BUILDING BLOCKS FOR A BEST PRACTICE GUIDE ON COLD IN-PLACE RECYCLING

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ABSTRACT

In order to facilitate the sharing of national experiences on dismantling and recycling of road and road related materials, the three-year Direct-Mat project was initiated in January 2009, within the EU 7th Framework Program Transport. The project addresses the recycling of unbound, hydraulically-bound and asphalt road materials as well as other materials not commonly recycled in roads. Among these technologies, this paper focuses specifically on cold in-place recycling, which is considered a very promising technique from the environmental point of view, since it allows for the reuse of reclaimed asphalt as well as for energy savings and reduction of harmful emissions.
The results obtained so far have shown that some European countries have already acquired experience with cold in-place recycling, but this has largely been done in isolation. Therefore, the practice at national level can differ significantly from one European country to another, and although some research has already been done, further efforts should be made in order to optimize the use of cold in-place recycling.
In the framework of this project a Best Practice Guide (BPG) was prepared. This was aimed at issuing recommendations for cold in-place pavement recycling in order to offer the highest added value. This paper highlights some recommendations included in the BPG on the following topics: pavement characterization, mix design, production, application, curing process, mix performance.
This paper is based on the work carried out within Direct-Mat project, which involved partners from 15 participating countries. Therefore, it reflects the views of its participating members.

Keywords: In-situ Recycling, Best practice, Cold asphalt

1. INTRODUCTION

In order to facilitate the sharing of national experiences on dismantling and recycling of road and road related materials, the three-year Direct-Mat project was initiated in January 2009, within the EU 7th Framework Program Transport. This project involved partners from 15 participating countries, comprising R&D institutions, universities and private companies.
The project addresses the recycling of unbound, hydraulically-bound and asphalt road materials as well as other materials not commonly recycled in roads.
Among the referred technologies, this paper focuses specifically on cold in-place recycling, which is considered a very promising technique from an environmental point of view, since it allows for the reuse of reclaimed asphalt as well as for energy savings and reduction of harmful emissions (CO_2).
The results obtained so far have shown that some European countries have already acquired experience with cold in-place recycling, but mainly on their own. Therefore, the practice at national level can differ significantly from one European country to another, and although some research has already been done, further efforts should be spent in order to optimize this technique.
In the framework of this European project, a Best Practice Guide (BPG) was prepared [1]. This guide aims to optimize the project impact by building on an earlier critical review of the international experience with asphalt recycling procedures [2, 3]. For some recycling techniques, such as cold in-place recycling, the various national approaches vary considerably. In these cases the Best Practice Guide gives a summary of the available approaches.
For cold in-place pavement recycling techniques, this paper highlights common trends and notable differences in international practice on demolition and characterization of reclaimed road materials. This also extends to mix design, construction techniques, curing process, quality control and performance assessment for new asphalt containing reclaimed road material.
This paper is based on the Direct-Mat project activities, namely in what concerns the state of art review regarding recycling of reclaimed road materials in new asphalt mixtures and practical applications in its participating countries [1, 2, 3]. Therefore, this paper reflects the views of Direct-Mat project participating members, in particular, the ones of its contributors.

2. PAVEMENT SUITABILITY FOR IN-PLACE RECYCLING

2.1 Pavement demolition

Pavement maintenance is needed when its surface and structural characteristics no longer meet the requirements due to deterioration caused by traffic loading, climatic influence and/or bad material quality. Maintenance works usually involve one or more layers of the flexible or semi-rigid pavement and sometimes demolition (or removal) of the complete bound structure. Another reason for pavement demolition may be that the pavement is no longer required.
According to European waste legislation, material resulting from demolition works shall be considered as construction waste. Options for the handling of waste in order of priority are:

- Reuse: use of the waste material in the same application as before;
- Recycling: use of the material in a new application;
- Disposal: deposition of material with best safety for health and environment.

For demolition of flexible pavements and recycling of road materials, several options have been developed in the past. Hence, today reclaimed road material can be referred to as “recourses” allowing the manufacture of new high-quality road material and the construction of new pavements.
For cold in-place recycling, existing pavements are usually demolished by milling, which, generally, present the following advantages:

- Flexible milling depth depending on milling equipment;
- Milling results in reclaimed road material with a grain size which usually allows the application in new asphalt mixes without further processing (crushing and/or sieving); this is critical for in-situ-recycling techniques;
- Prior removal of thick road marking materials by thin layer milling can improve RA quality.

The actual milling operation depends on milling equipment, milling speed, size of milling drum and cutters. The size of reclaimed material also depends on the pavement characteristics as cracked layers and missing interlayer bonding will affect the grain size. For cold milling operations, the temperature of the reclaimed layer affects the milling operation. For workers and environmental safety, it may be required to use feasible filter technology to reduce the dust emission during the milling process. The addition of water may be needed, but results in higher water content of the reclaimed road material [4].
When cold recycling techniques are applied during road demolition, the entire structure can be demolished in one working step.
The next section briefly summarizes information regarding in-place recycling of roads into new asphalt material layer used in the pavement under rehabilitation; this is based on a compilation of the literature and on case studies [2, 3].

2.2 Pavement characterisation

The most important characteristics controlling the economic recycling and reuse of reclaimed road material is the characterization of the material which will be demolished. The reason for the demolition or the need for rehabilitation can be used as an indicator of the condition of the paved material.
The aims of the characterization of a pavement prior to its demolition and recycling are:

- Detect deteriorated road layers to evaluate the need for road rehabilitation and to develop the pavement design of the new structure;
- Detect environmental hazardous substances in the structure;
- Evaluate homogeneity of the pavement prior to recycling.

In-place recycling techniques need closer inspection of the existing pavement because all reclaimed material is directly recycled into the new pavement.
The homogeneity of the structure and layer properties of the pavement to be recycled is of importance for all in-place recycling techniques. The homogeneity of the pavement section can be estimated by preliminary investigations on existing documents, visual inspection of surface characteristics and by Ground Penetration Radar (GPR). Besides the longitudinal homogeneity, the transversal homogeneity is also of importance as during the recycling process, the road is milled in its full width.
By taking cores, the structure of the existing pavement, the properties of the single layers and interlayer bonding are evaluated. If homogeneity of the pavement to be recycled can be assumed, the recommendations for the distance between core samples recommended in European countries vary between 200 m and 1 000 m.
The following characteristics are of primary importance for cold in-place recycling:

- Grading of RA after milling (evaluated by milling trial);
- Binder content (for quality control, less important for mix design).

3. COLD IN-PLACE RECYCLING

3.1 Asphalt cold mixtures

Asphalt "cold" mixtures are those whose bituminous binder is incorporated in the mixture in the form of bitumen emulsion or foamed bitumen, allowing the mixture to be produced and placed at ambient temperature. Some authors considered asphalt mixtures produced with foamed bitumen as half-warm or warm mixtures since in this case the bituminous binder is produced at high temperatures. In this paper, both mixtures produced either with bitumen emulsion and with foamed bitumen are considered as "cold" mixtures, being labeled, respectively, "cold bitumen emulsion mixtures" (CBEM) and "cold foamed bitumen mixtures" (CFBM).
The fact that no heating is necessary for the production and placement of cold asphalt mixtures provides some environmental and economic advantages to this technique in relation to the use of traditional hot mixtures, including:

- Reduction of energy costs;
- Reduction of pollutant emissions;
- Reduction of time and costs of materials transport, since lower complexity asphalt plants can easily be installed close to the job site or lower complexity recyclers can be used for in-place recycling.

Both bitumen emulsion and foam cold in-place recycled layers exhibit structural characteristics considered adequate for road base layers.
However, special attention must be paid to the fact that that curing of asphalt cold mixtures has a great influence on the evolution of the mixture properties and therefore on the performance of the entire pavement. Furthermore, the "final" properties of asphalt cold mixture are different of those from conventional hot mixtures, namely, in terms of its void content (generally is higher for cold mixes [5, 6, 7, 8]), stiffness (usually cold mixtures present lower modulus [5, 7, 8, 9, 10, 11]) and ductility (which is, in general, higher for cold mixtures [7, 9]). According to some practical experiences, asphalt cold mixtures can also act in some extend as an anti-crack mechanism, by allowing movement of existing cracks in the underlying pavement to be partially absorbed [7].
In this context, it is important to understand the role of cold in-place recycled pavements and the relation between expected traffic levels and the mechanical resistance of the pavement.
Concerning cold recycled mixtures' resistance and stiffness, several research studies have concluded that good performance can be achieved, among others, by using the appropriate bitumen emulsion [7, 12] or when higher layer densities after compaction are obtained [7, 8].

3.2 Mix design

Mix design methods for recycled cold mixtures are basically the same as for “new” dense graded asphalt cold mixtures. However, there is still no universally accepted mix design method for these types of mixtures. The recommendations for mix design and the applied test procedures vary among European countries considerably.
In the specific case of cold in-place recycled mixtures, reclaimed materials can include materials originating exclusively from the asphalt layers, or a mixture of these with materials from unbound granular layers. The addition of virgin aggregates or corrective materials such as cement and lime is sometimes required, so that the final mixture of aggregates presents the desired characteristics.
The addition of small amounts of cement or lime can also increase early age stiffness of the recycled layers and decrease water sensitivity, especially when the reclaimed material includes unbound granular layers. This however can also increase the risk of cracking at early ages (short-term curing process) due to trafficking. Besides, some research studies found that cement or lime addition can be a drawback at later ages (medium/long-term curing process), namely in terms of strength build-up [8]. It is worth mentioning that, as a general rule, cement or lime addition should be limited to 1 %.
On the other hand, slow curing materials exhibit a risk of damage during early-life trafficking due to deformation. Cracks occurring in early-life are likely to be healed during the slow curing process. Ultimately, the decision is often an economic one [13].
Generally, water is used in the production of asphalt cold mixtures in order to provide a satisfactory degree of coating of the aggregates by the bitumen emulsion/foamed bitumen, to improve the mix workability and to facilitate the layer compaction.
Although there is a high variety in mix design approaches for these types of mixtures, the most commonly used methods present the same general objectives: to find the optimum proportion of the mix constituents (aggregates + bitumen emulsion / foamed bitumen + water + other additives), in order to provide a good workability during construction, and to achieve adequate stability and strength during the pavement’s service life.
In broad terms, the general mix design procedures for cold in-place recycled asphalt mixtures comprise the following steps [6]:

- Determination of gradation of the RA grains and selection of the granular composition (RA and virgin aggregates if required) in order to meet quality requirements;
- Selection of a type and grade of bitumen emulsion / foamed bitumen considering not only the characteristics of the granular material but also the bitumen residue, i.e. hard or soft base;
- Preliminary evaluation of the physic-chemical compatibility of the granular material with the bitumen emulsion / foamed bitumen (coating tests);
- Evaluation of premixing water content in order to achieve a satisfactory degree of coating;
- Determination of water content for optimization of both the mix workability and the layer compaction;
- Determination of optimum bitumen residue content in order to ensure the desired mix stability and strength.

Cold in-place recycled mixtures are designed to the same objectives as “new” or plant recycled cold mixtures. However, special attention must be paid to a number of issues specific to the use of this technique, resulting from the fact that in this particular type of asphalt cold mixture, the aggregate source is the existing pavement and the mix is produced along the road [6]:

- The granular material will be formed by milling the existing pavement layers, which will most likely present more variable characteristics than conventional virgin aggregates or even plant recycled materials. Therefore, a detailed site investigation is needed in order to check this variability, to assess the work feasibility and to obtain representative samples;
- The nature of the granular material will mainly depend on the thickness and proportions of the existing road material to be recycled. Therefore, depending on the existing pavement characteristics and on the depth of recycling, the reclaimed material might be contaminated by material not considered during mix design (inhomogeneities, unbound base layers); in this case the disadvantageous effects can be compensated by the addition of hydraulic binders (lime/cement);
- The aggregate gradation will not only depend on the materials to be recycled, but also on the recycling machine to be used when milling those materials. The reclaimed material may not have the appropriate grading for the final dense graded mixture. This issue can be dealt with by adding new aggregate and/or by adjusting the recycling machine in order to achieve the desired gradation;
- In any case, the samples used for mix design should be extracted from the old pavement using equipment that will break the material in a similar way to the recycling machine; the final material characteristics should always be re-checked on an experimental test section, once the construction equipment is on the job site.

In general, the selection of the bitumen residue content is based on the mechanical properties of the mixture. Therefore specimens are compacted, cured and tested, although the procedures for this analysis differs considerably throughout Europe (Table 1).

Table 1 – Different approaches for selection of optimum binder content

Country / Institution	Optimum water content determination	Optimum binder content determination		Mechanical testing
		Compaction	Test specimens curing	
Germany [14]	Static compaction (50 kN)	Static comp. (50 kN)	2 days @ 20°C and 95% relative humidity + 26 days @ 20 °C, 55±15% relative humidity	Void content, Indirect tensile strength (5°C) after 7 days & 28 days, water sensitivity, Stiffness modulus (indirect tensile test)
Ireland	-	Static comp. (120 kN)	14 days @ 35°C and 20% relative humidity	Compactibility; Resistance to compression; Wet strength Indirect tensile stiffness modulus (dry), Indirect tensile strength (wet and dry) Unconfined compressive strength
Portugal [15]	Modified Proctor	Static comp. (21 MPa / 8 MPa)	1 day @ room temperature + 3 days@50ºC (after 2009)	Water sensitivity, Uniaxial compression strength (v=5,08 mm/min.)
Spain [16, 17]	Modified Proctor	Static comp. (170 kN/60 kN), Gyratory	3 days@50ºC	Water sensitivity, Uniaxial compression (v=5,08mm/min.) Indirect tensile strength
UK	Proctor	Proctor	3 days @ 60ºC	Indirect tensile stiffness modulus testing as per BS-EN 12697-26, SATS (EN 12697-45)
Wirtgen [18]	Modified Proctor	Impact comp. 2 x 75 blows	3 days @ 40 °C	Indirect tensile stiffness modulus (dry), Indirect tensile strength (wet and dry) Unconfined compressive strength

As a recommendation, the mix design shall be based on a selection of following properties:

- Detecting optimal water content:
  - Modified Proctor test.
- Detecting optimal binder content:
  - retained resistance after immersion (e.g. water sensitivity by indirect tensile strength ratio);
  - indirect tensile strength;
  - stiffness.

From previous recommendations, it can be concluded that for this type of mixtures retained resistance tests are of crucial importance, generally controlling its mix design.

The compaction method used in the laboratory should simulate as much as possible the compaction achieved in situ when good construction practices are used. Laboratory compaction of test specimens by static compaction with double plunger is considered to be suitable [6, 7, 10, 13]. However, research studies have shown that test specimens prepared by laboratory compaction present much higher densities than the ones achieved in the field (see example in Figure 1). Thus, the compression must be adjusted in order to obtain a density that can be considered as representative of “in situ” conditions. Compressive stress loads from 7 MPa to 8 MPa are recommended, resulting in compressive forces for 100 mm diameter specimen of 60 kN [7, 10]. According to A. Martínez *et al*. [8] equivalent densities are achieved using the gyratory compactor (0,6 MPa and 1,25º).

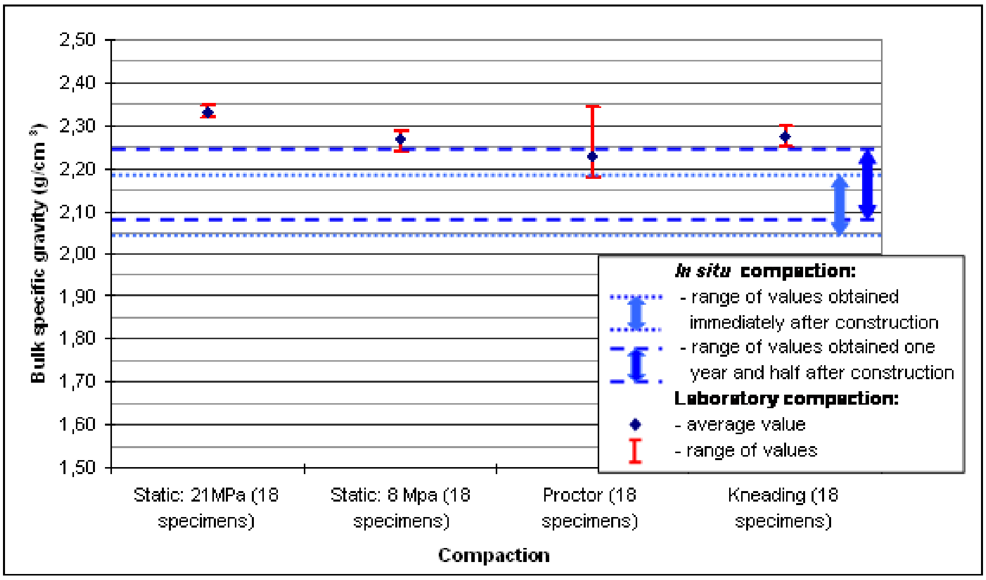

Figure 1 – Bulk specific gravity of mixtures compacted using different methods and/or load compaction [10]

Before conducting tests, specimens are submitted to a laboratory curing prior to further testing. Curing time and climatic conditions (temperature and humidity) vary considerably among European countries, e.g.:

- Germany: 2 days @ 20°C, 95% humidity + 26 days @ 20 °C @ 40-70 % humidity;
- Ireland: 28 days @ 40°C;
- Portugal and Spain: 1 day @ 20 °C + 3 days @ 50 °C.

3.3 Trial sections

Once a mix formula is achieved in the laboratory, trial applications should be performed, in order to check the final mix properties. This is even more crucial in the case of in-place cold recycled mixtures. The trial section is essential for the following objectives:

- adjustment of the speed of the recycling machine, in order to achieve the desired grading of the reclaimed material;
- Definition of compaction methodology;
- adjustment of optimum water content to achieve good homogeneity and compaction;
- Verification of the water content and curing evolution in time and estimation of the time before traffic re-opening without damaging the surface.

Trial sections should also be used for the verification of mix design properties and the establishment of quality control procedures, namely compaction control. For example, in Portugal, a good experience has been achieved by using nuclear density devices, after calibration of the equipment using conventional density test procedures (e. g. sand replacement method) on trial sections.

3.4 Work site production and application

Cold in-place recycling of asphalt mixtures is performed by “recycling trains” composed of a recycling machine connected to a water tank and a bitumen emulsion or foamed bitumen tank, followed by the compaction equipment. If necessary, corrective materials can be placed on the road prior to the passage of the recycling train. Presently available recycling machines perform the pavement disaggregation continuously, mix it with water and binder and lay the new mixture (Figure 2).

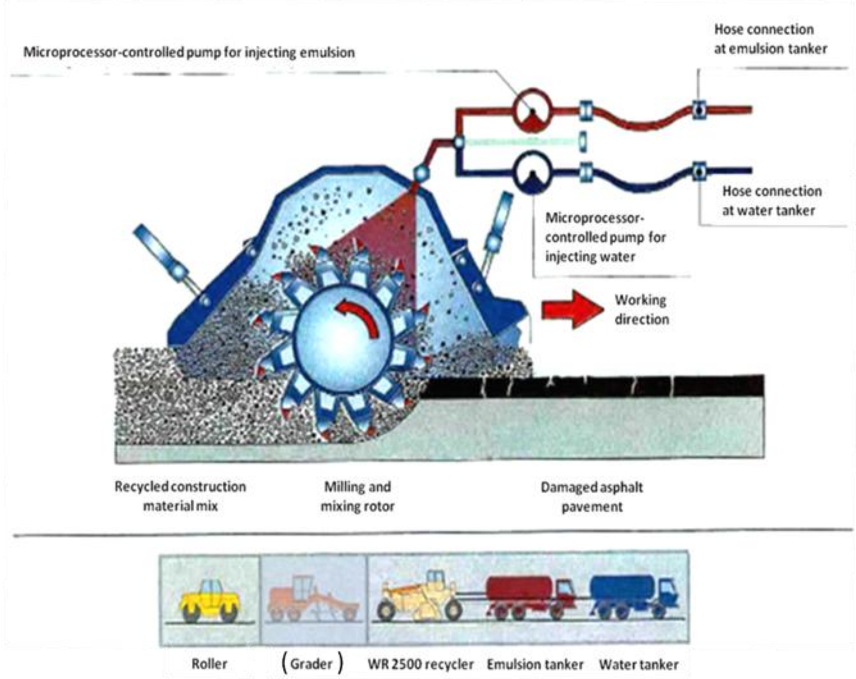

Figure 2 – In-place cold bitumen emulsion recycling operations [19]

The selection and set up of recycling and compaction equipment has a strong influence on the characteristics and homogeneity of the recycled layer. Recycling depth may also have a strong influence on the mix quality. For example, grading is strongly affected by the speed and power of the recycling machine.

Compaction is a crucial operation for the success of in-place cold recycling works, since this type of layers is often difficult to compact. Usually, heavy compaction equipment is necessary and it is recommended to use a combination of steel rollers (firstly) and tyre rollers (secondly). Normally, the steel rollers should have 11 tons or more, with vibration, and the tyre rollers should weigh 23 tones or more. Besides, some on-going studies are exploring “intelligent” compaction systems to ensure optimum recycled layers compaction.

In some countries, such as Ireland, the use of cold-mix materials is not recommended in weak subgrade conditions as they may not provide the necessary support for adequate compaction [13]. Minimum and maximum layer thickness of 150 mm and 300 mm respectively are specified for cold recycled materials.

Corrective materials are often placed on the road prior to the recycling operation. When cement or lime is used as corrective materials, care must be taken to limit the loss due to wind. It is recommended to place these materials on the road shortly before the recycling machine passes.

Weather conditions are also a factor that must be taken into consideration. Cold in situ recycling should be performed with good weather, in order to minimize the curing time, allowing the mixture to achieve its final characteristics as soon as possible. Experiences from Ireland restrict the laying of any cold mix pavements when the ambient temperature falls below 3 °C.

An important aspect to consider, when planning a cold in-situ recycling operation, is the width of the recycling machine and the width of the pavement, in order to determine the necessary number of passes of the recycling machine and to plan traffic diversions. A minimum of 10 cm (generally 15 cm to 30 cm) should be considered for the superposition of successive recycling operations. In the superposition areas, care should be taken not to introduce too much water or emulsion, for example, by turning off some of the water and emulsion injectors during the first passage.

3.5 Quality control

For in-place recycled mixtures, a significant part of the raw material will be formed by the milled existing pavement layers, which will most likely present more variable characteristics than conventional “new” aggregates. For this reason, performance related tests are recommended for quality control, in addition to the usual requirements concerning aggregate gradation, binder content, density and void content. For instance, in Spain and Portugal, compression strength and water sensitivity resistance of the recycled mixture are required, in UK requirements on indirect tensile strength, stiffness and water sensitivity are established, and in Germany requirements on bearing capacity are advised for this purpose. Water sensitivity tests are the most commonly specified tests. In Ireland, stiffness and water sensitivity tests thresholds are specified; if these are not satisfied then the contractor must determine compliance by taking cores from the pavement by dry coring after the period of 1 year. Pavement thickness is measured and the ITSM test conducted on all cores, the mean value must exceed 1900 MPa. Similar criteria apply in the UK where a minimum of 1 core is required per 75 m^2 of non-compliant material. The cores are then tested using the dry ITSM test; individual test results must exceed 2000 MPa and the mean value must exceed 2500 MPa. As these materials are sensitive to water content, the use of air-flushed coring is recommended.

3.6 Curing

One of the most important aspects related to these mixtures is the so-called "curing" process. This is mainly because one of the main constituents of this type of mixtures is water, both added to the aggregate mixture and present in the bitumen emulsion. After the mixing and placement of the cold mixture, the bitumen emulsion breaks and the bitumen separates from the water. At this stage, the water is gradually removed mainly through the compression induced by the rolling compactors and later by evaporation and traffic. At the end of this process, referred to as "curing", a continuous cohesive film that holds the aggregate in-place with a strong adhesive bond must be achieved.
Figure 3 shows the evolution of water content with the cold mix layer age during a period of around 2 months after the laying operation in Portugal [6].

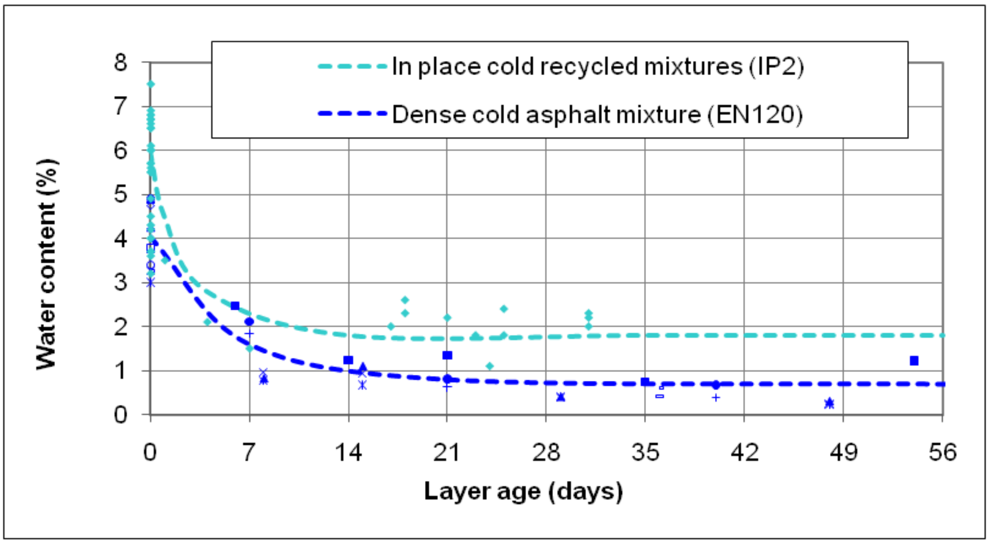

Figure 3 – Evolution of the cold mixture water content

One way of assessing the curing evolution of in place cold recycled materials is to drill cores from the cold recycled layer, for example, on a trial section, assuming that the depth until which it would be possible to extract the cores is a good indicator of the mixture cohesion and thus an indicator of its "curing". Figure 4 provides an example, for a mixture laid in Portugal, during the summer [6]. Other practical experiences have also shown that at early ages, the low cohesion of cold asphalt mixtures often doesn't allow coring [5].

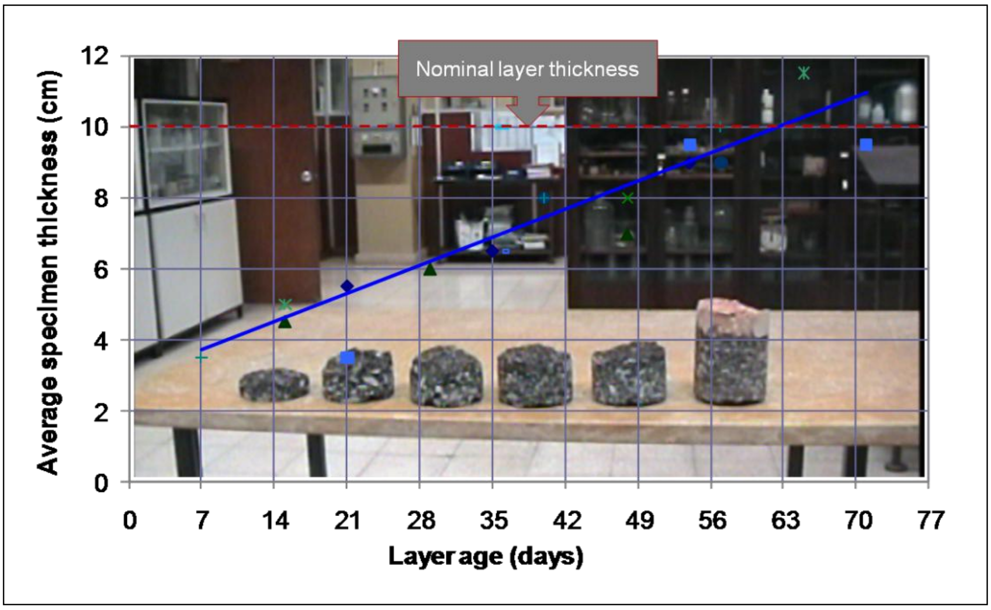

Figure 4 – Evolution of intact cored specimen thickness with the layer's age

For practical reasons, the knowledge of the curing evolution is essential for programming of the work, since it is necessary to ensure that:

- The layer has sufficient stability to withstand traffic loads when it is opened to traffic, which means that there must be a minimum curing of the surface (normally 2 days);
- The water content of the mix must be stabilized before a new layer is placed on the recycled layer, otherwise it will be difficult to evaporate the remaining water; from the experience gathered in Portugal and Sweden, 3 weeks is enough for this.

However, in Ireland, it is recommended that the cold recycled layer should be covered shortly after construction as the differing climate will slow down the curing process. If the cold-mix pavement is an open graded layer then it should be blinded and rolled using dry crushed rock fines. Before being subjected to trafficking, all cold-mix pavements must have a seal coat applied before being overlaid with a bituminous layer or a surface dressing.

3.7 Performance

When properly applied, in-place cold recycled layers have demonstrated a good performance after being in-service for more than 10 years. The Irish Interim Advisory Note [13] seeks to give advice and specification on the use of low-energy materials for the maintenance of road pavements carrying less than 5 MSA (million standard axes) for a 20 year design period.

Results from research studies undertaken in Portugal and Spain have shown that the stiffness modulus of cold recycled asphalt increases with curing, reaching their final values a few months after construction, and these are somewhat lower than the modulus obtained for hot mix asphalt. Values in the order of 3000 MPa at 20 ºC have been reported [6, 7]. F. Batista [6] has concluded that when the curing process of the cold mixtures is completed, their fatigue relationship (determined in lab tests both on lab-produced and field-cored specimens) is very similar to the one obtained for the hot mixture. Nevertheless, the fatigue life of a pavement is higher than the one determined in laboratory tests. Thus, shift factors are used in order to relate lab results to field fatigue life. According to some practical experiences, it seems that shift factors for cold in-place recycled asphalt layers' fatigue life prediction can be higher than for hot ones, but further research is needed.

From the results of permanent deformation tests performed on asphalt cold mixtures, mainly those cured for a short time (up to 2 months), it has been concluded that these mixtures have higher deformations in the first cycles (primary phase) when compared to hot mixtures. However, when this primary phase is concluded, the deformation rate of asphalt cold mixtures specimens decreases considerably, resulting in a secondary phase with a reduced deformation rate.

Usually recycled cold mixtures are used as base courses. Therefore, they will have one or more layers placed on top of them and any deformation that had already occurred (1st phase) will be corrected when the superior layers are applied.

4. FINAL CONSIDERATIONS

The demolition of asphalt pavements and the various recycling techniques of road materials in new asphalt layers can be considered as widely used technologies in the majority of European countries. Nevertheless, there are still a lot of special problems which need to be investigated in the future, namely in the field of cold recycling techniques. Some of the main research areas in this field are as follows [1]:

- Compared to hot-mix asphalt the mix design procedures applied for cold-mix asphalt vary considerably throughout Europe. Pre-normative research is needed to indicate common procedures for:
  - laboratory compaction methods;
  - curing procedures;
  - performance test methods;
  - mix design requirements.
- Investigation of the effect of multiple binders in reclaimed material on the quality of recycling: for asphalt recycling techniques that are performed using bitumen emulsion or foamed bitumen and cement as binders, the medium and long-term performance of these recycled layers should be evaluated and utilized in future research; besides, reclaimed asphalt can be contaminated during demolition by hydraulically bound materials, as for example lean concrete base material which can influence the required quality of the new asphalt layers using this crushed material.

This paper, based on the best practice guide prepared in the framework of the Direct-Mat project [1], aimed to summarize the European experience in the field of cold in-place recycling of road materials in new asphalt roads in order to give guidance for practitioners aiming to apply this recycling technique. This will hopefully encourage the application of recycling technology in road engineering. For countries with low experience in this field, the recommendations will help to improve the recycling rate for reclaimed road materials. But also in countries, where already nearly all of the road material is recycled or reused, this guide indicate alternative approaches which may improve the recycling processes in order to reduce economic and ecological costs.

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