage connected to the cold recycling technique is the possibility to use the
14 material without heating it. The cold recycling techniques can be subdivided into three different
15 methodologies: Cold In-place Recycling (CIR), Cold Central-Plant Recycling (CCPR), and Full
16 Depth Reclamation (FDR) (Tabaković et al., 2016). This subdivision is based on construction
17 technologies, the depth of reclamation, and the processing place. CIR is the in situ recycling
18 procedure that involves the milling of old road section to paving a new road at ambient
19 temperature. The CCPR is different from CIR, is less common, and is mainly conducted at central
20 or mobile plants. The FDR, on the other hand, has the same recycling process as CIR, but the
21 asphalt layers are milled with part of the base layers. The present study focuses on the CIR
22 methodology and precisely on the partial-depth recycling, which involves only the reclamation
23 of the surface layer of the pavement. Thanks to the use of the CIR, it is possible to utilize 100%
24 of the RAP generated during the milling process (Magar et al., 2022; Zhu et al., 2020). Today,
25 the most commonly used materials in cold recycling rehabilitation of road pavement are

1 emulsified asphalt and foamed asphalt (Widayanti et al., 2018). Furthermore, cold recycled
2 mixtures with asphalt emulsion with RAP, are a common sustainable practice. It is a
3 resourceful, energy saving and cost-effective approach for pavement rehabilitation (Dong et al.,
4 2021; Rodríguez-Fernández et al., 2019). The present study is based on the optimization of an
5 innovative milling machine that uses CIR methodology, RAP material and a chemical additive
6 for the maintenance of surface layers in urban areas. When dealing with repairing road
7 surfaces, and precisely utility cuts rehabilitation, the most common method is to carry out
8 patching. Patching is made for localized interventions and consists in filling the deteriorated
9 area with a consistent and resistant material, to prevent further damage. So, from both
10 economic and environmental perspectives, the use of CIR for road pavement maintenance and
11 repair is much more beneficial than traditional hot technology (Flores et al., 2020; Kwon et al.,
12 2018). The benefits that could be achieved in using this type of localized maintenance are
13 several, including the reduction of the time for the actual maintenance and its consequences on
14 local traffic. Furthermore, the transport of the material is not needed, and there is no disposal
15 of material in the landfill. Moreover, another innovation connected to the present study is the
16 milling machine itself, which is capable of directly and simultaneously milling and mixing the
17 RAP with the chemical additive, similarly to cold recycling but for more localized and superficial
18 maintenance. The innovative milling machine has been designed to intervene in localized
19 repairs and at the same time, it guarantees good quality of the intervention, durability of the
20 repairs, and the possibility of recycling the material in future works. These qualities, nowadays,
21 are difficult to find when talking about distress repair. Another aspect that has been taken into
22 account is the reduction of the environmental impact associated with the entire process.
23 Focusing on road construction and maintenance, different steps contribute to the production
24 and release of greenhouse gas (GHG) emissions (Bonoli et al., 2020; Giani et al., 2015). Road
25 construction is one of the three main drivers of resource use in the European Union because

1 requires large quantities of materials, for both production and maintenance phases
2 (Nascimento et al., 2020). Previous studies highlighted that the bulk of the emissions related to
3 road maintenance is usually associated with those incorporated in the production of the
4 materials (Hasan et al., 2020). This is why new techniques such as cold in-place recycling of
5 100% RAP, without the use of bituminous binders, represent a viable option for reducing the
6 environmental impact associated with localized rehabilitation (Garraín & Lechón, 2019;
7 Vandewalle et al., 2020). In fact, different studies confirm that the most effective way to
8 decrease the eco-burden is to reduce the heat needed during the manufacturing and
9 maintenance process (Chiu et al., 2008; Giani et al., 2015). So, the novelty associated with this
10 research was the integration of the characterization of an innovative technique for localized
11 rehabilitation with a brief analysis of its environmental impact by using a Life Cycle Assessment
12 (LCA) approach. It is noted that LCA is a widely used method for calculating emission and
13 environmental impact associated with any kind of product and processing, and it can be
14 properly applied also in the road construction and transportation infrastructure sector (Chen
15 & Wang, 2020; Pouranian & Shishehbor, 2019). Praticò demonstrated that the LCA analysis is
16 extremely important to obtain clear setup strategies and clear information about the
17 environmental impact in the pavement sector (Chiu et al., 2008; Praticò et al., 2020).
18 Furthermore, the LCA tools are often used to support stakeholders in the right selection of
19 materials, maintenance, and rehabilitation strategies to ensure appropriate road conditions
20 and reduce environmental impact (Oreto et al., 2021; Siverio Lima et al., 2021). Based on the
21 above statement, the present research aimed to analyse the provided materials at a particle size
22 distribution level and subsequently characterize the optimal mixture in terms of physical and
23 mechanical properties. The laboratory phase consisted mainly of the optimization of the
24 material and consequently of the setting of the innovative machine. This phase was crucial since
25 no other applications comparable to the innovative milling machine are known. The

environmental impact of the rehabilitation process for road pavement was evaluated using a LCA method in compliance with ISO 14040.

2. Experimental program, materials and methods

The study focuses on the optimization of an innovative milling machine for utility cuts rehabilitation. Based on the idea of CIR the machine is developed to rehabilitate up to 7 cm of road pavement. The choice of using the chemical additive is taken to avoid the possibility of segregation of the bitumen emulsion and because the nozzles of the machine were designed for the specific viscosity of the chemical additive. The research program was divided into three main phases:

- Laboratory: the objective of this phase was the mix design of a cold recycled asphalt mixture for pothole repair and patching that could be reproduced in situ with the experimental milling machine. In this phase, different RAPs were supplied from the same pavement and produced with different settings of the milling machine. The optimal mix in terms of dosage of chemical additive and Portland cement was defined, together with the physical and mechanical characteristics of the mixture. The performance of the experimental cold mix asphalt was evaluated taking as a reference an Italian technical specification for hot mix wearing course.
- Trial field campaign: considering the milling procedure needed to produce RAP with the targeted grading distribution and the optimized mix developed in the laboratory, three different pavement rehabilitations were performed in real trafficked roads.
- Life Cycle Assessment: in this phase, the evaluation of the environmental impacts related to the rehabilitation of a road section with the innovative milling machine was analysed.

The analysis aimed to determine the CO₂-eq emissions produced during the entire process.

2.1. Materials

The experimental study here presented, involved the laboratory and in situ characterization of 100% RAP mixture produced through an innovative cold in-situ recycling technique for the rehabilitation of small damaged areas of asphalt pavements. In order to verify the RAP geometric quality produced by the milling machine, several materials were provided. The materials were first analysed in the laboratory to identify the optimal configuration of the milling machine to obtain the best possible grading curve. All milled materials were characterized in terms of their gradation, but the mechanical characterization and the optimal mixture were only developed for the material that fitted better the reference Italian technical specification. After the physical characterization of the chosen RAP, the optimal mix design was studied and analysed. Based on preliminary studies conducted on the same materials, the optimal mixture was made with 2 % of chemical additive and 1.5% of Portland cement 32.5. It should be highlighted that the chemical additive chosen for the mixture was used as rejuvenator and carrier of some binding agents. In its composition a small quantity of bitumen is present.

2.2. Laboratory characterization

The laboratory phase concerned a first analysis of the RAP materials to assess the geometrical characteristic and a second analysis of the mix design in terms of mechanical and physical properties. At first, the different materials were characterized in terms of particle size distribution. The grading curve of the analysed materials must be in accordance with an Italian technical specification for wearing course to ensure established performance. When the selection of the most suitable material was concluded, 6 specimens of the optimal mixture were prepared to be tested in terms of physical and mechanical characterization.

2.2.1. Geometrical characterization of the mixture

1 The first laboratory characterization concerned the investigation of the geometrical
2 properties of the RAPs through a sieve analysis. In accordance with the EN 933-1 standard, a
3 representative sample for each material was separated on sieves of different sizes. Once
4 verified the grading distribution of the different RAPs, the results were compared with the
5 gradation bands suggested by the Italian technical specification for wearing courses, aiming to
6 define an optimized setting for the milling machine. Once the most suitable material was
7 chosen, the mix design was developed, and the specimens were compacted. The compaction
8 was carried out on 150 mm diameter gyratory compacted samples (EN 12697-31, 30
9 gyrations). As mentioned before, the designed mix was composed of 100 % RAP, 2 % of
10 chemical additive, and 1.5 % Portland cement 32.5. The low number of gyrations was defined
11 to simulate the relatively low level of compaction given by the vibratory plate compactors that
12 are generally adopted for asphalt patching and utility cuts rehabilitation. The evaluation of the
13 workability of the mixture was defined in terms of air voids content (V_a), based on the EN
14 12697-8 standard.

15 2.2.2. Mechanical characterization of the mixture

16 The static mechanical characterization was carried out in compliance with the EN 12697-23
17 standard, in terms of Indirect Tensile Strength (ITS) at 25 °C. The ITS aims to evaluate the
18 maximum tensile stress from the peak load applied on a cylindrical specimen loaded until
19 break. The 6 specimens were divided into two groups and the ITS is developed on dry and wet
20 samples. The test performed on wet samples is used to calculate the Indirect Tensile Strength
21 Ratio (ITSR) and it is based on the EN 12697-12 standard. The three samples tested in wet
22 conditions were conditioned for 72 hours in water at 40°C, in compliance with the standard.
23 The three specimens tested against ITS were previously analysed in terms of indirect tensile
24 stiffness modulus (ITSM). The ITSM test was made according to EN 12697-26 (Annex C), and
25 the stiffness modulus of the mixture was evaluated in the indirect tensile configuration. The

1 ITSM test was performed at three different temperatures (10, 20, and 30 °C) to evaluate the
2 temperature sensitivity of the material.

3 *2.3. Trial field campaign*

4 Once defined the optimized mix design and the geometrical, physical and mechanical
5 characterization of the cold recycled mixture, 3 different real trial sites were developed. The
6 aim of the trial field was to define a unique process and setting of the milling machine in order
7 to reproduce the mixture studied in laboratory. Furthermore, the performances of the final
8 mixture in real conditions were investigated. Real asphalt patching was performed with the
9 innovative milling machine on different road pavement sections with surface cracks. In situ
10 tests and collection of samples were planned after 30 days of traffic after the repair of the
11 pavement. The cores collected from each trial field were tested in terms of air voids content
12 (EN 12697-8) and ITS at 25 °C (EN 12697-23). The slip/skid resistance of the pavement was
13 evaluated through the Pendulum test, according to EN 13036-4, to indirectly assess the micro-
14 texture of the new asphalt patches. For what concerns the macrotexture of the new patches, it
15 was evaluated through the volumetric patch technique (EN 13036-1). The test involves the
16 application of a known volume of standardized material on the surface and the subsequent
17 measurement of the average diameter to evaluate MTD, that is the mean texture depth
18 expressed in millimetres.

19 *2.4. Life Cycle Assessment*

20 The LCA analysis is performed to predict the performance of the product and evaluate
21 compliance with the environmental requirements.

22 To regulate the LCA analysis, the International Organization for Standardization (ISO) has
23 established its principles, guidelines, and requirements (ISO 14040, ISO14044, ISO 14025, ISO
24 14024, and ISO 14020). In these standards the concern regards the effect of environmental

exploitation and pollution on human health, the quality of the earth, and the exploitation of the natural resources, taking into account even the economic and social aspects. According to ISO 14040, to perform an LCA analysis, the four steps to be performed are the definition of the goal and the scope of the analysis, the inventory analysis or life cycle inventory, the impact assessment, and the interpretation of the results obtained. For the present LCA study, the “Ecoinvent 3.5” database supported data analysis and collection and the impact assessment has been performed by means of the SimaPro software. This software allows the evaluation, monitoring, and analysis of the environmental performance of complex products, services, and life cycles, strictly following the guidelines of ISO 14040 and ISO 14044.

3. Results and discussion

3.1. RAP particle size distribution results

For each RAP material, the characterization in terms of particle size distribution was carried out. Based on the reference Italian technical specifications it was noted that none of the materials provided were suitable for the wearing course. It was therefore decided to create in laboratory a modified and optimized grading curve of the material here labelled F1, which best fitted the grading envelope. The optimization was developed by crushing the retaining portion at sieve 14 mm of the material. Figure 1 shows the grading curve of the chosen material before optimization. After the amendments, the particle size distribution of material F1 is displayed in figure 2 and perfectly fitted the reference envelope of the Italian specification.

3.2. Physical and Mechanical Test Results for the F1 mix

After the optimization of the grading curve, the mixture of F1 material was compacted in 6 specimens.

3.2.1. Air voids content results

The air voids content analysis was carried out according to EN 12697-8. It was calculated by using the maximum density of the mixture and the bulk density of the sample. The specimens were compacted with 30 gyrations to simulate low in situ compaction. Results are shown in Table 1 where higher values of V_a have been found if compared to the air voids content of traditional bituminous mixtures for wearing course. These results were in line with the expectation since the compaction energy was really low.

3.2.2. ITSM results

For the evaluation of the ITSM, the specimens were tested at 3 temperatures to investigate the thermal sensitivity and the stiffness modulus of the cold recycled mixture. The stiffness of the material is shown in Table 2 and it increased with the temperature decrease. Furthermore, all results are in line with the ITSM values for traditional asphalt concrete for surface layer. The thermal susceptibility can be evaluated with the ITSM versus temperature curve described by the following equation:

$$\log S = -\alpha \cdot T + \beta$$

S represents the indirect tensile stiffness modulus at the testing temperature, then α and β are experimental parameters referring to the properties of materials. Precisely, α can represent the temperature susceptibility and a higher α parameter implies that the material is more susceptible to temperature changes. The ITSM versus temperature curve and corresponding equation are reported in figure 3.

3.2.3. ITS and ITSr results

The tests were performed for dry and wet specimens at 25°C. Focusing on Table 3, the results of the dry test showed acceptable values and they were almost twice the threshold value of 0.35 MPa specified by the reference technical specification for cold recycled asphalt concrete. On the

other hand, some problems were highlighted for the wet specimen. The indirect tensile strength ratio (ITSR) values that represent the ratio between the dry and wet testing conditions, are shown in Fig.6 for each sample. The average value of the ITSR was equal to 50% which was lower than the traditional 75% value specified by the reference technical specifications for hot mix asphalt. This phenomenon represents a potential limit for the performance of the material. However, it should be considered that the ITSR is generally lower for cold mixtures if compared to hot mixes.

3.3. In situ tests result: slip/skid resistance and surface macrotexture

In general, the proposed mixture showed suitable properties for its application as patching asphalt. Thus, after the laboratory investigation and characterization, three full-scale trial fields were developed. The setting of the experimental milling machine was defined trying to replicate the mixture obtained in the laboratory phase. Different settings were chosen for the different trial fields since no references in the literature are available and no other applications like this one are known. The first operational step of the milling machine concerned the milling of the first 5 cm of the old pavement. The second and third phases concerned the addition of the chemical additive and the cement and a subsequent mixing to obtain a homogeneous product. After the third step, the compaction of the site took place and the pavement was immediately open to traffic. The aim of the different settings is to find out the right process for obtaining the optimized material since no literature references are present concerning this process. Table 4 reports the different operational phases developed for each trial field.

The rehabilitated sections were 10 to 20 m long, 1 m wide, and made on roads interested by traffic of light and heavy vehicles.

Figure 4 shows pictures of a rehabilitated section and the milling machine at work.

1 To evaluate the physical and mechanical properties of the obtained materials and the surface
2 properties of the rehabilitated road in situ tests were performed at each site after 30 days of
3 traffic.

4 *3.3.1. Slid/skid resistance results*

5 For each trial field, two points were evaluated in terms of PTV. As shown in figure 5 the
6 average values obtained for each site were not alike. The results were different from each other
7 due to the fact that the three rehabilitated sites were developed with different processes, in
8 terms of setting of the innovative machine, and the characteristics of the old pavement were
9 not specified and may be different in terms of properties of the aggregates. Nonetheless, the
10 PTV values from each site showed a good quality pavement in terms of grip despite these
11 differences. As a matter of fact, the Italian technical specification declares that, when a new
12 pavement is opened to traffic, the PTV values shall be higher than 55.

13 *3.3.2. MTD results*

14 To assess the surface macrotexture of the new rehabilitated pavement the volumetric patch
15 technique was used. Considering figure 6, the third trial field showed a higher value in terms of
16 MTD. In this case, a higher value of MTD confers to the pavement more roughness. The
17 discrepancy between the three sites in terms of surface macrotexture is due to the differences
18 in the rehabilitation processes developed for the different pavements and the origin of the old
19 pavement as seen for the PTV.

20 *3.4. Characterization of core samples: physical and mechanical results*

21 Two cores from each site were collected in order to evaluate the physical and mechanical
22 properties of the experimental layer. Figure 7 represents a cored specimen taken from the first
23 trial field. It is worth noting that there was no debonding between the new rehabilitated
24 wearing course and the existing binder layer.

1 The good bond generated between the two asphalt layers confirms the quality of the
2 rehabilitation procedure, considering that no bituminous tack-coat was applied on the existing
3 layer after the milling of the asphalt wearing course. The cored samples were consequently
4 investigated in terms of air voids content and ITS. Average results of the samples cored from
5 each site are listed in Table 5.

6 The pavement in the first trial field was well compacted and the entire procedure was of good
7 quality. Comparing laboratory and field results, the difference between the lab compacted
8 specimens and the cores was evident. As already mentioned, the reference value for this type
9 of material in terms of ITS is 0.35 MPa. The table shows that, in the first trial field, the average
10 ITS value of the cored samples was in line with those obtained during the laboratory
11 investigation. However, the results for the second and third sites were lower than expected. For
12 what concerns the second trial field, the lower quality of the pavement was already observed
13 during the rehabilitation process, where the material appeared to be too deformable after
14 compaction. The amount of chemical additive present in the layer was erroneously too high and
15 it gave to the rehabilitated section good air void content but negatively influenced the
16 mechanical characteristics. Also, cores taken from the third site exhibited low mechanical
17 characteristics. In this specific case, the rehabilitated section was wider than the previous ones
18 and compaction was not homogeneous. Cores were taken in the central part of the rehabilitated
19 section, where ineffective compaction occurred due to a lack of confinement.

21 *3.5. Life Cycle Assessment results*

22 This section describes the evaluation of the environmental impact related to the pavement
23 rehabilitation with the proposed technology, based on the LCA analysis. As a functional unit,
24 the rehabilitation of 1 m² of pavement with a depth of 0.05 m was chosen, while the boundary
25 conditions were from gate to gate. Within the boundaries are considered the production in situ

1 of the RAP, the mixing phase for the development of the final material and the compaction
2 process. It should be noted that the consumptions of raw materials, energy, and transport
3 concerning the old pavement were out of system boundaries, while the transport of the
4 machine from the plant to the rehabilitated pavement was included. The system object of the
5 analysis included the consumption of a small percentage of cement, chemical additive, and
6 water. The scope of this analysis was to assess the CO₂-eq emissions related to the innovative
7 cold in-situ recycling technique for patching utility cuts and pothole repairs. More specifically,
8 CO₂-eq emissions related to the phase of production and construction of the rehabilitation using
9 100% RAP were considered (figure 8).

10 The LCA was performed in compliance with the ISO 14040 standard, focusing on the calculation
11 of total CO₂-eq amount, imputable to the production phase of the RAP and to the construction
12 of the rehabilitation, and Global Warming Potential (GWP) impact category evaluation. The
13 software used for the analysis was SimaPro® 8 (*SimaPro Database Manual Methods Library*,
14 2021). The climate change factors of the Intergovernmental Panel on Climate Change (IPCC)
15 guideline methodology were evaluated within a timeframe of 100 years (Global Warming
16 Potential 100 in version 1.03). In the analysis, the RAP was introduced as a process where a
17 perfectly closed loop was considered. Therefore, the percentage of recycled pavement for
18 making the rehabilitation is equal to the percentage of pavement that is recycled at the end of
19 the old pavement's life. In that way, RAP was introduced in the analysis with a negative sign
20 since the old pavement was entirely recycled to produce the new one. Due to the lack of primary
21 and secondary data, the chemical additive was assumed as bitumen, taken from the USLCI
22 database available in SimaPro. This approximation could be done since the chemical additive
23 was declared by the company to be fossil fuel-based and labelled as green so with a low
24 environmental impact. However, the real composition of the chemical additive was not known
25 since the material is covered by patent. In the analysis are also included the Portland cement

1 and the transport of the milling machine to the site. Figure 9 represents the network model for
2 the innovative cold in-situ recycling process.

3 The network model represents the results of the LCA analysis on the basis of a Sankey-like
4 diagram, in which the width of the lines is drawn in proportion to the amount of flow. The
5 negative environmental impacts are represented by red lines whose size is proportional to the
6 amount of CO₂-eq, while the green ones indicate the positive environmental impact associated
7 with the RAP, also considered as avoided impact. Figure 10 shows the impact of each material
8 involved in the rehabilitation of the road section expressed in percentage: bitumen (yellow,
9 24.7%), transport of the machine (blue, 52.9%), cement (green, 34.9%), RAP (orange, -12.9%)
10 and water (grey, 0.40%).

11 Global warming potential was chosen as an impact category. Table 6 shows the total amount of
12 CO₂-eq produced by the innovative technology related to the selected functional unit.

13 From the literature, it is possible to understand that the innovative cold in-place recycling
14 reduces the kg of CO₂-eq up to 37% with respect to traditional rehabilitation (Chehovits &
15 Galehouse, 2010; Jiang et al., 2020). As mentioned before, bitumen was chosen instead of the
16 chemical additive. Even if the bitumen has not the highest environmental impact, it should be
17 underlined that the overall impact could be further decreased by at least 5 % if the composition
18 of the chemical additive would be known or if the bitumen would be not considered in the
19 analysis. From the results, it is possible to see that the highest environmental impacts are given
20 by cement and transport. Unfortunately, it is not possible to decrease the impact associated to
21 the transport of the milling machine in situ. However, with the diffusion of the machine in the
22 companies, the transport will depend on their radius of action, so the impact connected to it
23 may change.

24 A specific analysis of the actual characteristics of the composition of the chemical additive and
25 its production is recommended in future studies. Furthermore, the next steps in the research

1 will be oriented to evaluate the use and end-of-life of the proposed technology, in a cradle-to-
2 grave approach and in all environmental impact categories' evaluation according to a complete
3 LCA analysis. Nonetheless, the advantages of the new innovative cold in situ recycling
4 technology are described in this paper. First of all the possibility to recycle entirely the RAP
5 directly in the same place as it is produced by using just one machine, then the possibility to
6 obtain a good material in terms of mechanical properties, and minimize the environmental
7 burden connected to the rehabilitation phase of a road.

8 **4. Conclusions**

9 In the present paper an innovative technique for the local rehabilitation of damaged surface
10 layers, the distresses' repair and potholes repair is presented. The objective of the research was
11 to analyse a 100% RAP mixture developed with an innovative milling machine through a
12 laboratory and field characterization. The optimal mixture was developed with the addition of
13 cement and a chemical additive used as rejuvenator and carrier of some binding agents.
14 Furthermore, with the LCA analysis it was also possible to evaluate the environmental impact
15 of the entire process, considering that the experimental milling machine and rehabilitation
16 procedure do not require the use of heat, virgin materials, and neat bitumen. Based on the data
17 obtained from the laboratory and field characterization and from the LCA analysis, the
18 following preliminary conclusions can be drawn:

- 19 • Based on the lab results, with the use of 100% RAP, chemical additive and cement it is
20 possible to produce an asphalt mixture with suitable properties for the rehabilitation of
21 damaged wearing course layers.
- 22 • Adopting the optimized procedure identified during the trial field campaign, it was
23 possible to obtain from site-produced material, the same results obtained during the
24 laboratory phase.

- The functional characteristics (e.g., texture) of the rehabilitated sections were independent of the old pavement conditions. The high presence of RAP in the mixture leads to acceptable results in terms of macrotexture and microtexture.
- In terms of weaknesses, the results of the maintenance intervention are strongly affected by the dosage of chemical additive, the setting of the milling machine, the number of passes of the machine, and the final compaction system and process.
- The LCA analysis was conducted to evaluate the environmental impact of the production phase of the rehabilitation process, only in relation to CO₂-eq emissions and GWP assessment related to the realization of the road section. The proposed solution has the ambition to contribute to footprint reduction and to improve the sustainability of routine road maintenance. The results, expressed in carbon dioxide equivalent (CO₂-eq) emissions, showed that recycling in-situ the old pavement without transport and treatment in plant, has a positive impact on the environment.

The physical and mechanical properties, as well as the environmental performances of the innovative process have been evaluated. To better understand the advantages of the proposed rehabilitation technology, future studies shall develop a cradle-to-cradle analysis and compare it with traditional rehabilitation techniques for wearing courses.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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1 **Credit author statement**

2 **Beatrice De Pascale:** Conceptualization, data curation, formal analysis, investigation,
3 methodology, validation, writing—original draft, software

4 **Piergiorgio Tataranni:** Conceptualization, validation, project administration, supervision,
5 writing—review and editing

6 **Claudio Lantieri:** Conceptualization, validation, supervision, writing—review and editing

7 **Alessandra Bonoli:** Conceptualization, validation, supervision, writing—review and editing,
8 software

9 **Cesare Sangiorgi:** Conceptualization, validation, funding acquisition, project administration,
10 resources, supervision, writing—review and editing

11 All authors have read and agreed to the published version of the manuscript

12 Corresponding author, e-mail address: beatrice.depascale3@unibo.it

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Tables

Table 1

Average voids content (Va) of specimens.

Mechanical values	Unit	Mix1
avg. Av content	%	12.9 (± 0.61)

Table 2

Average results of ITSM test.

Mechanical values	Unit	10°C	20°C	30°C
ITSM	MPa	4837 (± 92)	2819 (± 139)	1639 (± 83)

Table 3

Average results ITS_{dry}, ITS_{wet}, and ITSR for each mixture.

Mechanical values	Unit	Average values
ITS _{dry}	MPa	0.60 (± 0.02)

ITS _{wet}	MPa	0.3 (± 0.02)
ITSR	%	50 (± 3.46)

1

2 Table 4

3 Operational phases developed for each trial field. Different settings and steps have been adopted.

N° Site	1 st Step	2 nd Step	3 rd Step
1 st Site	Milling of the old pavement with the optimized milling procedure	Manual addition of cement and following spraying of the chemical additive by the machine while it was mixing the RAP	Final mixing of the mixture to obtain a more homogeneous product all over the rehabilitated section
2 nd Site	Simultaneous milling of the old pavement with the optimized milling procedure and spraying of the chosen quantity of chemical additive	Manual addition of cement and following mixing of the final mixture to obtain a more homogeneous product all over the rehabilitated section	-
3 rd Site	Milling of two adjacent sections of the old pavement with the optimized milling procedure to obtain a wider rehabilitation	Manual addition of cement and following spraying of the chemical additive by the machine while it was mixing the RAP, first in one section and then in the next one	Final mixing of the mixture to obtain a homogeneous product all over the rehabilitated section

4

5 Table 5

6 Results of the laboratory characterization of the cored samples, following EN 12697-8 and EN 12697-23.

SITE	Avg. Voids [%]	ITS [MPa]
1 st Site	2.51	0.65
2 nd Site	1.06	0.10
3 rd Site	14.79	0.40

7

1 **Table 6**
2 Environmental impact related to the construction phase of the rehabilitation technology.

<u>Material</u>	<u>Process</u>	<u>Source</u>	<u>kg CO₂-eq</u>
Cement			1.49
Bitumen		Ecoinvent 3.5 allocation cut-off	1.05
RAP		by classification	-0.549
	Transport		2.26
<u>TOTAL</u>			<u>4.26</u>

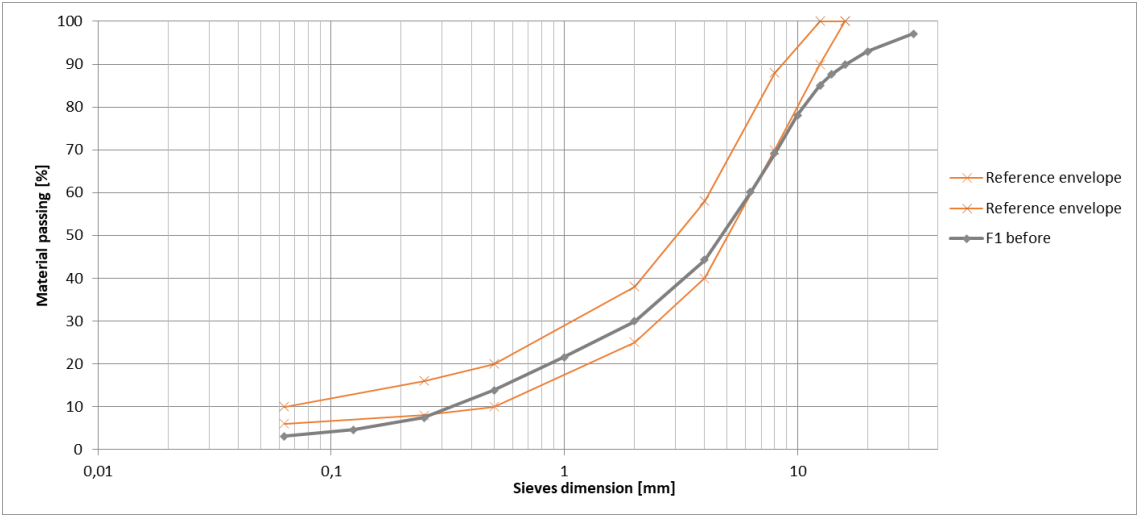
3

4 **Figure**

5 **Fig.1:**

6

7



8

9

10 **Fig.2:**

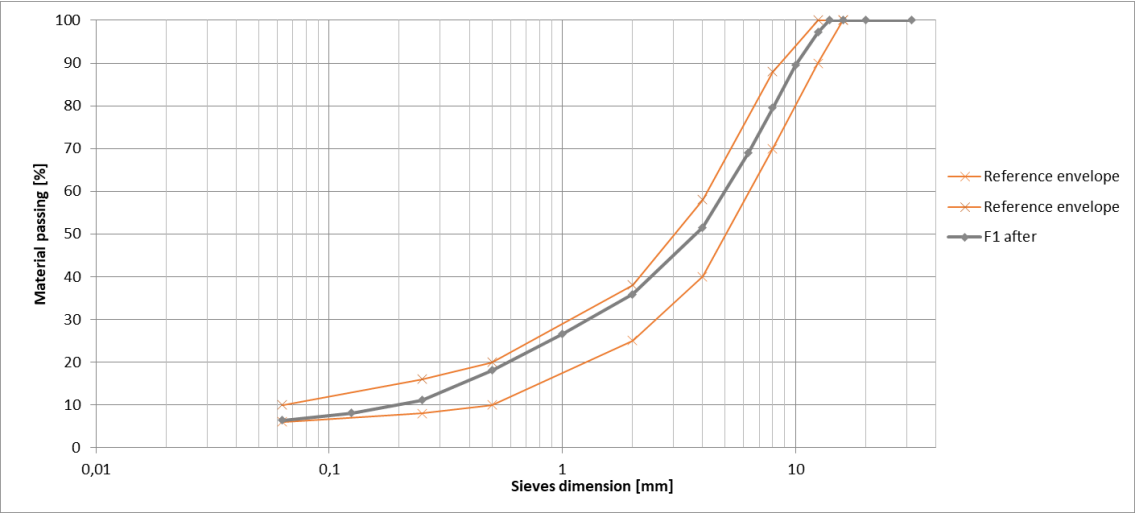


Fig. 3

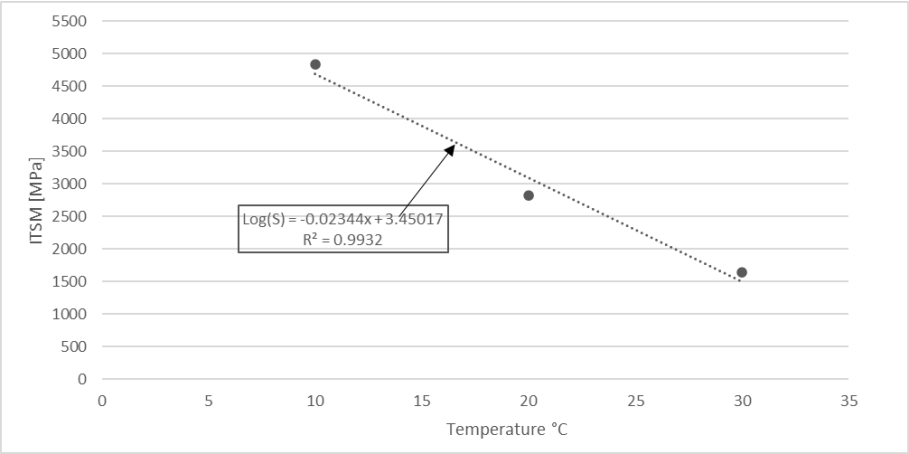


Fig. 4:





Fig. 5:

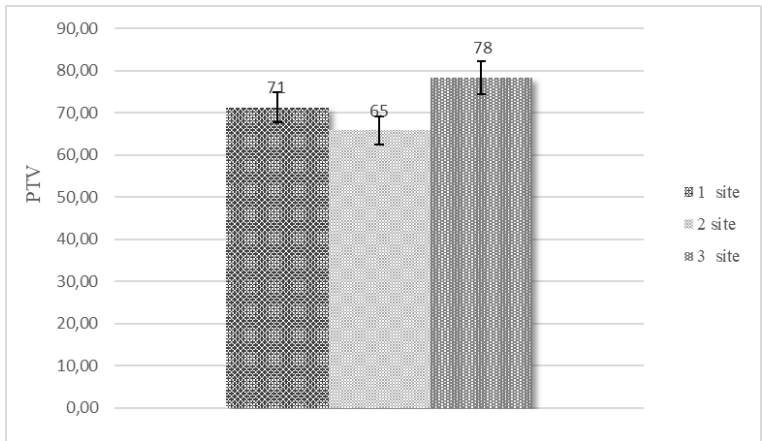


Fig.6:

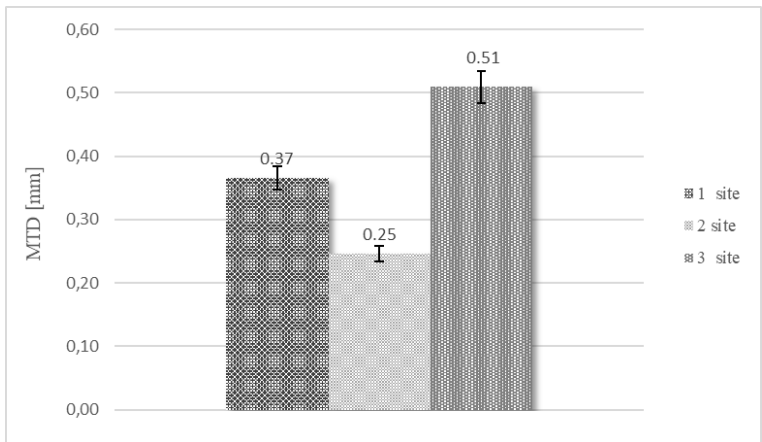


Fig. 7:

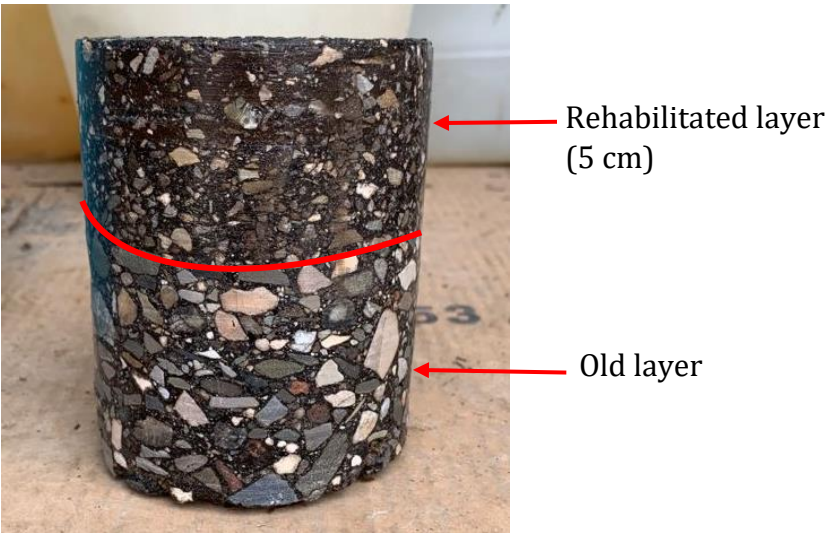
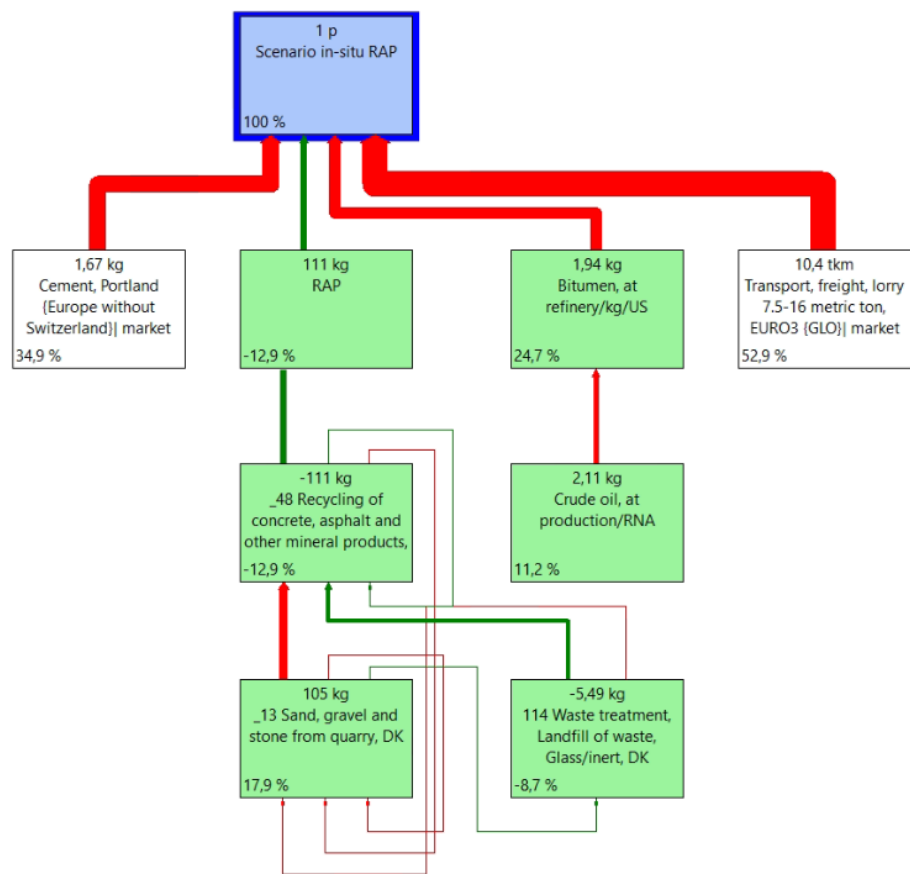


Fig. 8:

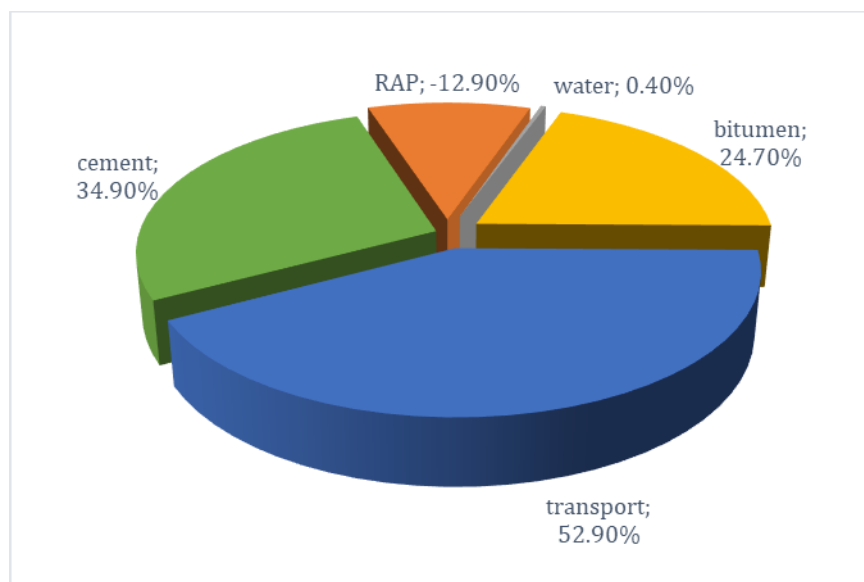


Fig. 9:



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2 **Fig. 10:**



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Figure captions

- 1 **Fig.1** The particle size distribution of material F1 and the reference envelope of the Italian Specification.
- 2 **Fig.2** The adjusted particle size distribution of material F1 and the reference envelope of the Italian Specification.
- 3 **Fig. 3** ITSM versus temperature curve.
- 4 **Fig. 4** Milling machine at work (a) and (b), and construction of the trial field in a trafficked road (c).
- 5 **Fig. 5** Average PTV results from the three trial fields.
- 6 **Fig.6** Average MTD results from the three trial fields expressed in millimetres.
- 7 **Fig. 7** 100 mm diameter core taken from the trial field.
- 8 **Fig. 8** Flow Diagram of the innovative cold in-situ recycling technique.
- 9 **Fig. 9** Network model of the proposed cold in-situ recycling technology.
- 10 **Fig. 10** Pie chart of the impact associated with each material