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Cold recycling of reclaimed asphalt with bituminous binders: A critical comparison of practices in the countries involved in the TC 308-PAR TG1 – Part I

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Abstract

The RILEM technical committee on Performance-based Asphalt Recycling TC 308-PAR focuses on research, knowledge exchange and dissemination on the asphalt material recycling. Specifically, the Task Group 1 (TG1) "Performance-based Evaluation of Cold Recycled Asphalt Mixtures" aims at matching laboratory testing methods with the in-service behavior of cold recycled asphalt mixtures. In this context, the TG1 members collaborated to share the different cold recycling procedures used in their respective countries, with the goal of comparing specific practices, technical requirements, and performance expectations. Considering the different areas of expertise and application environments, such as road type, traffic volume, climate and material resources, the information gathered provides a broad framework of the current practices and prospects a widening of future application of cold recycling techniques. The comparison among country practices was divide into two papers: Part I dealing with constituent materials and common mixture composition and requirements and Part II treating testing procedures and mechanical characteristics.

Particularly, Part I reports a critical comparison between standard frameworks for reclaimed asphalt (RA), cold recycling practices, materials and mixtures used in Italy, Canada, Poland, Brazil and USA, either adopted by selected road administrations or established by reference standards.

Keywords: Cold recycling practices; Reclaimed asphalt; Constituent materials; Mixture composition.

1 Introduction

Although operational and economical issues still play a relevant role in decision-making process for maintenance and construction projects, environmental awareness and the need to reduce energy consumption motivated the development and use of more environmentally friendly approaches to asphalt pavement construction. Especially in Europe, there is a significant drive toward eco-sustainable techniques that aims to reduce landfill waste and preserve natural resources, thereby providing strong motivation for adopting recycling methods in both pavement rehabilitation and new construction. Among these methods, cold recycling, that is typically performed without or with limited heating,

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has emerged as one of the most promising due to its proven performance, cost-effectiveness, and low environmental footprint. Cold recycling techniques can be mainly distinguished in Cold In-Place Recycling (CIR), Cold Central Plant Recycling (CCPR), and Full-Depth Reclamation (FDR) [1][2].

CIR and CCPR methods entail recycling the reclaimed asphalt (RA) to form a new pavement layer. The major difference between CIR and CCPR is that CIR recycling occurs on site and CCPR recycling occurs in a stationary plant.

The CIR is performed by means of either a single unit, two-unit or multi-unit trains on site. Working directly on site, CIR avoids any material transportation and is one of the most cost-effective methods, with minimal impact on the environment and surrounding area. Single-unit trains provide the least control over the material proportions and the simplest operation, two-unit trains maintain a high production capacity while having improved additive application, and multi-unit trains provide the highest productivity and quality as well as material sizing and proportioning. CIR involves only the asphalt layers and the treatment thickness is generally between 10 to 15 cm [1][2].

The CCPR is an alternative in projects when asphalt pavement materials are not available in the field or when specific requirements in production stability and mixture performance are required. The CCPR plants consists of cold feed bins for the RA, recycled aggregates (Rag) and virgin aggregate (VA), silos for fillers and hydraulic binders, tanks for bituminous binders and water (W), mixing facility and silos for mixture storage. The selection and control of constituent materials and final mixture can be easily monitored during production ensuring the highest production stability and mixture performance. The mixture is laid down by a paver working with thickness ranging between 10 to 20 cm [1][2].

When the milling depth extends beyond the asphalt layer into underlying foundation or granular materials, involving also Rag, the process is referred to as FDR. The process uses the same equipment used for CIR. Involving RA from asphalt layers, materials coming from the foundation layer and marginal material from the subgrade, this technique requires highest tolerance since the final granular blend can change (type and proportion) during production. FDR offers a significant advantage when efficient and fast structural rehabilitation is needed, with minimal impact on site operations and management. Treatment depth depends on the existing pavement layers, but typically ranges between 15 and 30 cm.

In each case, VA can be added to improve the grading and mechanical properties of the mixture.

The binders commonly used in cold recycling include bitumen, in form of foamed bitumen (FB), bituminous emulsion (BE) or modified bitumen emulsion (MBE), and cement (C). When needed, C is used to accelerate the curing process and enhance the strength and stiffness of the mixture. Lime (L) is also used to improve mastic cohesion and dispersion, to enhance the moisture resistance and performance of the mixture [1][2]. Lime works also as stabilising agent when the recycled materials contain clay or silt lenses with high plasticity.

Several mixtures can be produced combining different binders and dosages. Depending on the layer depth and structural role within the pavement, binders are blended to achieve the desired mechanical characteristics. Based on binder content and mechanical behavior, mixtures are typically classified as follows: cement-treated materials (CTM), when only cement is used; bitumen-stabilized materials (BSM), containing less than 1% cement or lime and no more than 2.5% bitumen; and cement-bitumen treated materials (CBTM), which involve higher dosages of both cement and bitumen. A key feature of recycled mixtures is the curing process, which governs the development of their mechanical properties [3].

The members of TC 308-PAR Performance-based Asphalt Recycling, working on the TG 1 project entitled "Performance-based evaluation of cold recycled asphalt mixtures" [4], have collected and critically compared the current technical practices of cold recycling as applied in their respective countries.

The present paper reports the materials and practical procedures most commonly used in the countries involved in the RILEM TC 308-PAR TG1. The use and concepts of cold recycling technology in Italy (IT), Canada (CA), Poland (PL), Brazil (BR), and the USA are critically compared to provide a broad overview of the state of practice in the selected countries.

2 Standard framework for reclaimed asphalt

Currently, in Europe, EN 13108-8 specifies how to identify and designate RA for use in hot bituminous mixtures (hot in-plant asphalt recycling), while EN 13108-1 through EN 13108-9 permit the addition of RA in asphalt products. In Italy, RA for cold mixtures is considered a "black" aggregate as the bitumen it contains is considered inactive. Consequently, RA is characterized according to EN 13242 which identifies aggregate for unbound and hydraulically bound layers (road embankment, subgrade, foundation, and base courses) when used for cold recycling. In Italy the technical standard UNI/TS 11688 serves as a complement to the EN 13108 since defines the qualification method and use of RA in road construction including cold recycling techniques.

A similar approach is applied in Poland, where, in the case of cold recycling, RA is treated as a black rock. The only requirements are an appropriate gradation (up to 63 mm) and the absence of organic matter. Specific requirements for different types of cold recycled mixtures are provided in the specifications prepared by the main Road Administration.

In Québec, the *Ministère des Transports et de la Mobilité Durable* (MTMD) provides the specifications for cold recycled mixtures. In the *Laboratoire des chaussées* (LC) method for the province of Québec, for both the CIR and FDR methods, the total binder content, including both added binder and the binder already present in RA, is accounted for in the mix design. Therefore, RA is not considered an inert black rock but rather a composite material contributing to both aggregate and binder. Also, if necessary, crushing and screening must be performed to reduce the RA to the required gradation before it enters the plant.

Brazil does not yet have a fully standardized system for the classification and description of RA. The Brazilian National Department of Transport Infrastructure (DNIT) has published a resolution stating that RA generated during pavement works must be reused in new pavement layers. DNIT has also published a specification (DNIT 033/2021) that provides some guidance regarding transportation, treatment, and moisture control, although it focuses on hot recycling. In addition, some road concessionaires have developed their own documents to regulate the logistics of RA. Regarding cold recycling, as in other selected countries, RA is treated as a black aggregate.

In USA, state highway and transportation agencies typically adopt their own specifications and procedures for characterizing RA for use in cold recycled mixtures. However, the Basic Asphalt Recycling Manual [5] emphasizes that it is essential to assess the properties of the RA, the extracted aggregate, and the recovered bitumen. Specifically, the gradation of the RA should be determined following AASHTO T 27 or ASTM C 136, or equivalent state agency specifications. The bitumen content of the RA is to be determined as well and are typically on a project-by-project basis. For smaller projects, where it may not be practical to determine the full properties of the recovered binder, the bitumen content can be measured using ASTM D 6307. For larger projects, it is recommended that the properties of the recovered bitumen be analysed to guide the selection of an appropriate recycling additive. This is often done using AASHTO T 164. Additionally, testing the recovered bitumen/binder to assess the effects of aging on its stiffness and consistency is critical. At a minimum, measurements should include penetration at 25°C and/or absolute viscosity at 60°C. These indicators are valuable for determining the appropriate grade of recycling or stabilizing additive for the cold recycled mixtures.

3 Cold recycling practices

Cold recycling practices may vary between countries due to several factors, such as climatic conditions, levels of expertise, environmental regulations, material availability and costs, binder production, traffic volumes, and waste management strategies.

Comparing cold recycling procedures in two European countries, i.e. Poland in the north and Italy in the south, along with a tropical country such as Brazil, and practices in North America and Canada, provides a broad overview of the application of these techniques, potentially leading to new approaches and improvements to the state of the art by drawing insights from each country.

Starting from the European countries, environmental issues are particularly important. Following the European new circular economy action plan, a new Italian national law, which sets the minimum environmental criteria to be applied to road construction and maintenance works, has effectively made recycling techniques mandatory, requiring a minimum material recycling rate of 50% when the rehabilitation involves foundation and base layers.

In Italy, *Autostrade per l'Italia S.p.A.* (ASPI), that manages about 3000 km of Italian motorways, and *Azienda Nazionale Autonoma delle Strade S.p.A.* (ANAS), that manages most of the national road network, have been applying cold recycling techniques since the early 2000s. However, the lack of specific knowledge and experience seem to prevent the diffusion of these techniques among local administrations and municipalities although a gradual change is in progress.

Italian motorway specification reports the following items: Cement-treated materials for foundation or subbase course using both in-place and in-plant production; Cold in-place and in-plant recycled foundation or subbase course with bitumen and cement; Cold in-plant recycled subbase or base course with modified bitumen emulsion and cement; Cold in-place improvement of unbound foundation courses using foamed bitumen and cement [6]. Recently, another motorway agency has introduced the use of lime with bitumen for cold recycled foundation courses. ANAS S.p.A. provides similar applications, whereas the specifications for local administrations and municipalities generally focus on in-plant produced cold recycled mixture for binder and base courses and in-place and in-plant production of cement-treated materials [7][8].

Foundation or sub-base layer can be cold in-place recycled with bitumen and cement through a recycling train. The existing pavement layers (unbound granular layers, cement-treated layers, bituminous layers) are milled and the obtained granular mixture is stabilized using a bituminous binder, in the form of emulsion or foam, and a cementitious binder. The material is immediately compacted with a single-drum vibrating roller and a pneumatic roller. The levelling phase is carried out through a motorgrader in accordance with the thickness and profile indicated in the design. Aggregates can be imported and included in the in-situ recycling process to correct the gradation or to compose the mixture. This type of rehabilitation modifies the stratigraphy of the pavement structure and is carried out when enhancing the bearing capacity is required. Foundation or sub-base layer can also be cold recycled with bitumen and cement through a mix plant. In this case, the granular mixture is mainly composed by selected RA (preliminary crushed and sieved) and VA can be used to improve the gradation. The material is laid down by means of a paver and compacted by a single-drum vibrating roller and a pneumatic roller. Combining the in-plant production and high performance using a modified bituminous emulsion and processed RA, the recycled mixture can be used closer to the surface as a base course. Similar procedures can be applied using only cement as a binder when a faster and more economical solution is necessary [6]. Especially when the impact of the working field affects traffic safety, FDR is generally applied without seasonal restrictions. Greater accuracy is required when high quality and production stability are needed.

Similarly, in Poland, cold recycling using cement and bituminous emulsion or foamed bitumen (used less frequently), is a recognized technique included in the specifications prepared by the main Road Administration (General Directorate of Roads and Motorways) and considered in the catalogue of flexible and semi-rigid pavement structures for national roads roads [9][10]. The main reason is to use RA as much as possible. Cold recycling is generally used as a base course for low (up to 0.51× 10^6 100 kN ESAL) and medium traffic roads (up to 7.3 × 10^6 100 kN ESAL), thereby using cold recycling for roads with heavy traffic volume is not a common practice. In motorway cold recycling is used in the base course of service roads along the main lane of the motorway [11]. The use of cold recycling for binder course (just underneath the surface course) has been generating increasing interest and several laboratory studies are in progress [12][13]. This technique also allows to reuse of old RAP containing tar, but recycled mixtures must be compacted following stricter roles, i.e. air void content lower than 15 or 12 % for low and medium traffic roads, respectively.

In Canada, there are federal, provincial and territorial transportation departments, each overseeing its own set of responsibilities. To maintain and rehabilitate roadways, various techniques, including hot in-place recycling, CIR, and FDR, are employed as rehabilitation methods. They are used for all types of roads, and the choice of rehabilitation techniques varies depending on the level of rehabilitation required (minor or major). For instance, Ontario applies CIR with emulsion or foamed bitumen for minor rehabilitation and FDR with resurfacing for major projects. In Manitoba, CIR with emulsion, CCPR, and treated subgrade and base materials with cement, lime, or emulsion are in use; whereas FDR is rare and used only in localized areas. Alberta incorporates FDR and CIR using both emulsion and foamed bitumen. Québec employs CIR and FDR with both emulsions and foamed bitumen. Although CCPR guidelines exist for Canada, the limited experience with CCPR in Canada means that this paper does not discuss CCPR in the context of Canada mentioned above. Also, the Québec specification is adopted in this study as it reflects the regional practices and standards of the Canadian authors.

The selection of the type of rehabilitation requires pavement inspection, identification of the cause, followed by choosing the appropriate solution. Pavement inspection includes core sampling, ride quality testing, structural capacity assessment, and a survey of crack types and detailed visual conditions. Therefore, the decision over using the in-place method is complex. Since in-place recycling does not change the subgrade bearing capacity, it is not recommended in conditions with subgrade failures.

In USA, based on a survey conducted as part of an NCHRP study [14], most CIR and CCPR projects typically repave fewer than 80 lane-km annually. Among recycling techniques, agencies have the most familiarity with CIR using emulsion-based recycling agents. Agencies identify suitable CIR and CCPR projects by evaluating pavement distresses and applying standard pavement maintenance and rehabilitation criteria. The selection process for candidate CIR and CCPR roadways includes thorough site investigations, coring, and assessments of subgrade strength and drainage capacity. Many agencies also consider traffic volume when selecting projects. Less experienced agencies typically restrict cold recycling to roads with an annual average daily traffic (AADT) below 5,000, whereas more experienced agencies apply cold recycled mixes to roads carrying over 10,000 vehicles per day. The majority of published research on CCPR can be traced to the ongoing initiatives of the Virginia Department of Transportation (Virginia DOT). Over the past years, Virginia DOT has actively studied and supported various cold recycling methods, including CCPR, by providing testing data and analysis for characterizing CCPR layers in pavement structures designed for interstate-level heavy truck traffic, contributing significantly to the body of knowledge [15].

In terms of FDR, reports from a recent NCHRP study [16] highlights FDR use by approximately 85% of state agencies across the U.S., primarily for lower-volume. Compared to other major rehabilitation techniques like mill and overlay, FDR is a relatively newer practice in the U.S. Most FDR projects have been implemented within the past 25 years, and the earliest trials are now approaching the end of their service life. Additionally, around one-quarter of agencies using FDR have a decade or less of experience with the process. Portland cement is the most widely used stabilizing agent in FDR projects across the USA, with its selection largely influenced by site-specific factors such as subgrade soil type, as well as the agency's historical experience and past performance outcomes. Among bituminous stabilizing agents, emulsified asphalt is preferred more frequently than foamed bitumen.

Considering a completely different country and climatic zone, in Brazil, cold recycled material is predominantly used as a base course in pavement rehabilitation works on medium- to high-traffic roads (≥ 10^6 100-kN dual wheels ESAL) [17][18][19][20][21][22]. Typically, the base course consists of loose granular materials and lies just beneath the asphalt layers. It is important to note that Brazilian pavements are generally thinner than those in North America or Europe, and the asphalt layer is often supported solely by unbound layers. The most widespread type of cold recycling is FDR with cement, used on both national and state roads [21]. In the past, there were several initiatives involving FDR roads and CCPR with foamed bitume bitumen [17][18][19], but this technique is not as commonly used as FDR with cement. This is probably due to the simplicity of the cement stabilization technique. In contrast, foamed bitumen recycling requires more specialized equipment and technical expertise, which may affect success rates and result in higher long-term costs. Currently, the use of foamed bitumen in cold recycling is almost exclusively limited to the city of São Paulo, where it is occasionally employed in CCPR applications. Over the past five years, due to the increased availability of recycling machines that allow the use of bituminous emulsion in the country, along with economic factors and the introduction of new specifications, FDR with bituminous emulsion has begun to be used in national and state highways by both public agencies and private concessionaires. There are even examples of municipalities adopting the technique, such as the city of Curitiba. Prior to that, cold recycling with bituminous emulsion was practically limited to CCPR [18][20][22], which continues to be applied even with the increasing use of FDR with bituminous emulsion.

Brazil has developed individual specifications for each type of cold recycling process and for each type of binder employed. National specifications are available for FDR with cement (DNIT 167/2013), as well as for both FDR and CCPR using foamed bitumen (DNIT 169/2014; DNIT 166/2013). Those specifications were developed by the Brazilian National Department of Transport Infrastructure, which operates under the supervision of the Ministry of Transport. Additionally, the state of São Paulo has its own specifications covering FDR and CCPR with bituminous emulsion (ET-DE-P00/055, 2024; ET-DE-P00/059, 2024). For the purposes of this technical letter, the document adopted as a reference is the final draft of the forthcoming national technical standard for FDR with bituminous emulsion, scheduled for publication in June 2025 (ABNT/ONS-034, 2025). This selection is justified by the fact that FDR with bituminous emulsion is the cold recycling method experiencing the most significant growth in Brazil. Furthermore, the draft document is the most comprehensive and up to date among those currently available, and it is also a national technical standard developed by the Brazilian Technical Standards Association.

As a summary of the described practices, Table 1 shows the use of cold recycling for foundation and base courses in the selected countries, comparing the road network, the service life of the pavement structure, the technique applied, the thickness of the recycled layer and the thickness of the multilayered overlay asphalt concrete. Even if every country expresses the service life of a road pavement in different units and methods, the pavement structures including cold recycling are compared considering the cumulative traffic to withstand during the service life. Moreover, given that a clear and universal definition of pavement layers can be hardly defined, especially when moving from a highway structure to a local road structure, it should be noticed that the foundation course is herein defined as the layer that distributes traffic loads over the subgrade, while the base course is defined as a layer that contributes to the structural function of the asphalt layers. The foundation course can lie just below the surface course in low traffic roads or it can be placed below the base course in high traffic roads. These definitions can be further simplified by referring to a foundation layer when it lies over the subgrade or over part of the existing foundation when maintenance operations are considered. In all other cases, the layer can be referred to as the base layer, i.e. the intermediate layer or part of it, between the surface and foundation layers. Of course, Table 1 aims to show the general context on the use of cold recycling and not the only field of application.

Table 1. General context of cold recycling application compared across the selected countries.

Characteristic	IT		CA		BR	PL	USA	
	Found.	Base	Found.	Base	Base	Base	Found.	Base
Road network	Motorway	Motorway	National/Local network	National/Local network	Highway	National/Local network	High volume roadways	Low-High volume roadways
Service life [100-kN dual wheels ESAL]	$\geq 1 \times 10^8$	$\geq 1 \times 10^8$	$\geq 2 \times 10^6$	$\geq 2 \times 10^6$	$\geq 1 \times 10^6$	$< 7.3 \times 10^6$	Up to 25 years	15-20 years
Technique	FDR	CCPR	FDR	CIR	FDR/CCPR	CIR/CCPR/FDR	FDR	CIR/CCPR
Layer thickness [cm]	20 - 30	15 - 25	15 - 30	7.5 - 12.5	15 - 25	15 - 20	10-33	8-10
Asphalt overlaying [cm]	20 - 30	10 - 15	6 - 9	6 - 15	4 - 12.5	8 - 16	varies	varies

As can be observed from Table 1, CIR is rarely used in Italy. Since the influence of treatment thickness on costs is moderate when using the in-place technique, the tendency is to involve as much material as possible to efficiently rehabilitate the bearing capacity of the road. Moreover, when the surface level cannot be raised, CIR can only be applied to a portion of the old asphalt concrete layer which must be then overlaid with a new surface layer. In this case, the application of CIR may not be cost effective. FDR and CCPR are also applied to foundation and base layers, respectively, in highways, connectors and local roads. In such cases, the thickness of the recycled layer and that of the new asphalt overlay can be adjusted based on the specific traffic loading. As far as Italian experience concerns, in addition to Table 1, which refers only to motorway applications, when cold recycling is applied to secondary and local roads, the thickness of the recycled layer does not change, as it mainly depends on the construction method. On the other hand, the asphalt concrete thickness changes significantly depending on traffic loading and can be reduced to about 10 cm or, in some cases, to no less than 4 [23].

Cold recycling techniques in the selected countries are not used for surface layers. In Poland and Brazil, cold recycling technology is not used for foundation courses.

4 Materials and mixtures

In this section, the gradations, binder types, and the mixture properties, used in Italy, Poland, Canada, USA and Brazil, either adopted by selected road administrations or established by reference standards, are gathered and critically compared.

Considering that the maximum aggregate size (D_{max}) typically reflects the layer thickness and its position within the pavement structure (i.e., the larger the maximum size, the thicker the layer and the deeper its position), and that there is no universally shared layer terminology, the aggregate envelopes were compared using a fixed maximum aggregate size as a threshold.

Figure 1 shows a comparison among gradation envelope for recycled mixture using D_{max} smaller than about 25 mm. On the other hand, Figure 2 compares the gradation envelopes considering a D_{max} larger than about 25 mm. There is a consensus that aggregates larger than about 25 mm should be included in the recycling process for layers thicker than 15 cm.

The Italian specification for motorway provides with two envelopes with different D_{max}: 20 mm for base courses and 31.5 mm for foundation courses, respectively. The production method, i.e. in-place or in-plant production, and the bituminous binder type (foam or emulsion), do not influence the prescriptions for the mixture. The sieve analysis is performed following the washed method and the RA is considered as a black aggregate. The particle distribution is defined by volume. When in-place recycling is applied, the aggregate must be sampled after one or more passes of the recycler before binder spreading. If the material passing to the 0.5 mm sieve is more than 15% and the plasticity index is more than 10, a pre-treatment with lime is required to eliminate the plasticity of the blend.

The approach is different in Poland as two envelopes are in use depending on the traffic volume: one for low traffic roads and one for medium traffic roads. The envelope for low traffic roads is wider than the one for medium traffic roads and allows to use finer RA. Moreover, in the case of mixture for medium traffic roads, higher quality of mineral aggregates is required. Considering that RA contains few fine particles, natural non-crushed sand is often added to improve the workability of the cold recycled mixture.

For Canada, the specification allows similar gradations for CIR and FDR and both BE and FB and envelopes with D_{max} of 28 mm. A washed sieve analysis is performed on unextracted RA and Rag to determine the volume passing through. To meet the design requirements, VA, RA, or both are allowed to be added. For FDR, the treatment should consist of the old bituminous layer and the underlying base, with a maximum portion of RAP of 50 %. Based on Annex 1 of "*Retraitement en place des chaussées*", the pulverized material gradation for in-place recycling should conform to Figure 2 for FDR and CIR. However, for the design, the passing percentage on the 28 mm sieve should be at least 95 %, and for the 5 mm sieve, the passing percentage should be within a ± 10 % tolerance. Otherwise, the gradation should be corrected using a supplementary aggregate, as outlined in Annex 2 of the aforementioned guidelines. The supplementary aggregate should be from 5/14 mm, or 5/20 mm with no fines.

In USA, several state transportation agencies adopt materials and their respective properties according to their specifications. Vermont, for example, has specifications for cold recycled materials, including FDR, and CCPR, as outlined by the Vermont Agency of Transportation (VTrans). VTrans specifications define two envelopes for cold recycled materials, D_{max} = 37.5 mm for FDR with BE and D_{max} = 25 mm for CCPR with BE. For FDR, grading requirements refer to the pulverized material consisting of the existing pavement blended with underlying subbase material and usually with additional aggregate material (crushed gravel). To obtain material to develop the mix design, existing pavement shall be sampled to represent the reclaimed aggregates that would be expected to result from the first pass of the reclamation process for FDR and from the milling process for CCPR. A minimum of four samples representative of the quarter points of the entire length of the project shall be taken for both recycling processes.

The Brazilian standard for FDR with BE defines two envelopes for the cold recycled mixture: one with D_{max} of 25 mm and another with D_{max} of 12.5 mm. However, these envelopes are not linked to the layer in which the cold recycled mixture is applied. The sieve analysis is conducted with washing, and RA is considered as an aggregate. The percentage passing each sieve is determined by mass. The material to be recycled must be milled using the selected recycler for the construction. Sampling must be performed for each homogeneous segment defined in the project, and the sampling depth is established accordingly. The addition of VA is allowed for gradation correction of the cold recycled mixture. Of course, VA must satisfy the quality requirements defined in the standard. The cold recycled mixture must have a sand equivalent greater than 30% and a plasticity index lower than 6%. It is important to note that the São Paulo State specification for CCPR with bituminous emulsion adopts the same envelopes. However, the Brazilian specifications for FDR and CCPR with foamed bitumen define a different envelope.

Figure 1 and Figure 2 show that the envelopes for $D_{max} \leq 25$ mm are narrower than those for $D_{max} > 25$ mm, except for the envelope used in Poland, which refers to low-traffic roads. This is due to the higher accuracy required for mixtures that can be used as a base course or in CCPR, where the processing of RA allows greater precision to be achieved and the layer thickness is generally thinner. The highest gradation tolerances are applied for mixtures with $D_{max} > 25$ mm which generally refers to the application of FDR for foundation courses.

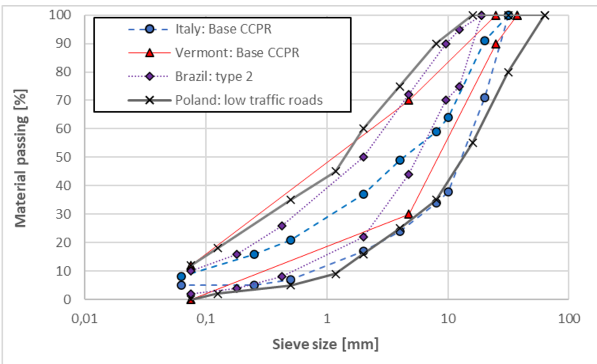

Figure 1. Typical envelopes for cold recycling considering $D_{max} \leq 25$ mm.

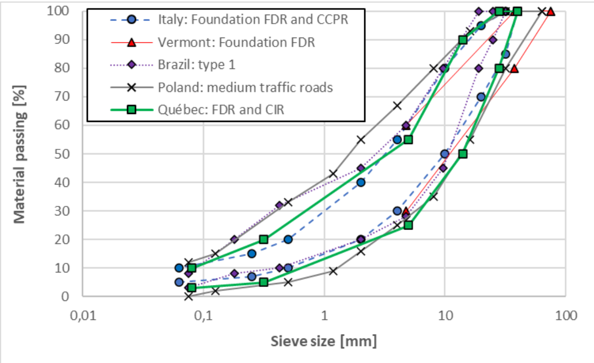

Figure 2. Typical envelopes for cold recycling considering D_{max} > 25 mm.

Table 2 shows the characteristics of the commonly used foaming bitumen in Italy, Poland, Canada, USA and Brazil. It can be noticed that Canada and USA classify the bitumen using the PG grade method, whereas Italy, Poland and Brazil use the penetration grading method.

The Italian motorway allows using only 70/100 paving grade bitumen and requires the highest expansion ratio and half-life time which are met by blending specific foaming additives. Conversely, two paving grade bitumens are allowed in Poland, i.e. 50/70 and 70/100 penetration grade. Considering that the air temperature influences the foaming process of bitumen and recycling techniques are generally applied from early spring until late autumn, the requirements for expansion ratio and half-life time are defined on as a function of air temperature. The highest foaming performance are required at the lowest temperature (5 °C).

In Brazil, there are four types of paving grade unmodified bitumen (30/45, 50/70, 85/100, and 150/200). Among these, only 30/45 and 50/70 are commonly used in hot mix asphalt; the others have a low production share and are primarily used for industrial applications such as emulsions. Moreover, only three are recommended for foaming: 50/70, 85/100, and 150/200. The foaming properties are fixed and do not depend on the selected bitumen grade. The choice of bitumen type depends on the region, based on the local production availability, with 50/70 being the most widely used across the country.

The use of polymer modified bitumen is not considered in the common foamed bitumen recycling practices. The use of additives is also not included in the specifications for foamed bitumen recycling, whether in situ or in plant.

Table 2. Characteristics of foamed bitumen for cold recycling.

Parameter	IT	CA	BR	PL	Minnesota
Performance grade	-	PG 58-28	-	-	PG 49-34
Penetration at 25 °C [mm×10^{-1}]	70-100	-	50-70; 85-100; 150-200	50/70; 70/100	-
Softening point [°C]	43-51	-	-	46-54; 43-51	-
Expansion ratio [%]	≥ 20	8 - 15	10	> 12 (5-10°C) > 10 (10-15°C) > 8 (>15°C)	≥ 10
Half-life [s]	≥ 25	6 - 12	8	> 8 (5-10°C) > 8 (10-15°C) > 6 (>15°C)	≥ 10

Table 3 reports the characteristics of the most common emulsion used in Italy, Poland, Canada, USA and Brazil by the selected road administrations or standards.

In Italy and in Poland the same overstabilised emulsion is in use. The overstabilised emulsion is characterised by a bitumen content ranging from 58 and 62 %, a high stability with cement and a penetration value at 25 °C lower than 100 mm × 10^{-1}. The Italian motorway specification provides for the use of SBS polymer or latex-modified bituminous emulsion with higher softening point and elastic recovery values. The high-performance emulsion is required when cold recycling is applied for base courses.

For cold recycling projects, several state agencies across the U.S. have recently adopted a modified cationic slow-setting emulsion (not polymer-modified), referred to as engineered emulsions. This emulsion type is custom-designed to meet the specific requirements of each project. In particular, the formulation is tailored to break according to the chemical characteristics of the in-place material. The bitumen or binder used in the engineered emulsion is selected using the Long-Term Pavement Performance LTTPBind Software to ensure climate-specific performance, while the emulsifier chemistry is chosen based on the chemical properties of the in-situ materials targeted for stabilization [24]. A key advantage of engineered emulsions is its ability to incorporate higher asphalt binder/bitumen contents, achieve superior coating of the milled reclaimed asphalt pavement, and, as a result, potentially deliver enhanced durability [25]. The research group of the University of New Hampshire is currently conducting research on this emulsion technology, providing pavement design inputs and performance functions.

Table 4 reports the general proportions of constituent materials including RA, Rag, VA, BE, FB, MBE, C, L, and W for the recycled mixtures.

In Italy, the constituent materials vary depending on the layer where the technique is applied, whereas the selection of constituent materials is entirely independent of the production technique. The ratio between bitumen and cement content must be higher than 1. Typically, this ratio decreases (indicating lower flexibility and higher bearing capacity) as the depth of the layer increases, i.e. from the surface to the bottom of the pavement structure, and vice versa.

In Poland, where tar was in use in the past, cold recycling allows to use RA with tar binder (otherwise it should be disposed) as it does not require heating of the base materials and therefore toxic emission are minimised. The mechanical requirements for mixture containing RA with tar do not change from those of typical recycled mixtures. However, when including RA with tar, a lower air void content is required. Preferably, the cement content is minimized to reduce the risk of reflective transverse cracks on the surface of the pavement.

In USA, at present there is no nationwide specific guideline for constituent materials. In Minnesota, the use of cement as an active filler is limited to 0.5 %. In Vermont, the limit is 1.5 % for CCPR processes, which also require a minimum emulsion content of 2.5 %. Regarding the ratio between residual bitumen and cement, a maximum ratio of 2.5:1 is allowed for FDR, and a maximum ratio of 3:1 is allowed for CCPR.

The Brazilian standard does not specify limits for the amounts of RA, Rag, or VA. The limit for the active filler, cement or lime is 1%.

In each country, the water content considers both the natural water content of the aggregates and the prewetting water (if any) including the water brought into the mixture by the emulsion (if used).

Table 3. Characteristics of bitumen emulsion for cold recycling.

Parameter	IT		CA		BR	PL	Minnesota
Designation	C60PB10	C60B10	CSS1	CSS1-h	EARP	C60B10 ZM/R	Engineered Emulsion PG 58-28
pH	2 - 4	2 - 4	-	-	-	2 - 4	-
Residual bitumen [%]	58 - 62	58 - 62	> 57	> 57	64	58 - 62	-
Sedimentation [%]	≤ 10	≤ 10	< 5	< 5	≤ 5	≤ 10	-
Saybolt viscosity at 25 °C	-	-	20-100	20-100	≤ 100	-	-
Stability with cement [%]	< 2	< 2	-	-	≤ 4	< 2	-
Penetration at 25°C [mm × 10^{-1}]	≤ 100	≤ 100	100-250	40-125	40 - 150	≤ 100	-
Softening point	≥ 55	≥ 43	-	-	-	≥ 43	-
Elastic recovery at 25 °C [%]	≥ 50	-	-	-	-	-	-
Force ductility at 10°C [J/cm^2]	≥ 1	-	-	-	-	-	-
Ductility at 25°C	-	-	≥ 60	≥ 40	-	-	-

Table 4. Constituent materials for cold recycling in the selected countries.

Materials	IT		CA		BR	PL	Vermont	
	Found.	Base	Found.	Base	Base	Base	Found.	Base
RA [%]	No limitation	No limitation	No limitation	No limitation	No limitation	No limitation	No limitation	No limitation
Rag [%]	No limitation	-	-	-	No limitation	allowed	allowed	allowed
VA [%]	allowed	allowed	allowed	allowed	Allowed	allowed	allowed	allowed
BE or FB [%]	1.5 - 3.0	-	> 1.2	> 1.2	2 - 3	BE: 3 - 6 FB: 1.2 - 3.6	BE (% not specified)	BE > 2.5
MBE [%]	-	4.0 - 5.0	-	-	Not specified	-	-	-
C [%]	1.5 - 2.5	1.5 - 2.5	< 1.5	< 1.5	≤ 1	BE: 1 - 4 FB: 1 - 3	< 1	1
L [%]	Pre-treatment if IP ≥ 10	-	-	-	≤ 1	-	-	-
W [%]	3 - 5	3 - 5	-	-	Not specified	3 - 6	Not specified	Not specified

5 Conclusions

Cold recycling practices differ across countries due to a range of factors, including climatic conditions, technical expertise, environmental regulations, the availability and cost of materials, binder production methods, traffic levels, and waste management policies.

This paper reports and compares the key information about practices and materials in use for cold recycling in the countries involved in the RILEM TC 308-PAR TG1 "Performance-based Evaluation of Cold Recycled Asphalt Mixtures", namely Italy, Canada, Poland, Brazil and the USA. A comparative analysis of cold recycling procedures in two European countries, Poland in the north and Italy in the south, together with a tropical nation like Brazil and practices observed in North America and Canada, offers a comprehensive perspective on how these techniques are applied. Such a comparison may contribute to advancing the state of the art by identifying practices and potential innovations inspired by each context.

Based on the information gathered, it can be asserted that cold recycling can be considered a recognized technique for road construction and maintenance and is widely used in the selected countries. However, its application is generally hindered by the limited experience of road authorities. In some countries, this has led to its use being mostly limited to low-volume traffic roads, whereas in some parts of the USA, Brazil and in Italy, it is also widely used on high-volume traffic roads.

Many research studies and practical experiences should help overcome skepticism in the near future.

Technique and material specifications are generally well defined, even though national standards on cold recycled mixtures and reclaimed asphalt for cold recycling are often incomplete or lacking. A specific qualification and classification method for cold recycled mixtures and reclaimed asphalt for cold recycling remains an open challenge.

Cold in-place recycling, particularly FDR, is highly valued for road maintenance due to its cost-effectiveness, low environmental impact, and practical process. As far as CCPR is concerned, it is expected to expand in production, especially within local road networks and municipalities, since it can be easily adapted to small-scale production and upper road layers, offering significant economic benefits.

The use of a combination of binders, such as bitumen and cement, is widely reported in the scientific literature; however, in practical applications, the use of cement alone as a stabilizing binder remains in use due to its lower cost and simpler procedure.

When using a combination of bitumen and cement, even if the dosage of cement is usually lower than that of bitumen, the cement content in Italy and Poland is generally higher than that used in other countries, which often impose strict limitations (cement content less than 1 % by aggregate weight). On the other hand, among bituminous binders, bituminous emulsion appears more favorable compared to foam bitumen.

Authorship statement (CRediT)

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Conflict of interest

The authors declare no conflict of interest.

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