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Original Article

Skid resistance and mechanical performance comparison between in-place and in-plant cold-mix recycling 100% RAP: A sustainable design for bicycle lanes

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HIGHLIGHTS

- CMA recycling techniques involving 100% RAP designed for urban mobility solutions.
- A trial field is realized to compare in-place and in-plant recycling by a new additive and a cutting-edge in situ machine.
- Laboratory characterization to evaluate additive percentage and mix mechanical properties on compacted and cored samples.
- Texture and skid resistance analysis comparing the surface performance of the two RAP pavements.
- Results show that the investigated in-place recycling technique is a good alternative for urban wearing course repaving.

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ABSTRACT

Technological advancements have produced sustainable approaches to pavement preservation and reconstruction procedures. Specific recycling processes are being developed to reuse the asphalt concrete guaranteeing costs and environmental effects reduction. Reclaimed asphalt pavement (RAP) is the material worldwide used in the road construction sector to ensure the sustainability of asphalt pavement. RAP employment percentages in asphalt concrete layers are increasing. The development of cold mix asphalt (CMA) recycling technique including high amount of RAP is becoming popular especially for localized patching and potholes. Wearing course layers designed for bicycle lanes realized with 100% RAP and CMA technologies are presented in this research. Two cycle paths rehabilitated with different construction technologies in-plant and in-place recycling techniques are compared by performing a trial field and laboratory analysis on compacted and cored samples. An innovative rejuvenator used as additive specifically designed for CMAs is added as rejuvenator in both RAPs. The main goal is to determine the frictional, physical and mechanical characteristics of solutions produced by using high quantity of recycled materials. British pendulum tester (BPT) and Micro GripTester are applied to assess skid performance and indirect tensile strength test (ITS) and Marshall stability is performed to analyse the mechanical behaviour. RAPs skid resistance and physical-mechanical properties provide positive outcomes with viable characteristics for urban soft-mobility solutions. The innovative machine used in the in-place technique demonstrated excellent performance in terms of milling and mixing, representing a valid alternative for repaving applications in the urban context.

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1. Introduction

1.1. Background

Sustainable pavements improve public transportation users' safety and comfort while reducing energy consumption and greenhouse gases (GHGs) emissions and avoiding the exploitation of natural resources. Over the last decade, it is exponentially increasing the use of recycling materials in the roads' construction to reduce the environmental impact and design eco-friendly solutions. The integration of recycled materials and innovative low-impact production techniques is a step forward to sustainable construction policies.

To date, many second-hand materials are used in asphalt mixture to address the sustainability aspects in the field of road pavement engineering (Bocci 2022; Yao et al., 2024). Construction and demolition waste (CDW) are frequently used for the realization of unbound granular layers destined for subbase, foundation or embankments (Sangiorgi et al., 2015). Many studies have investigated the structural performance of unbound layers realized with CDW in terms of bearing capacity (Jiménez et al., 2012; Lancieri et al., 2006; Mehrjardi et al., 2020). However, other environmentally friendly materials have been studied to substitute or integrate virgin materials in asphalt concrete solutions for road pavement. The effectiveness and positive benefits of adding crumb rubber (CR) have been assessed, also in cold-mix applications or used as a binder modifier (Dondi et al., 2014; Khan et al., 2021; Sangiorgi et al., 2017; Xu et al., 2024). Considering porous asphalt mixtures with the integration of recycled materials, De Pascale et al. (2023a) have highlighted the positive mechanical and functional performance of using electric arc furnace (EAF) steel slags and reclaimed asphalt.

In this perspective, technological developments have led to sustainable solutions for reconstruction treatments and pavement preservation strategies (Chan et al., 2011; Zhang et al., 2023). Specific recycling technologies have been implemented for the aforementioned applications aiming to reuse the asphalt concrete ensuring costs and environmental impact reduction. Asphalt concrete recycling is a major area of interest in the field of road pavement engineering understanding the viability of incorporating up to 100% of recycled asphalt in new bituminous mixtures (Antunes et al., 2019). Reclaimed asphalt (RA) is the product derived from the milling operations of road layers, the slab removal from an existing pavement or excess production of asphalt concrete (Yu et al., 2024). In detail, reclaimed asphalt pavement (RAP) indicates the product obtained from the removal of asphalt pavement. RAP is widely utilized into asphalt mixture allowing to reduce the exploitation of virgin aggregates for road construction with high-quality and valuable performance comparable to conventional mixtures (West et al., 2013). Several studies have been developed to assess the mechanical properties of RAP mixtures or the feasibility of RAP recycled binders, comparing their performance with traditional solutions. Multiple mixing-related and performance-related studies have been carried out to demonstrate that RAP properties are not so far from traditional asphalt (Karlsson and Isacsson, 2006). Asphalt concrete samples realized with variable dosages of RAP have been analysed in terms of moisture susceptibility and resistance to deformation (Pradyumna et al., 2013). The specimens including 20% RAP reveal adequate performance comparable to virgin mixes. Recent evidence suggests that the percentage of RAP influences the characteristics of the asphalt mixture highlighting the importance of a correct mix design. Thus, the higher is the content of RAP, the higher are the stiffness associable to cracking occurrence and the rutting resistance (Tarsi et al., 2020). High-content RAP mixtures are defined for asphalt concrete including more than 25% of RAP (Copeland, 2011). Ma et al. (2015a) analysed recycled high-modulus asphalt concrete (RHMAC) with different RAP content to assess the mechanical behaviour and performance indicators at different temperatures. This study reveals that RHMACs mixture with RAP content between 30% and 50% meet the French specification requirements for road pavement. An evaluation of both modulus and high-temperature stability has been conducted to assess the feasibility of utilising the RHMAC solution for base and binder layers with the objective of enhancing rutting resistance. However, it has been determined that its application in surface layers is not recommended due to its performance at low temperatures. Few satisfactory attempts have been made to analyse asphalt surface courses for road construction with increasing percentages of RAP. Meroni et al. (2021) have compared the cracking and rutting resistance of four different highly recycled surfaces mixtures from road pavement sites in Virginia (USA). Mixtures including 30% and 45% of RAP, warm mix asphalt (WMA) additives and the use of rejuvenators show great results, highlighting the importance of volumetric and aggregate gradations properties that affect final performance (Sarkar and Elseifi, 2023). Lower percentages of RAP are indicated as a good solution as they unaffected surface performance significantly. The results of laboratory and trial field studies for a provincial road in China show that mixtures with RAP ratio above 20% are not suitable for high-volume roadways as they fail to achieve the performance required by the specification (Hu et al., 2012).

High percentages of RAP seem to be adequately integrable in patching solutions or delimited surface rehabilitation due to the lower mechanical performance required. Research related to the development of an HMA realized with 100% RAP including different chemical additives have been conducted (Bruno et al., 2023). The possible adoption of HMA mixtures with very-high RAP percentage has been positively assessed as patch asphalt use for pothole repair. Recently, cold patching materials (CPMs) have become more central for pothole repair with growing interest in the impact of aging and gradation in mixtures (Wang et al., 2023) and the use of RAP in specific applications such as spray injection patching (Kwon et al., 2018; Li et al., 2024).

Other aspects that significantly affect the performance of RAP are the production methods and processes. The literature has a variety of classifications for asphalt recycling techniques and the most widespread considers the location of the reclaiming process and the heating temperature. Hot mix asphalt (HMA) applications provide multiple technologies that are the most well-known and ideal re-using solutions for the production of recycled hot mix asphalt (Zaumanis et al., 2014). Both in-plant and in-place solutions are world widespread applications for asphalt production, but a recent study has highlighted the disadvantages occurring to RAP binders' properties due to the heating process (Liu et al., 2017). Long overheating can lead to accelerated degradation and aging of bitumen characteristics becoming more vulnerable to UV deterioration through oxidation when laid as wearing course layer. Hence, the development of in-plant and in-place recycling asphalt techniques is moving towards warm mix asphalt (WMA) and cold mix asphalt (CMA) technologies. The integration of RAP usage and low-production temperature allows to greatly reduce the emissions, the energy/cost and fuel consumption. Focusing on CMA technologies, two main recycling methodologies have been developed. Cold central-plant recycling (CCPR) is the process taking place at a central plant where stockpiled or recently milled RAP is turned into paving material. Once mixed with water, recycling agents and any chemical additives, it is obtained the final mixture to transport to the recycling pavement site for paving. Cold-in place recycling (CIR) procedures are executed directly on-site, from the milling phase of the distressed pavement section to the re-paving of a new-recycled road section at low temperature. The CIR procedure is further distinguished into 2 applications depending on the recycling thickness: full-depth recycling (FDR) and partial-depth recycling (PDR). Despite its environmental benefits, CMA solutions suffer from several major drawbacks, which complicate their application on a large scale for road pavement applications. In particular, many studies have provided evidence that inferior mechanical performances are associated with CMA mixtures especially in relation to durability and long-term properties (Xiao et al., 2018). Cold recycling and RAP techniques require in-depth analysis given the numerous variables involved, including the interaction between additive binders and aggregates, as well as the properties and source of the materials. The influence of the physical characteristics and grading size distribution of RAP on mechanical performance of cold recycled asphalt mixtures (CRMs) has been studied previously, showing that Indirect Tensile Stiffness Modulus (ITSM) test and dynamic impact resonance (IR) have a high dependence of air void contents (Orosa et al., 2022). In addition, it is underlined that the RAP source impact on the compactability of the mixture as noted by Raschia et al. (2019). The source of the RAP also affects the interaction between aggregate surface, bitumen, additive, and cement. Moreover, focusing on the contribution of cement to mechanical properties of CRMs, it has been noted that it can improve the specimens' strength but the effect is restricted by the structure-strength properties of RAP (Ma et al., 2015b).

Recently, researchers have shown an increased interest in studying physical-chemical, mechanical, and skid resistance performance of RAP at intermediate and low-recycling temperatures. Hettiarachchi et al. (2019) have thoroughly reviewed the WMA technique and RAP mixtures highlighting that the integration of these two construction solutions improves rutting resistance, moisture susceptibility, and workability. These outcomes match those observed in earlier studies that show notably good results for high RAP mixtures above 40% realized with WMA process in terms of rutting resistance and fatigue cracking (West et al., 2012). Moving to the pavement surface features, few studies aim to evaluate the skid resistance characteristics of road pavement constructed with innovative and recycled materials combined with RAP. In most recent surveys, it has been examined in a laboratory-scale experiment the skid resistance consequences of using crumb rubber (CR) and RAP into HMA for wearing course layers (Pomoni and Plati, 2022). This study, comparing the skid resistance analysed through British pendulum tester for the different mixtures, reveals no negative effects of applying these types of recycled materials. Similarly, Hu et al. (2023) have investigated the impact of 20 different mixtures including RAP on the skid resistance. The test has been carried out by means of dynamic friction test (DFT) proving that adding high skid-resistant RAP provides great DFT values. Additional researches have highlighted that the combination of RAP and steel slag enhances the mechanical and friction characteristics reaching the requirements of skid resistance even with 70% of RAP (Yang et al., 2022).

1.2. Objective

Questions have been raised about the feasibility of CMA solutions combined with RAP usage for road pavement sections and few researches are moving in this direction. Meena et al. (2023) analysed the performance of CMA with different percentage of RAP, additives and binders to ascertain the mechanical and volumetric properties of the mixtures. CMA realized with 100% RAP show reduced Marshall stability and resilient modulus respect the 50% RAP. A further study highlights the significant sustainability benefits associated with the incorporation of RAP in CRAMs (Elaskary et al., 2024). The incorporation of 100% RAP highlights good mechanical properties in terms of ITS and fatigue cracking but a negative impact on moisture resistance. The incorporation of 100% RAP exhibits robust mechanical properties with regard to tensile strength and resistance to fatigue cracking. However, it is observed that this material displays a diminished level of moisture resistance.

Most of the aforementioned papers were developed at the laboratory-scale on asphalt samples produced following the standard procedure assessing the materials' behaviour under controlled conditions and there is a lack of knowledge on real-case studies involving CMA and very-high RAP applications. The objective of the present study is to evaluate a wider deployment in the field of road construction with particular reference to cycle paths. This study sets out with the aim of assessing the friction and mechanical characteristics of two wearing course asphalt layers, comprising 100% of RAP obtained through the implementation of two cold-mix asphalt recycling techniques. The objective of the study is to compare two recycling technologies realizing an experimental trial field involving a unique cutting-edge machine and an innovative rejuvenator used as additive specially designed for CMA with high amount of RAP. Firstly, the mix design varying the rejuvenator percentage is defined in laboratory to evaluate the physical and mechanical performance of mixtures for the in-plant technique. No preliminary analyses are carried out for the in-place mixture. The trial field involves two repaved bicycle lane sections realized with in-place and in-plant technologies, respectively. Firstly, the mixture characterization is carried out in the laboratory using cored samples and compacted specimens collected from the construction site. The laboratory tests offer some important insights related to the quality of mixtures and mechanical performance of the material in terms of: determination of the maximum density, bitumen extraction, particle size analysis, determination of the percentage of voids, and indirect tensile strength (ITS). The in situ skid resistance properties are studied by applying traditional and innovative equipment: British pendulum tester (BPT) and Micro GripTester. The data collection for the classification of the skid characteristics analysis is related to two parameters: pendulum test value (PTV) and grip number (GN), which represent the output parameters of BPT and Micro GripTester, respectively. In addition, Sand Patch test is performed to measure the texture of the asphalt surface.

2. Materials and methods

2.1. Experimental programme

The experimental program presents three main phases: the mix design of the in-plant mixture, the trial field analysis for the evaluation of the skid resistance and the laboratory characterization of cored and compacted samples. The mix design phase was oriented to the assessment of the adequate percentage of rejuvenator. The objective of the trial field and laboratory characterisation is to provide a comparison of the properties of the two mixtures produced through different cold-recycling techniques, which include 100% RAP (Fig. 1).

The experimental trial field involves two different asphalt sections and two cold-mix recycling technologies, which have been implemented to construct recycled asphalt pavement 3 cm thick destined for bicycle lanes. The two bicycle lanes are 40 m in length and 2.5 m in width. Both techniques have guaranteed the total reuse of asphalt material (100%). The first solution restores the existing wearing course layer completely in-place, recycling the previous sidewalk. The second application involves the laying of milled materials from another construction site, which has been previously analyzed and mixed in-plant. The cold recycling technique used was produced at a central location using a stationary cold mix plant and an existing stockpile of mixed RAP previously accumulated. Many steps are required for each technique and below are reported the main operational phases followed for the in-place and in-plant procedure for the rehabilitation of the cycle paths.

- In-place cold-mix: the first step has been the milling of the existing pavement using an innovative machine. This machine is destined for road surface rehabilitation and operates at a depth varying between 3 and 10 cm. In this case, the milling operation was 3 cm thick and the equipment is able also to perform the RAP processing, the spraying of additives and the mixing of binder. In the present study, the rejuvenator has been added in 2.1% on the weight of the aggregates and the cement has been released manually by the operators in 2% on the weight of aggregates. Finally, the machine is equipped to carry out the mixing of the mixture to obtain a homogeneous section. It is important to note that in this case no bituminous tack-coat has been applied between the old binder layer and the new recycled pavement.
- In-plant cold-mix: firstly, the particle size distribution of RAP has been checked in laboratory to optimize the mixture characteristics and define the final dosage of rejuvenator. The milled material, adding in this case the rejuvenator in 2.1% on the mixture, has been

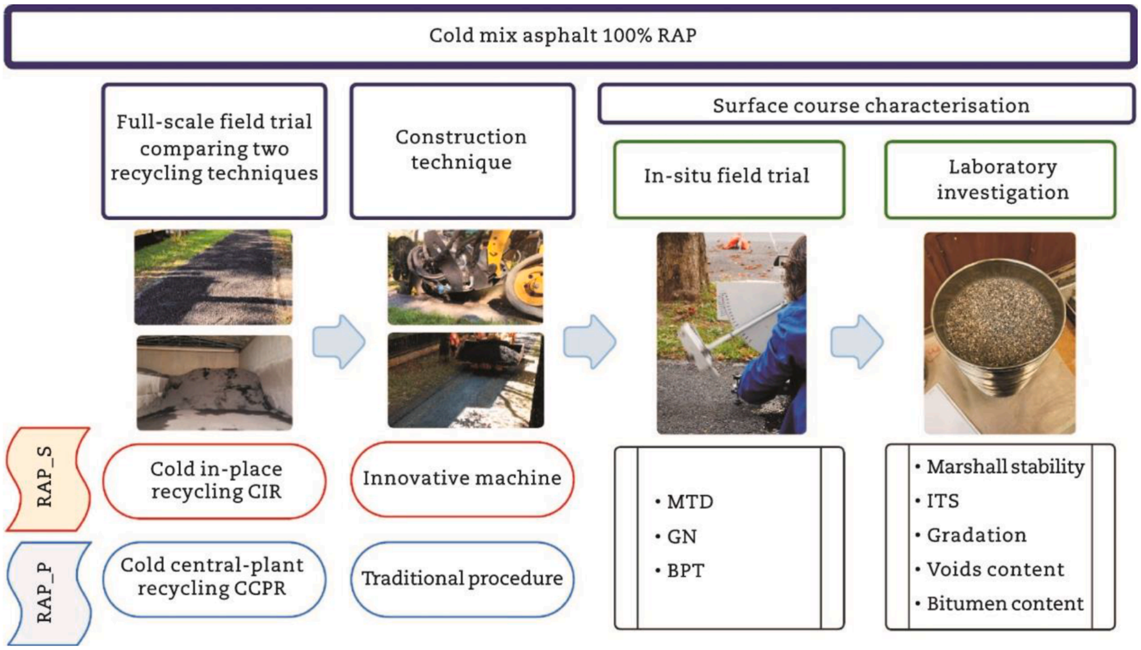

Fig. 1. Experimental programme flowchart.

early prepared to be transported on site. The cold mix recycling technique follows the traditional operations for this section of bicycle lane involving the milling operation, the cold paving and the final compaction. It is noted that the reclaimed asphalt comes from another site different from the present survey site. In addition, in this application was sprayed a tack-coat on the existing base layer after the milling operation (Fig. 2).

The machine, designed for in-place cold mix, is configured to rehabilitate up to 10 cm of pavement based on the CIR procedure. The machine is equipped with a component that allows the configuration of the milling machine according to the characteristics of the asphalt layer to be rehabilitated. The main innovation provided by the use of this unit is the ability to offer a viable alternative to traditional paving techniques, reducing energy costs and emissions.

Fig. 2. Trial field construction steps. (a) In-place CMA. (b) Asphalt surface in-place CMA. (c) In-plant design phase. (d) In-plant CMA.

Subsequent the completion of the two sections under study, it was expected a 24 h period before the site would be opened to traffic and no specific on-site curing procedure were necessary prior to traffic opening.

2.2. Materials

The realization of the two bicycle lanes object of this study involves 100% of RAP. The main difference between the two sections is represented by the applied cold-mix recycling technique. The in-place practice used 100% of the existing pavement, milling and mixing it directly in situ with an experimental innovative machine. The results of tests and material referred to the in-place solution is labelled RAP_S. The in-plant practice produced a repaved pavement with 100% of RAP, which mix design has been previously studied in laboratory to define the adequate percentage of rejuvenator. The results and analysis referred to the asphalt pavement realized with in-plant technique is labelled RAP_P.

The optimal mix design has been studied to assess the dosage of the rejuvenator. Specimen preparation by impact compactor with 50 blows per side at 20 °C were realized in compliance with EN 12697-30 (European Union, 2018a). Three different percentages of rejuvenator were studied: 1.7%, 2.1%, and 2.5% on RAP weight. The mechanical characteristics in terms of Marshall stability and indirect tensile strength (ITS) were evaluated after 7 days of curing at 25 °C. On the basis of the results illustrated in Table 1, the percentage of rejuvenator chosen for both recycling techniques is 2.1%. This percentage was also chosen according to the dosage required for the in situ solution, for which the mix design could not be carried out. It is worth to notice that all the mixtures meet the requirements imposed by technical specifications developed by the Municipality of Milan on performance testing of CMRA with 100% RAP. The results of the mix design analysis and minimum threshold values are reported in Table 1. The results of the mechanical tests are presented as the average value of two samples.

As anticipated, both the sample mixtures are composed by 100% RAP and an innovative rejuvenator used as additive has been mixed with RAP. This is a unique technology that allows to recover 100% of asphalt concrete treated with CMA techniques. The innovative rejuvenator, tested in the present paper, enables to stabilize the chemical ratio during the rejuvenation process, returning the bitumen composition to its initial state or close to it as feasible. This environmental friendly rejuvenator is indicated for low-volume roads and bicycle lanes and it is designed for cold recycling solutions. The chemical rejuvenator is added in 2.1% by the weight of aggregates for both RAPs mixtures. Table 2 illustrates the physical properties of the liquid rejuvenator.

A secondary binder to improve the strength and durability of the resulting pavement has been added in RAP_S mixture. Portland cement belongs to the category CEM II/B-LL 32.5R in accordance with EN 197-1, which provides a mechanical resistance of 10 MPa after 2 days of curing. The incorporation of cement into the RAP_S mixture was essential to guarantee the effective regeneration and blending of RAP, as a preliminary control of the mixture characteristics was not feasible, as was the case with in situ recycling.

Table 1
Mix design RAP_P at variable percentages of rejuvenator.

Mixture	Rejuvenator test/(range) (% by weight)	Stability test/(range) (kN)	ITS (MPa)
RAP_P1	1.7	14.76 (>4)	0.188 (>0.05)
RAP_P2	2.1	13.40 (>4)	0.158 (>0.05)
RAP_P3	2.5	11.55 (>4)	0.143 (>0.05)

Table 2
Physical properties of rejuvenator.

Testing items	Value/description
Phase state	Liquid
Color	Brown
Density at 20 °C	(0.94 ± 0.02) g/cm^3
Viscosity at 20 °C	400–500 cP
Flash point	>150 °C

2.3. Methods

2.3.1. In-situ characterization

The texture and skid resistance quality of cold-mix repaving techniques are evaluated through multiple surveys one month after the construction of the trial field. Texture measures assist in recognizing and assessing pavement surface features, which can both assure driving functionality and safety and enable road managers to detect the need for maintenance. Functional surface properties are influenced by the type of aggregate used in the surface layer, in particular they are sensitive to coarse aggregates (Liu et al., 2021). The adoption of specific factors that have an impact on a number of road features, including the surface texture, allows for the evaluation and classification of road performances (Bitelli et al., 2012). Skid resistance is one of the pavement's key functional characteristics, defining smoothness, safety, and comfort during driving. Faced with this phenomenon, it is necessary to conduct research geared to evaluate the skid resistance characteristics of road pavement constructed with innovative and recycled materials. The macrotexture depth of the pavement is determined through the sand patch test according to EN 13036-1 (European Union, 2010). The sand patch test has been carried out in multiple sections to assess the macrotexture uniformity for both innovative cold-mix techniques. Texture characteristics were assessed in the vicinity of the pendulum test points for a more detailed evaluation and a direct comparison between texture and friction. The results are reported in terms of mean texture depth (MTD). It is calculated as the ratio between a defined volume of sand and its footprint area obtained once the material has been manually distributed on the floor as indicated by the standard.

Two in situ testing measurements are applied to assess the skid resistance of the recycled pavement, which are the British pendulum tester (BPT) and Micro GripTester. The BPT provides information on skid resistance and micro-texture in terms of Pendulum test value (PTV), which is calculated as the average of five measurements. The final value is obtained by applying a correction factor that depends on the asphalt temperature at the time of the survey. The test procedure has been carried out in wet condition and using the wide slider in accordance with EN 13036-4 (European Union, 2011). The Micro GripTester is a three-wheel device used for determining the slip resistance of a road surface in continuous implementing the fixed slip approach with the braked wheel. The British standard BS 7941-2 defines the procedure to apply for grip tester explaining also the procedure in pushing mode (British Standard Institution, 2000). The signal-processing unit (SPU) receives information on the tractive drag force and the load force measured by two strain gauge bridges on the stub axle, and it continuously calculates the instantaneous friction readings in terms of grip number (GN) every 0.048 m. The GN parameter is the result of the ratio of the skid resistance applied on the front measuring wheel (Drag) and the vertical load on the wheel itself (Load). The survey can be carried out in dry or wet conditions, and the latter is preferable to realize the survey in conditions of low friction. In addition, the majority of traditional friction equipment operates on wet asphalt surfaces. A water film of 0.25 mm depth is set on the measuring wheel of the Micro GripTester allowing to evaluate the grip on a wet surface. Moreover, it is possible to fix the speed of the test setting out the target speed for each run at 0.4 m/s or 0.7 m/s. The user manual indicates the survey speed of 0.4 m/s as recommended speed for data consistency. Hence, the grip tester runs are performed at the survey speed of 0.4 m/s and in wet conditions.

The grip evaluation has been uniformly performed on both bicycle lanes to compare the friction performance of the recycled asphalt and evaluate the comparability of innovative and traditional skid resistance equipment.

The sand patch test has been executed in 8 points for each bicycle lane nearby the BPT points of investigation to obtain detailed information of macrotexture and microtexture features of the recycled asphalt pavement. The BPT has been carried out in 8 points for each bicycle lane for a total amount of 16 measurements, as for sand patch test. The Micro GripTester has been conducted in two main directions overlapping multiple runs on the same trajectory. For each lane, two trajectories were selected for which two overlapping runs were performed. Hence, the total number of runs for each bicycle lane is 4. In addition, the BPT surveys were performed in correspondence of Micro GripTester runs to compare the skid resistance results provided by the two equipment. The GN data collection provided by the Micro GripTester is every 48 mm. Once defined the incremental distance where testing BPT is performed, the pendulum is positioned so that the slider's ground slip corresponds with the Micro GripTester's measurement path. The single GN value, calculated for this specific comparison, is evaluated as the reading average of 40 cm survey in correspondence of BPT survey. This length represents a complete wheel rotation and it is considered significant for point correlation. This evaluation aims to enlarge the range of applicability of Micro GripTester highlighting its benefits related to continuous skid resistance monitoring.

2.3.2. Laboratory characterization

The laboratory characterization phase aims to determine the characteristics of in-place and in-plant recycling techniques and the final results of 100% RAP mixtures. The mixtures physical properties are assessed in terms of bitumen and air voids content, determination of particle density, aggregates grading curve on cored samples. Moreover, the mechanical performances of asphalt mixtures were evaluated to determine ITS and Marshall stability of cylindrical field sampled and laboratory compacted specimens of RAP mixtures. Laboratory samples are compacted at a temperature of 20 °C.

The laboratory experimental programme includes the air voids content analysis that is evaluated in accordance with EN 12697-8 standard (European Union, 2018c), which describes the procedure for calculating volumetric characteristics of specimens laboratory compacted or cut directly from the pavement. High air voids content represents a common issue for RAP cold-mix applications. It is observed that an increasing percentage of RAP corresponds to a higher percentage of air voids (Imaninasab et al., 2022). The bulk density of the bituminous specimens is evaluated as specified in EN 12697-6 (European Union, 2020b). The maximum particle density has been evaluated to the aggregates after the extraction and it is calculated with reference to EN 12697-5 (European Union, 2018b). The determination of soluble binder content has been carried out in accordance with EN 12697-1 standards (European Union, 2020a). The extraction method has been implemented by utilising the asphalt mix analyzer (AMA) for a loose mixture sample of 1.5 kg. The AMA signifies a pioneering device that integrates all processes associated with bitumen extraction and recovery. The particle size distribution has been obtained after the bitumen extraction process for both the RAPs solutions. The grading size distribution is evaluated in compliance with EN 933-1 (European Union, 2012) to compare the in-place milling technique with the controlled in-plant procedure for RAP production.

The mechanical characterization of mixes is performed on both compacted and cored samples that are tested after 7 and 30 days of curing, respectively. Four replicates are used for the mechanical analysis. ITS test is performed to analyse the static mechanical characteristics of the RAPs samples compacted in laboratory and cored from the site. The test was performed in compliance with the EN 12697-23 standards developed for the determination of the indirect tensile strength of bituminous specimens (European Union, 2017). The test was carried out in dry condition and curing the specimens at room temperature of 25 °C. The specimen placed inside the machine between the loading plates to be subjected to constant compression at a speed of 50 mm/min until the failure is reached. In addition, the stability of compacted specimens after 7 days at 25 °C preparing the specimens in accordance with the compaction procedure followed for the preliminary characterization.

3. Results and discussion

3.1. Trial field results

3.1.1. Macrotexture: sand patch test

The surface macrotexture of the repaved bicycle lanes has been assessed through sand patch test. The results are reported referring to the Italian specification, which defines the classification in relation to pavement texture characteristics. Eight points of investigation have been performed nearby the BPT points. The bicycle lane realized with the in-place technique presents a macrotexture that is classified as "average". The values belong to the category 0.4 mm < MTD <0.8 mm, with a peak value of 0.66. The bicycle lane constructed with the in-plant technique is classified as "average/coarse-grained". Even in this case, the majority of the values belong to the aforementioned category, but the general trend is higher with a peak value of 0.8 mm. Table 3 reports the results of average MTD value for each type of recycling technique.

3.1.2. Skid resistance analysis: BPT and Micro GripTester

To determine the skid resistance of the asphalt surface two tests BPT and Micro GripTester were conducted. By combining the results of both traditional and innovative tests, it is possible to obtain a comprehensive understanding of the grip properties of the two RAP surfaces. Table 4 shows the average PTV values of skid resistance analysis from BPT considering the 8 survey points performed along the entire cycle path. The friction values determined on both cycle paths are within the PTV range 70–78. This result is indicative of excellent skid resistance and no-slippery surfaces, which is comparable to road pavement indications for asphalt surfaces. Comparing the two results, it can be seen that the skid resistance characteristics are very similar, and the bicycle lane RAP_P presents a higher variability than RAP_S.

The analysis related to the continuous measuring and monitoring of friction characteristics along the two bicycle lanes is carried out using the Micro GripTester. The surveys covering a distance of 30 m were divided into six sections, each measuring 5 m in length. Table 5 shows the average GN value for each section calculated referring to 4 long runs for each bicycle lane. The table reveals a different GN trend for the two RAP pavements obtained with in-place and in-plant cold recycling techniques. In particular, the bicycle lane realized with the in-plant procedure presents a marked GN variation along the path, as previously confirmed by the BPT analysis. On the other hand, the RAP_S path seems to be more uniform with lower variations over the entire length. Despite the different trend, the final GN value calculated on the entire length is equal to 0.78 GN for both RAP_S and RAP_P lanes. This outcome meets what has been observed with the BPT surveys demonstrating that the two investigated solutions have similar skid resistance characteristics.

To further investigate the distribution of friction values derived from the Micro GripTester, Fig. 3 represents a heat map based on the GN analysis along the two main directions of investigation and extended to the entire survey area in length (30 m) and width (2.5 m). The trend observed is the result of the interpolation of the GN values derived from the overlapped Micro GripTester runs, which average results are extended to the entire width of the bicycle lanes. The GN values considered for this graphical representation span a range of 0.4–1.0,

Table 3
Average results of MTD.

Mixture	Average value (mm)
RAP_S	0.59 (±0.06)
RAP_P	0.74 (±0.04)

Table 4
Average results of PTV.

Mixture	Average value
RAP_S	75
RAP_P	74

Table 5
Average results of GN from 4 runs.

Section (m)	Average value	
	RAP_S	RAP_P
0–5	0.75 (±0.04)	0.82 (±0.04)
5–10	0.79 (±0.03)	0.81 (±0.03)
10–15	0.79 (±0.02)	0.81 (±0.03)
15–20	0.78 (±0.02)	0.82 (±0.03)
20–25	0.78 (±0.03)	0.77 (±0.05)
25–30	0.82 (±0.02)	0.65 (±0.05)

which has been assumed to represent a spectrum of friction conditions, from low to excellent grip. It can be seen from the proposed trend that the RAP_S path presents a more uniform distribution of friction than the RAP_P case.

In the detailed comparison of friction characteristics provided by BPT and Micro GripTester, 8 survey points are analysed for each bicycle lane to assess and compare the skid resistance parameters in specific locations. Fig. 4 compares the results in terms of PTV and GN obtained in the survey points. A comparison of the recorded values for GN and PTV reveals a correspondence in terms of trend. To illustrate, when GN RAP_S is greater than GN RAP_P, the same correspondence is evident for the values of PTV RAP_S and PTV RAP_P. It is worthy of note that at points 4 and 7 anomalies are observed. At point 4, the BPT survey provides identical values for PTV RAP_S and PTV RAP_P, whereas the calculated average GN measurement indicates a higher value for GN RAP_S than for GN RAP_P. In the case of point 7, however, the trend for GN and PTV is reversed. Indeed, a higher value for GN RAP_S than for GN RAP_P is not reflected in a correspondingly higher value for PTV RAP_S than for PTV RAP_P. The difference in the trend in this case can be associated to higher variability of skid resistance observed along the bicycle lane RAP_P. The GN in the final section of the cycle path is in general lower than the initial part as confirmed looking at the trend in Figs. 3 and 4.

3.2. Laboratory results

This section presents a comprehensive examination of the mechanical and physical findings derived from laboratory analyses conducted on cored and compacted asphalt specimens. This facilitates a direct comparative analysis of the two CMA technologies under investigation. The samples of loose mixes were taken from each bicycle lane during the construction phase. These samples were then compacted and cured in the laboratory to analyse the physical and mechanical properties of RAPs mixtures. In particular, the analysis related to RAP_P is compared with the results of the mix design phase. The different techniques of milling, mixing and production of RAP influence the final properties of

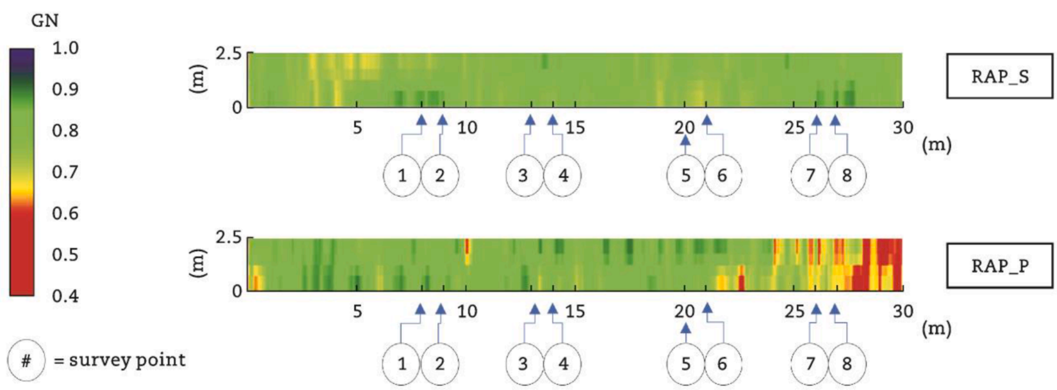

Fig. 3. GN friction distribution for RAP_S and RAP_P bicycle paths.

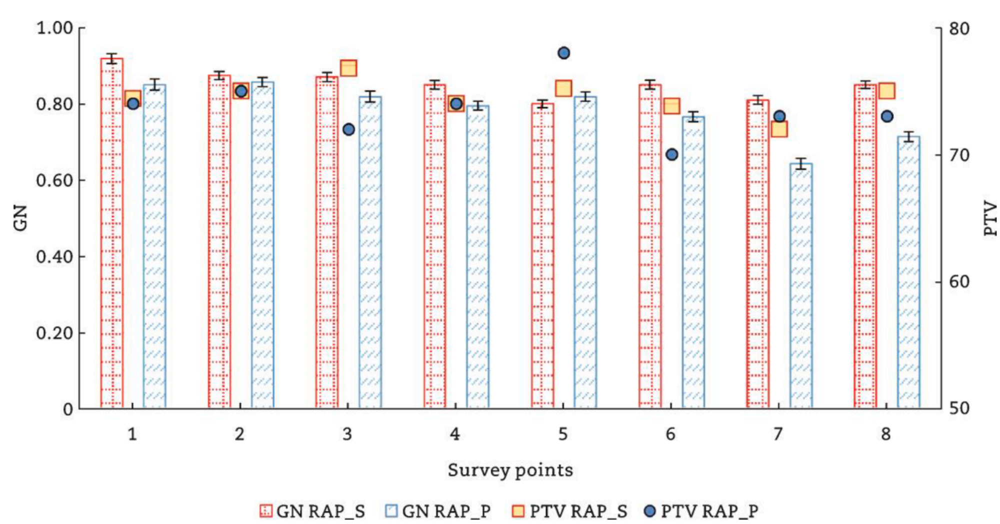

Fig. 4. Comparison of GN and PTV values in correspondence of correlation points.

the final wearing course layer. Concerning the cored samples, before proceeding with the laboratory experimentation and where necessary, the specimens have been cut to investigate properly the wearing course layer. Four cored samples have been collected from each bicycle lane to assess their physical and mechanical properties. Fig. 5 illustrates an example of cored samples, wherein a clear distinction is evident between the new wearing course layer and the existing binder layer.

3.2.1. Mixture characterization: compacted samples

The mechanical properties of compacted samples in terms of ITS and Marshall stability are evaluated. The loose mixtures were compacted at the temperature of 20 °C. Table 6 shows the average value obtained for both test after 7 days of curing. Focusing on the results related to RAP_P mixture, the average Marshall stability is lower than at mix design stage. Looking at the ITS test, there is no significant difference between the obtained values for the two mixtures testing on compacted samples. The results obtained at the conclusion of the short-term study period indicate that the differences between the two mixtures are less pronounced than those observed in samples extracted one month after the construction phase. Both mixtures meet the technical specifications for cold recycled asphalt concrete as Marshall stability and ITS values that are above the threshold values, reported between brackets in Table 6.

3.2.2. Mixture characterization: cored samples

The particle density has been evaluated on the mixtures after bitumen extraction as the particle size distribution. Fig. 6 shows the comparison of the results related to the particle size curves of the two investigated mixtures. The curves show similar trends that demonstrate the effectiveness of the in-place recycling technique realized with the innovative machine especially with regard to the milling phase of the existing pavement. No relevant differences can be found unless the lower passing percentage of aggregates at the intermediate sieves (0.5–4 mm). Both mixtures are in general well-graded, more acceptable findings can be associated to RAP_P, which presents percentages of retained materials above sieve 10 mm. This is the result of the different selection and extraction process of RAPs, which is characteristic of the two different recycling techniques. Additionally, it is worth to note that the two types of RAPs have distinct sources.

Table 7 reports the characteristics of the mixtures analysed after the extraction of bitumen. The bitumen percentage is higher for both solutions taking into account the addition of rejuvenators in the mixture.

Table 6
Average results for Marshall stability and ITS for compacted samples.

Mixture	Stability test/(range) (kN)	ITS test/(range) (MPa)
RAP_S	7.06 (>4)	0.100 (>0.05)
RAP_P	6.17 (>4)	0.116 (>0.05)

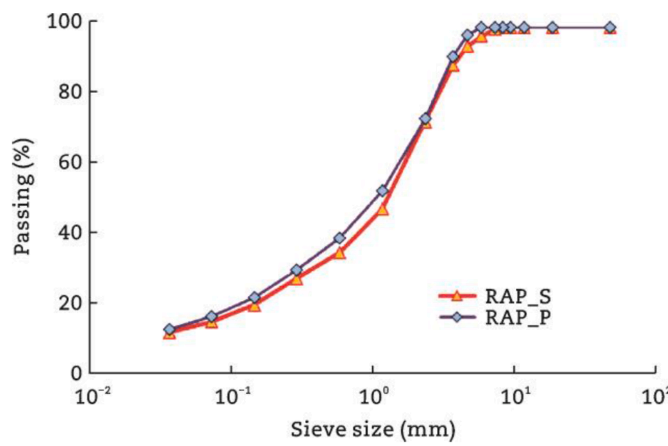

Fig. 6. RAPs gradations after extraction.

Recent studies have shown that the bitumen percentage within RAPs mixtures varies from 4% up to 7.5% and it is influenced by the percentage of RAP included in the asphalt mixture (Tarsi et al., 2020). It is important to note that the aforementioned percentage range of bitumen do not consider 100% RAP mixtures. The air voids content is high for both the two mixtures and this can be associated to the compaction process, which need probably to be further investigated for cold-mix solutions.

The mechanical properties of cored samples in terms of ITS are evaluated. All the tested samples have recorded a type failure that according to standard is categorized as "combination" (type c). A combination failure is recorded when specimens exhibit a limited tensile break line and larger deformed areas close to the loading strips. Fig. 7 reports the average results of the samples cored from each type of pavement. The results in terms of mechanical behaviour are good for RAP_S

Fig. 5. Samples cored from the trial field with layers separation.

Table 7
RAPs asphalt properties.

Mixture	Bitumen (% by weight)	Bulk density (g/cm^3)	Particle density (g/cm^3)	Air voids (% by volume)
RAP_S	8.03	2.129	2.625	8.34
RAP_P	7.66	2.183	2.652	7.66

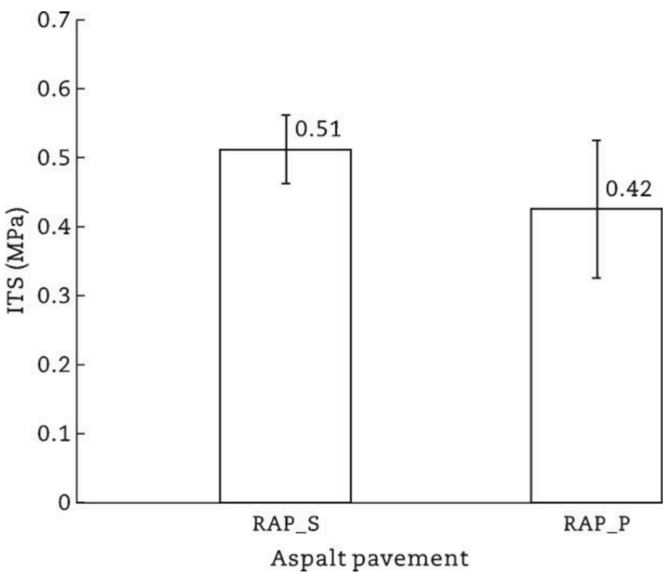

Fig. 7. ITS results of cored samples collected from the trial field.

considering the average value of Indirect Tensile Strength equal to 0.51 MPa. The obtained value is higher than the threshold value of 0.35 MPa defined by technical specification for dry cold mix asphalt samples produced in laboratory. The average RAP_P value is lower than RAP_S and it is equal to 0.42 MPa. This condition can be traced to the low thickness of specimens and the higher variability of the results. Until recently, there has been no reliable evidence on cored samples of CMA including RAP. A recent study has presented good mechanical performance for road pavement maintenance, and the present study is in line with those outcomes (De Pascale et al., 2023b). It is important to underline the visible difference between laboratory-prepared and in situ cored samples. It is well-known that field samples subject to ITS test present lower values compared to laboratory mixtures (Iskender and Aksoy, 2012).

4. Conclusions

Environmental issues have led the research and technology construction process to develop sustainable solutions. In light of growing environmental concerns, there is a drive towards a transition to a circular economy model that encourages more efficient resource management and an increased utilisation of recycled materials in road pavements. Nowadays, the realisation of an infrastructure necessitates the fulfilment of a multitude of aspects. In particular, it is of paramount importance that infrastructures constructed with high percentages of RAP and cold recycling techniques meet the physical and mechanical performance standards to ensure durability throughout their service life. The present paper investigates the properties of asphalt pavement destined for bicycle lanes involving 100% RAP and applying cold-mix recycling techniques. A mechanical and frictional performance comparison between in-place and in-plant cold-mix asphalt recycling solutions is performed. The RAP processing includes the addition of an innovative green rejuvenator that allows to recover up to 100% of RAP through cold recycling process. Moreover, the innovative aspect related to the in-place cold-mix recycling technique presented in this survey is the unique repaving machine used as first experimental application destined for cycle paths repaving. The aim of this survey is to analyse the effectiveness of 100% RAP solution for bicycle lanes and to assess the characteristics developed by the experimental in-place technique comparing it to traditional and controlled in-plant technique. Based on the findings of this study related to the in situ frictional characterization and in-laboratory analysis, it can be stated that:

- The texture and skid resistance performance of the surface layer are in line with those observed for traditional asphalt concrete applications. High amount of RAP does not affect the surface characteristics. The skid resistance value is markedly above the threshold value of 65 PTV, indicating a highly favourable grip condition. The mean PTV values for RAP_S and RAP_P were recorded at 75 and 74, respectively. Positive friction trends are recorded by comparing BPT and Micro GripTester demonstrating the reliability of GN as a new skid resistance indicator. A comparison of the two recycling techniques in terms of functional properties reveals that the in situ solution exhibits greater homogeneity. In-situ CRA technique enables the milled material to be mixed, thereby reducing the segregation of material that can occur during transport from plant to site.
- The mechanical behaviour of the RAP_S specimens is greater than RAP_P showing acceptable results in terms of ITS analysis. It is worth to note that the addition of cement in this mixture has contributed to enhance the stiffness properties of the RAP_S samples. Average ITS value for RAP_S and RAP_P is 0.51 and 0.47 MPa, respectively. Moreover, the Marshall stability analysis confirms the mechanical behaviour in line with ITS results.
- The mixtures characterization demonstrates no relevant differences related to grain size distribution and particle density of the aggregates underlining the reliability and accuracy of in-place recycling technique. The bitumen content extraction revealed a good percentage within the maximum acceptable bitumen range, if considering the addition of the rejuvenator in both RAP mixtures. High percentage of RAP influence in both case the air void content.

The present study makes several noteworthy contributions to the implementation of CMA solutions including 100% RAP as a valid alternative for urban design applications for sidewalks and cycle paths. In addition, the evidence from this survey suggests that the investigated in-place recycling technique represents an excellent alternative, which may be adopted as a replacement to traditional solutions applied for urban soft-mobility wearing course repaving. Further researches are needed to enhance the mechanical characteristics of CMA 100% RAP solutions to enlarge the application to low-traffic roads.

CRediT authorship contribution statement

Luca Cotignoli: Data curation, Writing – original draft, Investigation. **Loretta Venturini:** Project administration, Supervision. **Claudio Lantieri:** Formal analysis, Conceptualization, Validation. **Piergiorgio Tataranni:** Supervision, Methodology. **Andrea Simone:** Writing – review & editing, Supervision. **Valeria Vignali:** Writing – review & editing, Conceptualization, Supervision, Project administration.

Declaration of competing interest

The authors do not have any conflict of interest with other entities or researchers.

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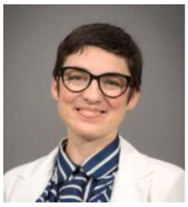

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