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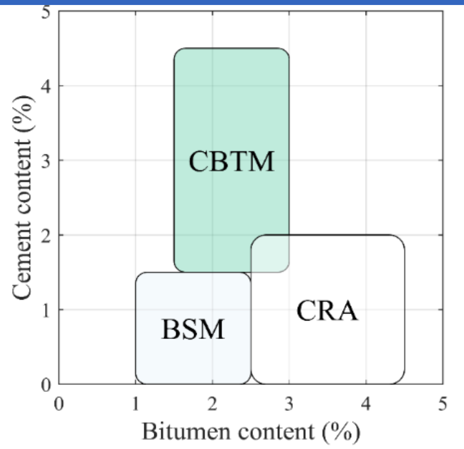

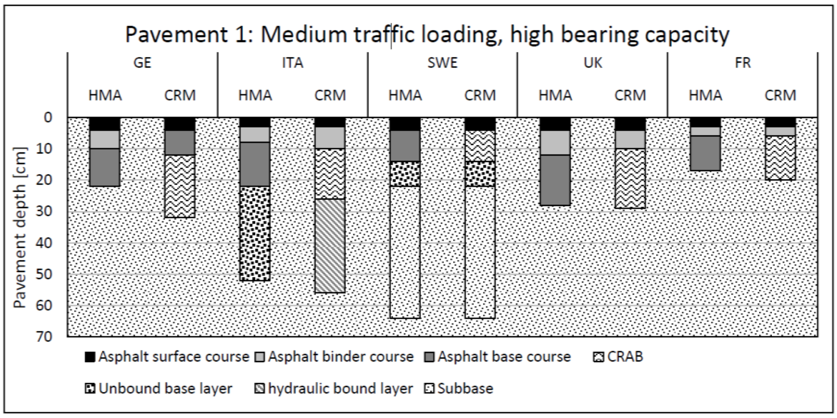

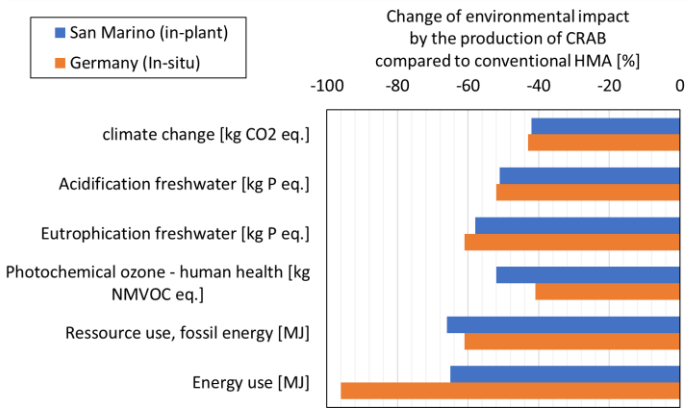

CRAB for OERE

December 2021

Call 2017 New Materials CRABforOERE Project Final Report

CEDR Contractor Report 2022-04

Guideline for RA assessment, mix and pavement design as well as maintenance needs for cold recycled asphalt bases for flexible pavements

by
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Executive summary

Compared to the usually applied hot-mix asphalt pavements, the use of cold recycled asphalt base layers (CRAB) in flexible pavements is less common in road construction. However, several European countries have a long experience in these materials, which are usually composed of high contents of reclaimed asphalt (> 75 %), bitumen emulsion and cement. Recently, harmonised test procedures and material requirements were proposed for cold asphalt mixtures with bitumen emulsion within CEN 336/WG1 (EN 13108-31, EN 12697-53 to -56). However, for the wider use especially in countries with less experience in cold recycling some aspects of these road materials need to be assessed. The short-term performance which is highly dependent on the development of moisture within the CRM layer and therefore of climatic conditions is not fully understood so far and therefore cannot be properly adopted during mix design properly. Furthermore, durability as well as failure modes need to be examined in order to introduce sustainable pavement design procedures. In order to enable the application and implementation of these road material, a guideline for mix and pavement design principles were established within a collaborative research project.

In order to derive suitable procedures for mix and pavement design, the specification documents in five European countries were assessed in detail and compared for commons and variations. Additionally, 17 existing pavement structures including cold recycled asphalt base layers were assessed in detail regarding service life, traffic loading, pavement structural design, material properties and surface condition. These structures were used for verifying the analysed national design procedures.

Within CRM, the RA granulates takes the role of aggregates, as its binder is not reactivated by any heating. By testing of nine RA samples, derived from stockpiles of nine asphalt plants in Sweden, UK, France, Germany and Italy it could be shown, that the usually applied test procedures for assessing the properties of natural aggregates can be applied also for the assessment of RA. The tests procedures don't need any modification but for reducing the temperature for oven-drying to 40 °C.

As a result, the wide range of mix designs for applied cold recycled materials regarding applied binder contents (bitumen and cement) could be confirmed including cold asphalt mix according to "grave emulsion" principles with low or no addition of reclaimed asphalt (≤ 30 %) and without any mineral binder, cold recycled asphalt mixtures with moderate cement contents (1,5 – 2,0 %) and RA contents of up to 90 % as well as cement-bitumen treated materials (CBTM) with cement contents of ≥ 2 % and high RA contents ≥ 90 %.

As a result from comparative laboratory mix design tests, it could be concluded, that the addition of cement is required for reaching strength and stiffness properties at young service life for enabling high traffic loads already shorty after construction. In order to avoid shrinkage cracking and enable flexible material behaviour, the content of cement shall be limited to 2 % at maximum. The content of added emulsified or foamed bitumen shall be in a range resulting in a bitumen:cement ratio of 1:1 to 1,5:1. High contents of added bitumen would reduce the materials strength.

The laboratory compaction shall result in similar compaction success as site compaction. Therefore, the applied compaction energy in most nationally applied laboratory compaction procedures needs to be adjusted. Curing conditions (temperature, moisture) affect the evolution kinetics of strength and stiffness of the specimens. In situ curing depends on the regional climate of the pavement location, weather conditions, structure of the roadway and road traffic. Therefore,

a perfect simulation in the laboratory is illusory. In order to achieve some harmonisation, following procedures are proposed:

- for high temperature conditions (southern Europe): Curing at 40 °C for 3 days
- for low and intermediate temperature conditions (northern Europe): Curing at 20 °C for 28 days

The moisture during curing shall be selected according to the site and construction conditions:

- In case of a quick covering of the CRAB with seal or a surface or binder asphalt layer within 24 h, the curing shall be done in sealed conditions (e. g. in a plastic bag).
- In case of several-days drying of the CRAB layer without cover, the laboratory curing shall be conducted at unsealed specimens.

The assessment of the existing CRAB pavements showed that observed surface conditions in CRAB pavements can be linked to their structural design properties (structural thickness, subbase layers) and service lifetime. A pavement design "rule of thumb" could be derived, which would allow the application of national empirical pavement design procedures. Here, the HMA base layer can be changed to a CRAB layer by considering a higher layer thickness:

- $h_{CRAB} = 1,5 \cdot h_{HMA\ base}$, or
- $h_{CRAB} = 1,2 \cdot h_{HMA\ base}$, when a cement stabilization is applied below the CRAB.

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1. Definition of the Issue

1.1. Purpose

This report summerises the results of the research project "Cold Recycled Asphalt Bases for Optimised Energy & Resource Efficient Pavements (CRABforOERE)", which was funded by CEDR within the call 2017 "New materials".

Hot recycling is the recycling procedure for the use of old asphalt materials reclaimed from existing road pavements most often applied in Europe. In terms of economic value, hot recycling is usually considered as the best option for reducing the need for new resources of high-quality aggregates and bitumen. However, in several regions within Europe, the technical and economic capacities for reuse of reclaimed asphalt (RA) by approx. 30 % have been reached. For further increasing the recycling rate special installations are required (parallel recycling drums) within asphalt plants. Larger plant ground area for optimised RA management is needed also to improve the RA quality in terms of homogeneity. Inadequate characteristics of the RA binder demands for the addition of rejuvenating additives. Especially highly-aged binders and/or applied modifications within the reclaimed asphalt limit the use of these resources in hot-mix asphalt. These reached capacity limits result in increasing storage stockpiles for less recyclable reclaimed asphalt sources.

As an alternative, recycling of RA in cold recycling materials (CRM) is applied internationally with success. Also, in Europe (especially Italy and the UK) significant proportions of incurred RA are already cold recycled by application of foamed bitumen, bitumen emulsion and/or mineral binders. Good experience regarding mechanical properties and durability was further made with CRM for recycling of tar-contaminated pavements, for example in Germany. Generally, RA contents ≥ 75 % are reached within CRM. In France, annually ~1,5 mil. tons of cold asphalt mixtures based on natural aggregates and bitumen emulsion are applied since centuries in base layers (EAPA 2017). Due to the mix preparation at ambient temperature, CRM demand for comparably less energy. Therefore, cold recycled asphalt bases (CRAB) can be considered as pavement layers of optimal energy and resource efficiency (OERE).

Recently, harmonised test procedures and material requirements were proposed for cold asphalt mixtures with bitumen emulsion within CEN 336/WG1 (EN 13108-31, EN 12697-53 to -56). However, for the wider use especially in countries with less experience in cold recycling some aspects of these road materials need to be assessed. The short-term performance which is highly dependent on the development of moisture within the CRM layer and therefore of climatic conditions is not fully understood so far and therefore cannot be properly adopted during mix design properly. Furthermore, durability as well as failure modes need to be examined in order to introduce sustainable pavement design procedures.

Within CRAB for OERE project, following steps further for establishing harmonised standards for cold recycling technologies were aimed:

1. Assessment of long-term performance of existing cold recycling and/or cold asphalt pavement structures
2. Validation and – if necessary – adaption of existing test methods and qualification procedures for RA aggregates.
3. Validation of laboratory curing and performance assessment procedures for CRM
4. Demonstration of harmonised mix design procedures based on EN 12697-53ff and EN 13108-31
5. Demonstration of pavement design procedures for pavements with structural layers composed of cold recycling materials
6. Scientific supervision of new test pavements with optimised energy efficiency allowing the application of sensors and monitoring of short-term performance

7. LCA- and Risk analysis for assessment of environmental and economic benefits by using cold recycled materials and evaluate applications risks (e. g. weather during construction, RA variability)

1.2. Scope

As a result of CRABforOERE project, the results obtained from monitoring existing structures, extended lab test programmes, observations during the construction of a demonstration site and a life-cycle assessment are transferred to the guidelines within this document. These intend to give information for enabling first steps to be taken for implementing cold recycled asphalt bases into road network. It is expected that each actual application of cold recycled asphalt mixtures in road pavements can be further optimised on basis of the following guidelines. Therefore, these shall be seen as a first step approach, which can be modified and complemented according to the applied national specification procedures.

Details regarding the background of following guidelines can be obtained from the deliverable reports D2 to D7, each of which discusses selected topics under research within the project, see Table 1.

Table 1: Titles and submission dates of deliverable reports discussing details to these guidelines

Deliverable report	Title	Date
D2	Compendium of CR performance in different climatic zones and critical review of the impact of mixture composition on performance	04/2020
D3	Simple and practical testing protocol to assess the effect of the RA aggregate on CRM properties	05/2020
D4	Report detailing mix design methodology improving and the test results on CMA formula studied	09/2021
D5	Proposal of pavement design procedure including structure catalogue and identification of failure modes for MEPD	04/2020
D6	Synthesis of job reports about demonstration structures	09/2021
D7	LCA, LCC and Sustainability Assessment of CRABforOERE technologies	10/2021

1.3. Methodology

Within CRABforOERE project, the information required for drafting these guidelines were elaborated within six work packages (WP) by following means, compare Figure 1:

By **assessing 17 existing pavement structures** with cold recycled asphalt bases within their structures, information about the width of experience within Europe were learned. This includes especially various binder concepts with different contents of bitumen emulsion, foamed bitumen and/or cement. Further differences and commons regarding pavement design were assessed in detail. The actual surface conditions were assessed and together with pavement design compared to the actual pavement design, traffic loading parameters and age of the structures (WP2).

Nine **reclaimed asphalt materials**, sampled in five European countries were assessed by application of aggregate test methods, because of the role of the RA conglomerates as grains within the CRM (WP3).

The **mix design procedures** applied in five European countries were assessed in detail and the different methods for binder content selection, specimen compaction, curing and mechanical testing were practically applied for comparing the resulting materials performance. From the results summarising conclusions for harmonised mix design procedures could be obtained (WP4).

By comparing five national **pavement design procedures** applied for road structures with CRAB and with more experienced fully hot-mixed asphalt layers, the existing trust and expectations in these road materials were analysed. Three empirical pavement design procedures were applied on model pavements defined by given traffic loading and subsoil conditions as well as on the 17 assessed existing structures. Later results were compared to the actual pavements condition and age (WP5).

A **demonstration pavement** structure was built by incorporating sensors for measuring the moisture and temperature within the CRM layer. Further, core specimens were assessed 28 and ~300 days after construction of the pavement for assessment of the site curing effects. By implementing falling weight deflectometer (FWD) tests, the overall bearing capacity could be measured at the beginning of service life and after one year of service (WP6).

The **environmental and cost benefit** to be expected by the application of CRAB in flexible pavements were assessed for two pavement structures in central and southern Europe (WP7).

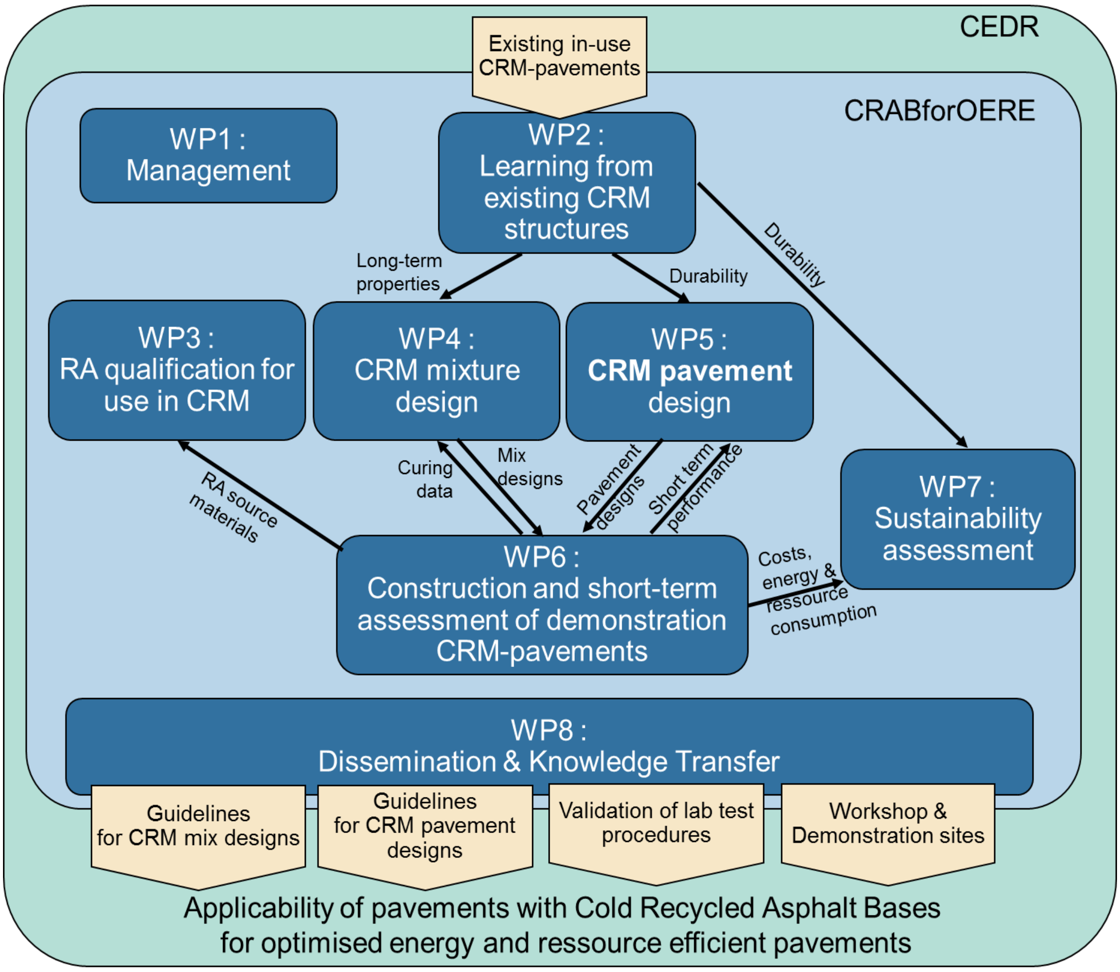

Figure 1. Organisation structure within CRABforOERE project.

2. Possible ways forward (solutions)

2.1. Learning from existing CRAB structures

In order to acquire data from existing pavements, in which cold recycled materials were applied as base layer, a questionnaire was formulated and distributed among the project partners. The questionnaires were filled in either by the project partners or the National Road Authorities. Data regarding year of rehabilitation, traffic volume, mix design, structural design and any damages on the surface were collected.

In Table 2, a short summary of the most important data is given. Regarding the mix designs applied within the assessed CRAB layers (Figure 2), the CRM materials can be classified into cold asphalt/grave emulsion (CMA/GE) which contain no cement (four materials from structures in France and Sweden), cold recycled asphalt (CRA) with low cement addition (≤ 1,5 %; two structures from UK) and cement-bitumen treated mixtures (CBTM) with higher contents of cement (nine structures applied in Germany and Italy).

Table 2. Most important data about the studied pavement sections.

Country	Road name	Rehabilitation year	Average Annual Daily Traffic (AADT) [Vehicles/day)	Average Annual Daily Traffic of heavy vehicles [Vehicles/day)	Proportion of Reclaimed asphalt in mix granulate (%)	Bitumen emulsion content (%)	Cement content (%)
GE	B52 (1)	2009	26000	3900	100	4,0	4,0
	B52 (2)	2009	26000	3900	100	2.5*	3,0
	B52 (3)	2009	26000	3900	100	4,0	4,0
	L52	2011	1500	60	100	2,5	4,5
	L386	2007	7000	240-490	90	3,0	3,5
IT	SP18	2008	5000	250	20	4,0**	2,0
	SS38	2007	30000	1850	34	3,0	2,0
	A14	2007	44000	11000	50	3,0	2,0
	SS268	2016	19661	2115	100	4,0**	2,0
UK	A21	2002	47714	11700	No data		
	A46	2006	19192	3664	73	3,5*	1,5***
	A38	2006	37000	3700	88	3,0*	1,5***
SE	Rv95	2014	3136	380	30	4,8	0
	E45	2012	1233	333	0	4,2	0
	Lexby	2012	<1000**	~0**	30	4,8	0
FR	RD26	2011	No data	25-50	0	7,0	0
	RD44	2008	No data	100-150	0	6,7	0

* refers to foamed bitumen, not emulsion
** polymer modified
*** +5% fly ash

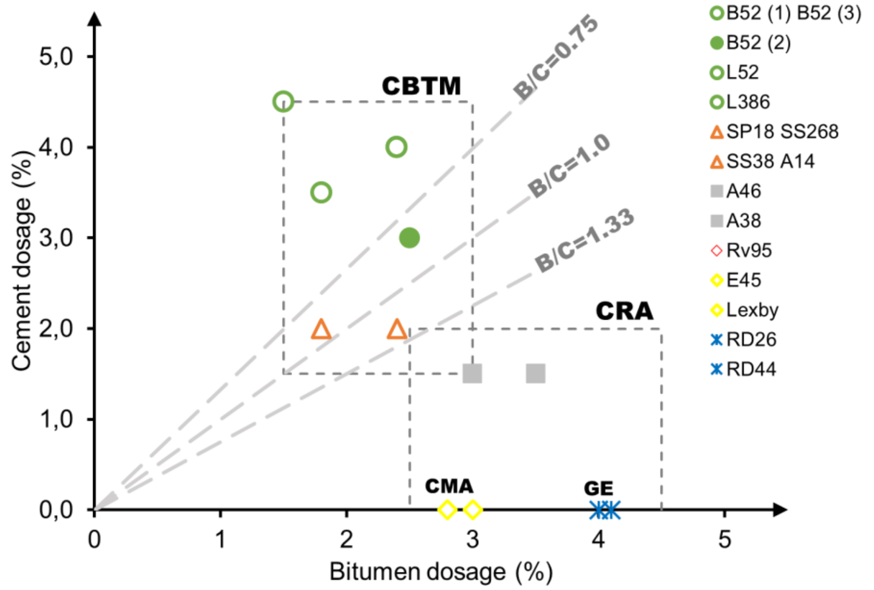

Figure 2. Contents of added bitumen and cement in assessed CRAB layers

Figure 3 shows the grading of the mix granulate (RA and added natural aggregates) applied within the CRM mixtures in the assessed road sections. It can be concluded that a wide variety of roads were studied, regarding both traffic volume, applied mix design (binders and their contents) and pavement design. Except of one (Swedish) CRAB, all CRM composition follow a dense grading (asphalt concrete) concept.

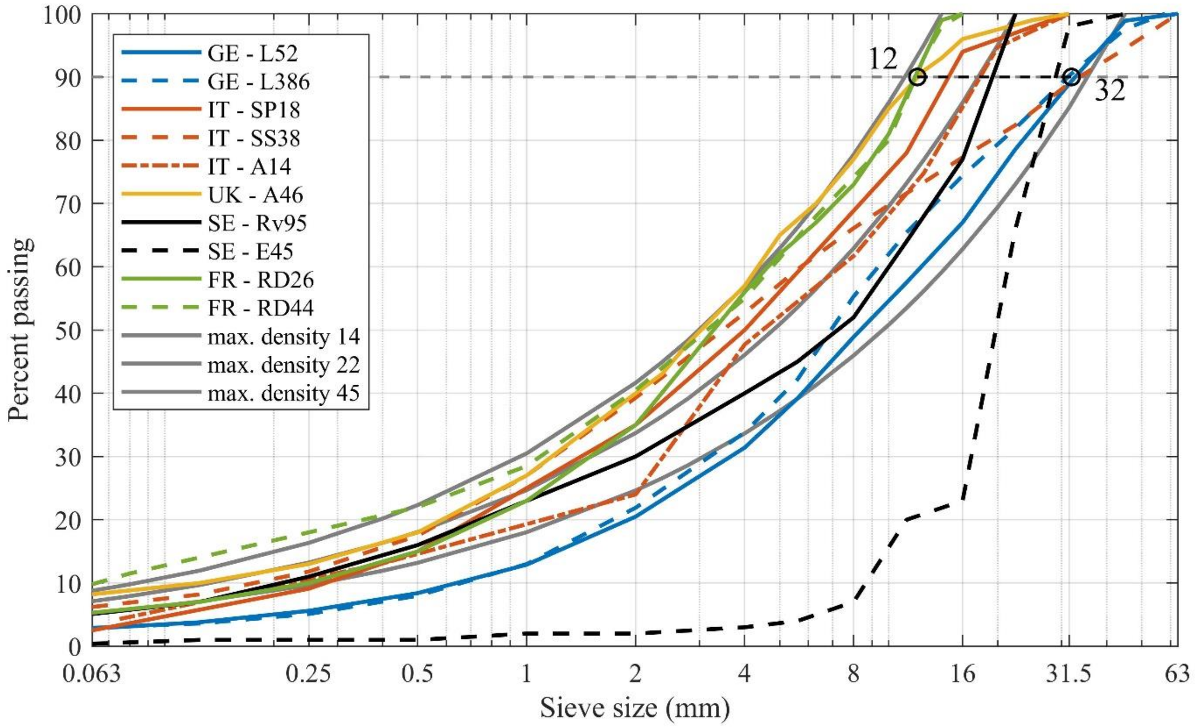

Figure 3. Particle size distribution representing nine of the studied CRAB layers.

The structural design of the various pavements differs significantly, both due to traffic volume but also to national design procedures. In Figure 4, structural designs of the 17 studied pavements are displayed in terms of bound layer thicknesses.

The total thickness of the bound pavement structures varies considerably. In seven structures, three asphalt layers (surface, binder and base layer) composed of hot-mix asphalt are paved on top of the CRAB, in five structures, only surface and binder asphalt layers are applied. In four structures, the CRAB is covered by a single hot-mix asphalt surface course.

As plotted in Figure 5, the applied thickness of all asphalt layers (including CRAB) follows a common trend according to the traffic loads of the structures for pavements applied in France, Italy and Sweden. The thickness applied in German structures is independent of the actual traffic loading. A reason could be that the pavements were used for recycling tar-contaminated reclaimed road material, without other comparable recycling options. Here the designs aimed at incorporating a high amount of the contaminated road material in selected projects. Two of the UK pavements are indicated with lower asphalt layer thicknesses compared to the general trend (A21, A46), where cement-bound foundation layers were applied below the CRAB.

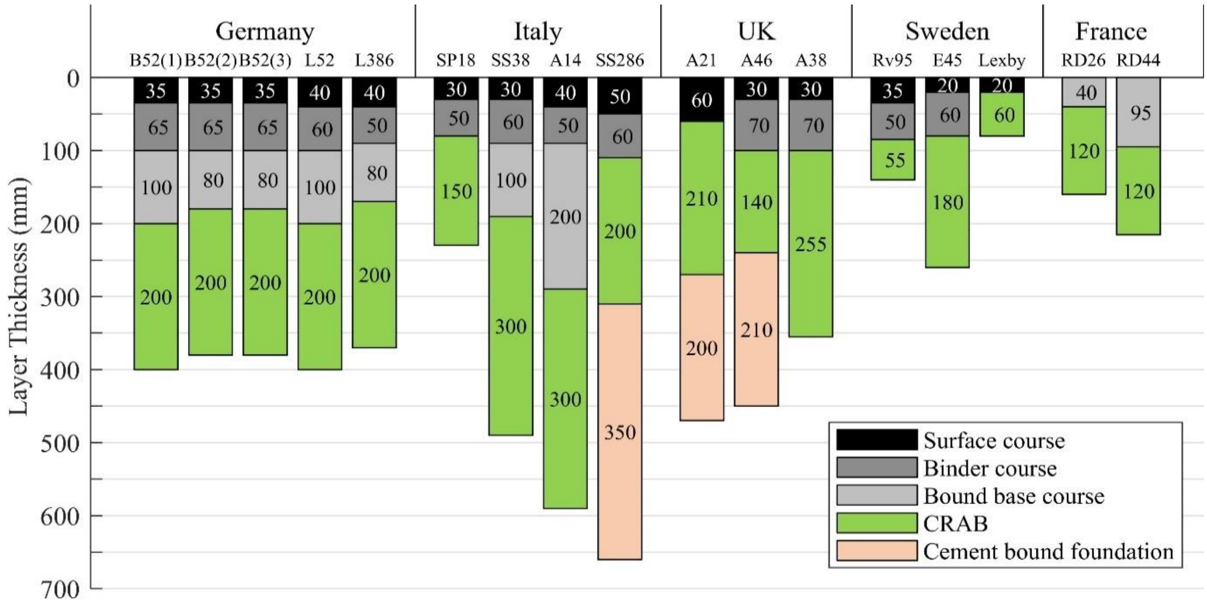

Figure 4. Structural design of the 17 studied road sections. Unbound layers are omitted from the plot.

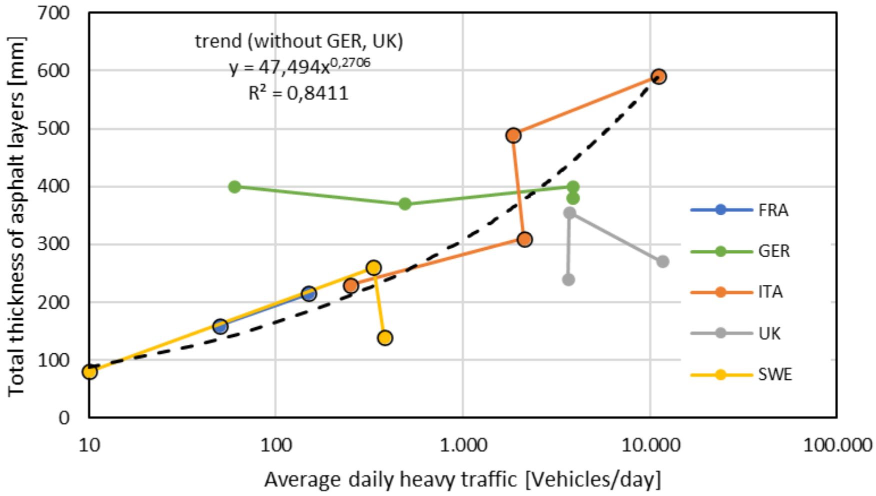

Figure 5. Comparison of total asphalt layers thickness in assessed pavements (including CRAB and hot-mix asphalt layers) and traffic loading

No major distresses were reported from any of the studied road sections. However, surface cracks developed on the German road L386 soon after the rehabilitation. This was concluded to be an effect of the high cement content, which was reported to be even higher than the planned 3 %, causing shrinkage cracking. The cracked surface layer was replaced with a new layer and no new distresses have been reported since.

In order to give an approximate status of the road, each studied section was assigned one or two status values. The status values range from one to five and represent cracking and rutting. Each road section was assigned its status value(s) depending on the available information. Rutting data was provided by the project partners from systematic condition assessment data available. The information about cracking was assessed by studying photos provided or by Google Street view. Depending on the maximum rut depth and the area percentage affected by surface cracks, status values were assigned using nomographs. The status value results showed that all the mean condition of the sections were classified as in '*very good'* or *'good'* condition except for one Italian structure (SP18). However, three additional sections in Germany (L386) and in Sweden (Rv95, E45) showed only satisfactory cracking condition in some subsections of the structures. None of the assessed structures showed problematic rutting.

2.2. RA assessment

In Europe, the qualification of RA aggregate is currently carried out according to EN 13108-8. This standard focuses on the reuse of RA in conventional hot mixtures where the aged bitumen is re-heated and blended with "fresh" bitumen. Since CRM are produced at ambient temperature the aged bitumen in the RA particles remains solid and thus blending with fresh bitumen is not happening – neither during mixing, nor in long-term conditions due to low ambient temperatures. Moreover, since the aged RA bitumen is stiffer and less temperature-susceptible than the fresh bitumen, RA particles can be considered as "black rock" during CRM mix design and production phases. The aged bitumen affects the RA particles dimensions, shape, resistance to fragmentation, water absorption and many other physical, mechanical, and chemical properties (including surface charge). Therefore, to facilitate the use of RA in CRM it is natural to measure and declare its properties using the same approach currently adopted for natural or recycled mineral aggregates in other paving mixtures.

The objective of Work Package 3 (WP3) was to select a set of testing procedures for characterising RA aggregate properties for cold recycling applications. National/local specifications for aggregates were reviewed and a common set of properties was established. Afterwards, nine RA aggregate samples produced in five European countries were collected and tested. Possible range of variability for RA aggregate properties was estimated and the existence of mutual relationships was assessed.

2.2.1. Review of specifications

National and local specifications for unbound materials, hydraulically bound materials, hot, cold, and cold-recycled bituminous mixtures were collected from the five participating countries. Requirements for aggregates to be used in base and binder layers, among those listed in the standards EN 13043 (Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas) and EN 13242 (Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction), were analysed and compared resulting in a list of common properties to be measured (Table 3).

Table 3. List of consensus properties proposed among those listed in EN 13043 and EN 13242.

Requirement	Testing Reference
Upper aggregate size	EN 933-1
Maximum value of fines content	EN 933-1
Flakiness index	EN 933-3
Shape Index	EN 933-4
Crushed aggregate particles	EN 933-5
Sand Equivalent	EN 933-8
Resistance to fragmentation (Los Angeles)	EN 1097-2
Resistance to freezing and thawing	EN 1367-1
Water Absorption	EN 1097-6

Besides the requirements listed in Table 3, the following tests were identified as potentially useful for characterizing RA aggregate to be used in CRM:

- The Atterberg Limits, according to ISO/TS 17892-12,
- The rise in pH test, mainly adopted in France to evaluate the compatibility between RA and bitumen emulsion (Ziyani et al., 2014);
- The XRD test, to evaluate the mineralogy of the aggregate and help in assessing its compatibility with bitumen emulsion;
- The Fragmentation test, developed within RILEM TC 237-SIB, to evaluate RA stability under compaction (Perraton et al., 2016). The test was introduced to allow a rapid characterization of the RA aggregate used in the field in an amount of time compatible with the times of construction work plan.
- The soluble binder content (EN 12697-1) to help in estimating the influence of the aged binder on the mechanical response of CRM mixtures.

2.2.2. Experimental results

The tested RA aggregate samples had maximum grain sizes of between 12 mm and 16 mm and binder content comprised between 3,1 % and 6,5 %. Table 4 summarises maximum, median, and minimum values of the most significant properties. As it can be observed, the ranges of variability on RA properties overlap with those of natural aggregates and therefore the categories defined in EN 13043 and EN 13242 can be employed also for RA aggregates. It is important to underline that all tests were carried out using the same procedures adopted for natural aggregate, except that drying was carried out at 40 °C to avoid the softening of the aged bitumen.

Table 4. Summary of testing results on the RA aggregate samples.

Requirement	Max/median/min values
Fines content (%)	5,6 / 0,9 / 0,3
Flakiness index (%)	10,2 / 5,9 / 3,7
Shape Index v	16,9 / 6,1 / 2,6
Sand Equivalent (%)	97,1 / 70,6 / 51,9
Los Angeles (%)	17,2 / 14,8 / 10,7
Water Absorption (%)	2,1 / 1,4 / 1,1
Binder content (%)	6,5 / 5,1 / 3,1

Figure 6 summarises the Rise in pH results. Figure 6a shows that RA aggregates can be identified either as reactive (marked increase in pH) or as non-reactive (GER1, UK1, SWE1). The plot also shows that the reactivity of RA aggregates was similar to that of the extracted aggregates (coded “e”). This suggests that the aged bitumen had no effect on the kinetics of the mineral fractions rise in pH. By x-ray diffraction (XRD) tests on the extracted aggregates, the two groups of RA aggregates could be linked to the mineralogy of the aggregates within RA.

Figure 6b shows the behavior of one non-reactive extracted aggregate (GER1e) when cement was added. A strong and quick increase in pH was observed, indicating that the rise of pH was ruled by the cement only. Therefore, the breaking of the emulsion is expected to occur quicker when cement is added in the mixture, leading to an early decrease in its workability, unless specific emulsion formulations are used (e.g., overstabilised emulsions). Further, the actual mineralogy of the RA aggregates seems not to influence the breaking properties of the emulsion if cement is added to the CRA mixture.

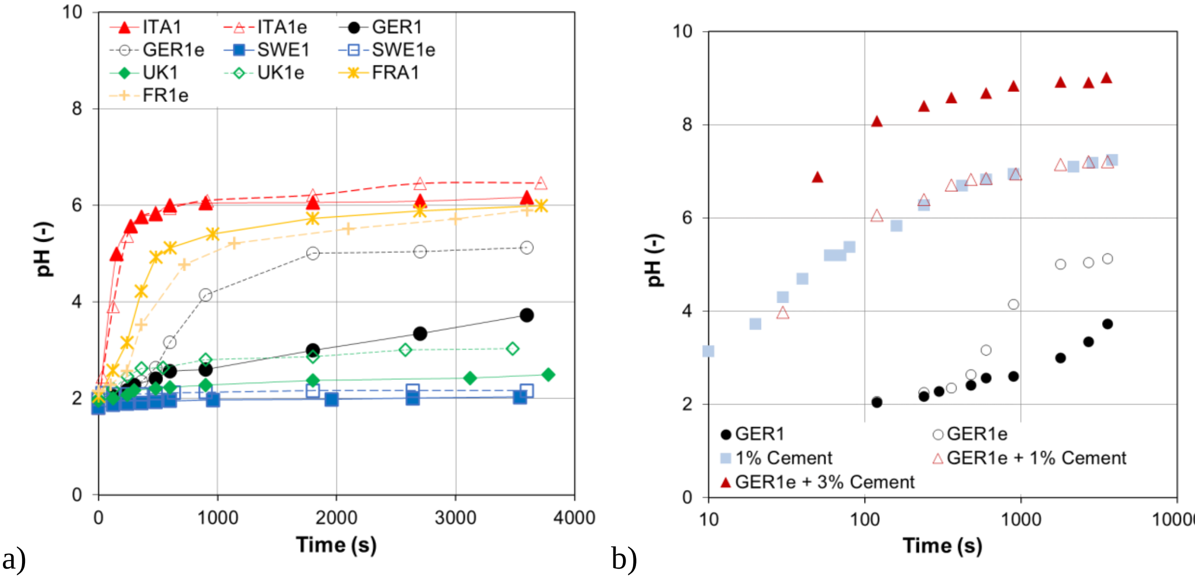

Figure 6. Summary of rise in pH test, a) comparison between RA aggregate and extracted aggregate ("e"); b) effect of cement addition on GER1e.

Figure 7 outlines the results of the comparison among the RA aggregate properties. In most cases the correlation among different properties is low, as exemplarily shown in Figure 7a where the binder content and the sand equivalent are compared. On the other hand, Figure 7b shows the good correlation between the results of the fragmentation test (expressed in terms of passing to the control sieve) and the LA values. This suggests that the fragmentation test could be used for a quick field-assessment of the RA aggregates during in-place recycling.

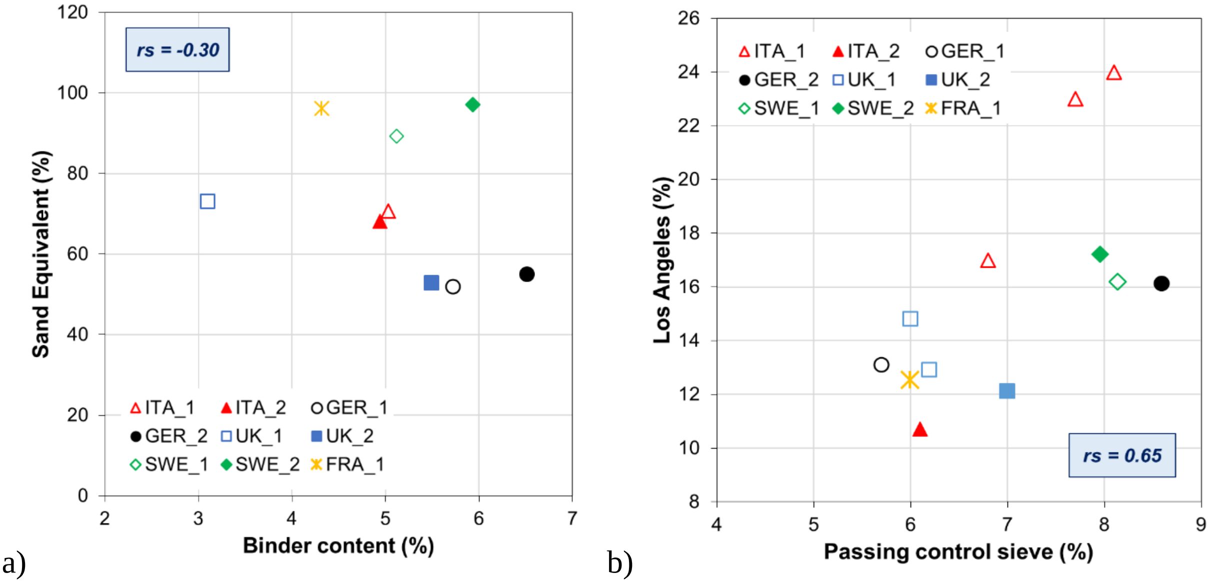

Figure 7. Outline of the comparison among test results, a) Sand equivalent Vs Binder content, b) Passing control sieve from fragmentation test Vs Los Angeles value.

2.3. Mix design

2.3.1. International mix design procedures

National specification documents, from the five participating countries, prescribe mix design procedures for cold recycled materials produced. RA aggregates and added natural aggregates are mixed with “cold” bitumen emulsion as well as water and cement. The mix design procedure can be divided in following main phases:

1. materials selection (reclaimed and virgin road materials),
2. choice of binders (bitumen emulsion/foamed bitumen/cement),
3. choice of optimum compaction water content and binder content,
4. mix preparation and specimen compaction,
5. behaviour of fresh (workability, compactability, modulus) and cured mixtures (stiffness, water content and rutting).

The summarised mix design procedures applied in five European countries follow similar procedures.

Sampling of RA: For obtaining a representative sample material for the mix design, the reclaimed asphalt sample should comply with the material actually applied during the construction process. In case of reclaimed material from a specific road structure, the application of real millings for obtaining a representative sample is required. If RA is used from a well-managed stockpile within a mixing plant with known ranges of the properties, these samples can be used.

Analysis of RA characteristics: The reclaimed asphalt materials shall be thoroughly assessed according to EN 13043 and EN 13108-8. Most important information is the grading of the RA particles ("black rock"). The binder content and bitumen characteristics of the RA as well as its aggregate grading is required for checking the mix composition during the construction.

Composition of mix granulate: In all countries, the mix granulate shall meet a dense mix composition, see Figure 8. The maximum grain size varies between ranges of 10 to 20 mm (UK) to 20 to 64 mm (IT). Regarding the size of the specimens prepared and tested during mix design, the grains larger than 22 mm should be excluded from the mix granulate for the mix design experiments.

As freshly milled reclaimed asphalt usually has low contents of fines and fine particles, usually fine natural aggregate and/or fillers are added to the mixture in order to achieve a favourable gradation.

Assessment of compaction water content: For reaching water content enabling a good workability and compactability, modified Proctor tests or similar tests applying other compaction procedures (static, gyratory or vibratory compaction) are conducted. As results, the reference dry density and an optimal water content are derived. For evaluating the added water content for the mix preparation, the moisture of aggregate and the bitumen emulsion water content are subtracted from the optimum water content.

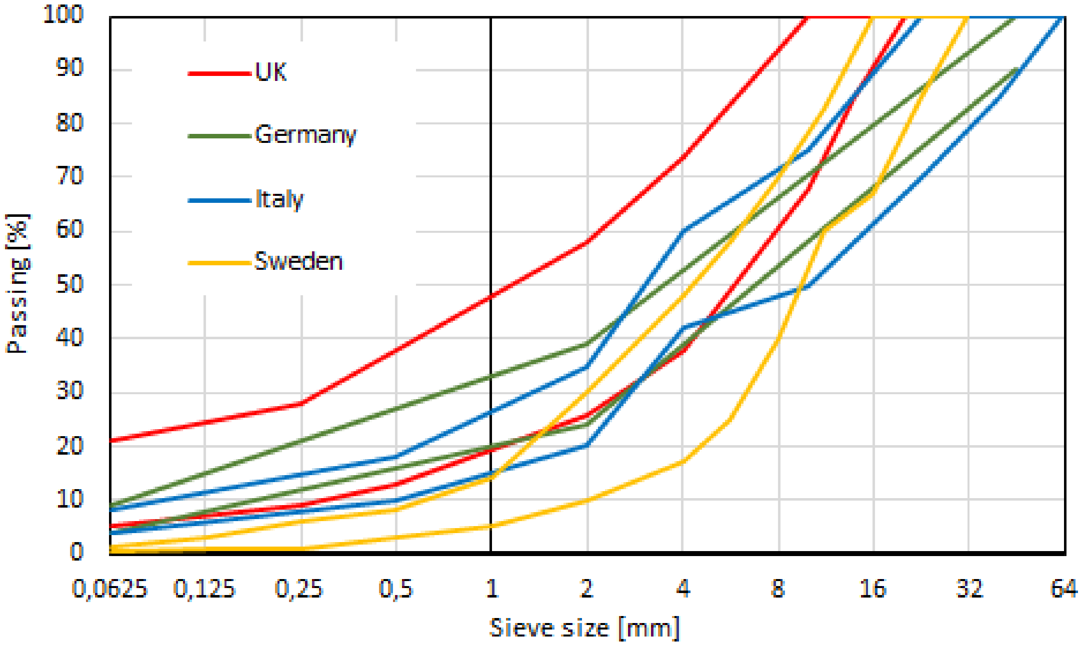

Figure 8. Grading envelopes for mix granulates for cold recycled materials according to four national mix design specifications.

Selection of binders and binder content: Most mix design methodologies prescribe minimum contents or content ranges for bituminous emulsion and cement addition, see Table 5. As bitumen emulsion, cationic slow-breaking emulsions with unmodified bitumen are commonly applied. The emulsified bitumen usually applied in base layers is a medium (50/70) or soft pen-graded base binder (70/100 to 160/220).

Table 5: Binder content specifications in national mix design procedures

Country	Content of binders [%]			
	bitumen emulsion	residual added bitumen	total bitumen (incl. RA)	cement
France	≥ 4,0	≥ 2,4	-	-
Germany	3,0 – 5,0	1,8 – 3,0	-	1,5 – 2,5
Italy	3,0 – 4,0	1,8 – 2,4	-	1,5 – 2,5
Sweden	1,3 – 2,8	0,8 – 1,7	4,4 – 6,5	-
UK	3	1,8	3,0 – 6,0	1,0*
*additionally, fly ash can be added as filler to the mix granulate				

Laboratory mixing trials include mix preparation, compaction and curing of specimens and assessment of their volumetric and mechanical parameters. For finding suitable mix compositions, trial mixtures are usually prepared in laboratory with varied binder contents. After mix preparation at ambient temperatures, specimens are compacted using various compaction procedures. After compaction, the specimens are cured in order to allow the breaking of the bitumen emulsion as well as to simulate medium-term and long-term field conditions of the material properties considering drying and hydration processes. In Table 6, the applied compaction and curing procedures are summarised.

After curing, the void content as well as mechanical properties of the specimen are tested and checked if specified values are obtained. Besides the strength of the mixtures, derived by indirect tensile tests or uniaxial compression test, the stiffness modulus as well as the water sensitivity are controlled. The specification limits as well as test conditions are summarised in Table 7.

Table 6. Applied compaction and curing procedures for mix design.

Country	Compaction procedure	Curing procedure		
		temperature [°C]	moisture [%]	Duration [d]
France	Duriez (static) EN 12697-56: s_{comp} = 15 MPa	35	20	14
Germany	Duriez (static) EN 12697-56: s_{comp} = 2,8 MPa	20	~95 (sealed) 40 - 70	2 28
Italy	Gyratory EN 12697-31 100 gyr.; 0,6 MPa	40	-	3
Sweden	Gyratory EN 12697-31 ≤200 gyr.; 0,6 MPa or Duriez (static) EN 12697-56: s_{comp} = 7,0 MPa	40	-	7
UK	Vibratory EN 12697-32	30	-	3

Table 7. Specification limits and test conditions for assessment of mechanical properties during mix design.

Specification		France****	Germany	Italy	Sweden	UK
Void content		≤ 15% (≤ 12%) @ 100 gyrations	8 – 15 %	-	6 – 14 %	≤ 7 %
Strength [MPa]	procedure*	UCS, 18 °C	ITS, 5°C	ITS, 25 °C	MS, 25°C	-
	specification	≥ 2,5 (≥ 3,5)	0,7 – 1,0	≥ 0,40	≥ 7	-
Stiffness [MPa]	procedure	2PB, 15°C ITSM, 10°C	ITS**, 5 °C	ITSM, 20°C	ITSM	ITSM, 20°C
	specification	≥ 1.500 (≥ 2.500)	3.000–7.000	≥ 3.000	≥ 2.000	≥ 2.500
Water sensitivity*	water cond.	7d @ 18°C	14d @ 20°C	1h, vac.sat.	1h, vac.sat + 23 h @ 25°C	
	specification	≥ 55 %	≥ 70 %	≥ 70 %	> 50 %	≥ 2000***

UCS: Uniaxial Compression Strength (Duriez), EN 12697-12
ITS: Indirect tensile strength (EN 12697-23)
2PB: 2-pont-bending (EN 12697-26, method A
MS: Marshall stability (EN 12697-34)
ITSM: Indirect tensile stiffness (EN 12697-26, method C)
*Water sensitivity: remaining strength/stiffness [%]
** stiffness measured in monotonic indirect tensile test
*** stiffness after water conditioning
**** Class 1 (Class 2)

2.3.2. Comparative mix design study

In order to identify commons and differences within the various mix design strategies, the different parameters for specimen compaction and curing as well as for testing the specimens were applied within three participating laboratories. Four mix compositions were defined representing typical mix compositions applied in participating countries (compare Table 8).

With these mixtures, an experimental program was conducted in order to identify the effects of the variety of compaction, curing and testing parameters from the national specifications.

Table 8. Composition of CRM mixtures investigated.

Material		A Bitumen stabilised material (BSM)	B Bitumen-cement treated material CBTM	C GE-type: Cold recycled asphalt (CRA)	D Sealing cold recycled asphalt (CRA)
Cement dosage	%	1,5	3,0	0,0	1,5
Emulsion dosage (Residual bitumen)	%	3,3 (2,0)	3,3 (2,0)	5,8 (3,5)	5,8 (3,5)
Total water	%	4,5	4,5	4,5	4,5

Furthermore, complex stiffness was assessed for the four mixtures after applying one selected curing procedure (28 day @ 20 °C). The resulting stiffness versus temperature is shown in Figure 9 together with the stiffness measured from core specimens taken from a verification structure in Sweden (Rv95) and specimens compacted from the CRM material used for the demonstration road constructed in San Marino, compare section 2.5.

The following conclusions could be drawn from the assessment discussed within this report:

- Relevant effect of binder content
  - At moderate bitumen emulsion content (3.3%), high cement content (3%) results in higher strength
  - At moderate cement addition (1,5 %), high bitumen content (5.8%) will reduce the strength
- Compaction and curing of specimens
  - Procedure and energy affect void content and mechanical properties,
  - Compaction procedure is less important than curing procedure if void content is achieved,
  - Curing time, temperature and moisture strongly affects strength and stiffness of specimens,
  - Accelerated curing at higher temperature is possible when low cement contents are applied,
  - First days of curing (here: 2) predominates long-term performance for CRM with cement,
  - For laboratory-curing, moisture and temperature during site curing shall be considered, which vary by weather conditions and construction procedure (sealing of CRAB by surface layer),

- The compaction protocol and the mechanical tests carried out (geometry, stress, temperature) influence the mixtures performance properties. To reach comparable quality levels, a harmonisation is recommended between the various national mix design procedures,
- The nationally applied specification documents seem to specify the materials on a different quality level,
- Performance properties can be assessed:
    - The standard tests for assessment of complex stiffness (EN 12697-26) can be applied specimens, which were cored from CRM pavements as well as from laboratory-compacted specimens,
    - Stiffness modulus of CRM is considerably lower compared to hot-mix asphalt, especially at high temperatures when no cement is added to the mixtures,
    - Temperature-effect is reduced by adding cement,
    - Shear strength to assess non-linear strength can be assessed by triaxial testing.

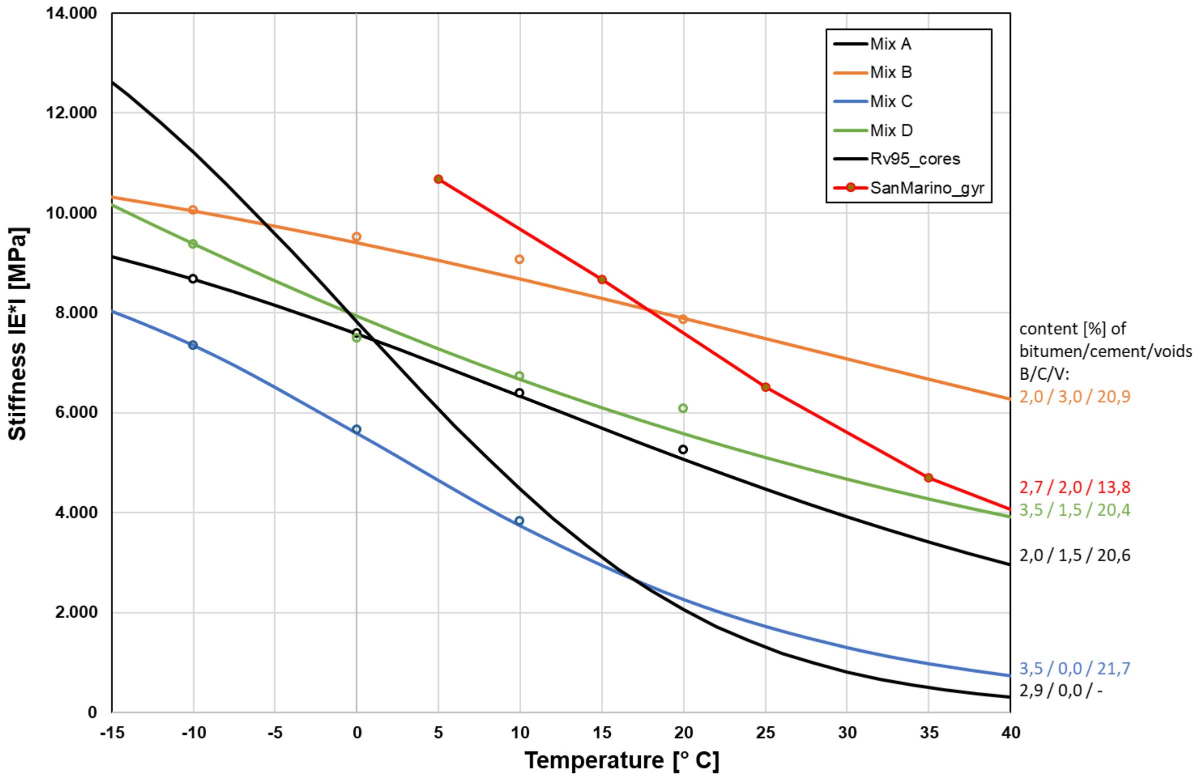

Figure 9. Stiffness modulus versus temperature for a frequency of 10 Hz of the assessed laboratory mixtures (A-D), as well as of long-term cured core specimens from a verification structure in Sweden and medium-term cured specimens compacted from the demonstration site CRM.

2.4. International pavement design procedures

Within the CRABforOERE-work package (WP 5) a comparison of the different national existing empirical and empiric-mechanistic pavement design procedures was made. By including results from the durability assessment of several existing pavement structures (compare section 2.1) the pavement design procedures were validated. From this synthesis, a proposal for design procedures for pavements including CRAB layer was drafted.

In a first step, the individual pavement design procedures from the participation countries were applied for four model pavements with specific subbase bearing capacity and traffic loading conditions. Here, besides the pavement designs for pavements with CRAB layers, also the designs with traditional HMA pavements are assessed. By comparing the differences of pavement structures between CRAB and HMA bases, the different levels of expectations in the CRAB were evaluated. The in-service durability and long-term performance of the assessed existing pavements with CRAB will be used for validating the identified design principles.

As a result, Figure 10 shows the resulting pavement structures according to the different pavement design procedures, for one of the model pavements. The structures vary considerably in total thickness. Regarding the difference between pavements with a bituminous base layer of CRM and HMA, it can be observed, that according to German empirical design, the asphalt layer thickness is increased for 45 % for high bearing capacity subground conditions and up to 100 % for low bearing capacity conditions. In Italy and UK the asphalt layer thickness is increased by 18 % to 37 % when CRM is applied instead of HMA as asphalt base layer. The resulting pavement designs indicate, that for traditional pavement materials, the various design strategies result in comparable structures. Obviously, the different calculation approaches were originally designed on a common basis.

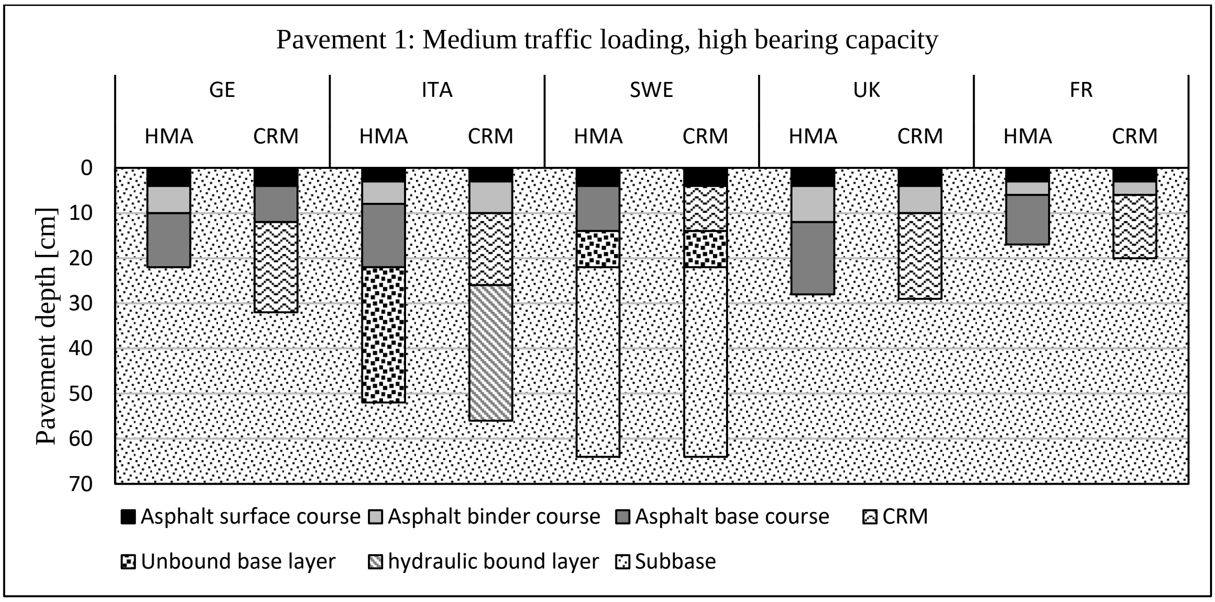

Figure 10. Resulting designs for model pavement 1 (medium traffic loads, high bearing capacity).

To further compare and validate the empirical pavement design procedures from Germany, Italy and UK, they were applied for designing the pavement structure of the existing 17 road sections, which were assessed before (compare section 2.1). This validation was split in three phases:

1. Comparative evaluation of the traffic loads;

2. Theoretically design of the pavement structures according to German, UK and Italian pavement design procedures;
3. Calculation of structural condition parameter and compare with actual surface condition.

The three applied empirical design procedures result in pavement structures which differ of the actually applied structural design. In general, the three pavement design procedures result in structural designs of higher layer thickness or lower layer thickness compared to the actual pavement structure, which therefore seems to be under-designed or over-designed, see Table 9. For most structures, the three design procedures result in the same estimation of under- or over-design, except for four structures.

Table 9. Bound layer thickness according to national standards.

Section	Actual thickness [cm]	Thickness according to national standards [cm]			Crack condition value: (mean 95%-quantile)
		GER	UK	IT	
B52	38	38	42	35	1,04
	Δ [cm]	0	4	-3	1,2
L52	40	28	28,5	21	1,0
	Δ [cm]	-12	-12	-19	1,0
L386	37	32	27,5	21	**1,36**
	Δ [cm]	-5	-10	-16	**3,45**
SP18	23	32	37	21	**2,74**
	Δ [cm]	9	14	-2	**4,5**
SS38	49	40	34,5	36	1,0
	Δ [cm]	-9	-15	-13	1,0
A14	59	38	44	35	1,18
	Δ [cm]	-21	-15	-24	1,73
SS268	31	36	35,5	30	1,0
	Δ [cm]	5	5	-1	1,0
A21	27	34	32	31	1,0
	Δ [cm]	7	5	4	1,0
A46	24	34	30	25	1,36
	Δ [cm]	10	6	1	1,82
A38	35,5	36	34	36	-
	Δ [cm]	+0,5	-1,5	+0,5	-
Rv95	14	40	33,5	31	**1,35**
	Δ [cm]	26	20	17	**2,75**
E45	26	40	33	31	**1,54**
	Δ [cm]	14	7	5	**2,79**
Green: actual thickness is higher compared to re-designed thickness Grey: actual thickness is the same (± 2 cm) as the re-designed thickness Red: actual thickness is lower than the re-designed thickness.					

Despite of differences in re-design thickness of up to 7 cm (section E45), the German and UK design procedure are capable to identify the same sections as under- or overdesigned. However, the pavements designed according to the UK specifications are generally thinner compared to the

German design thickness, with B52 as an exception. For the Italian re-design results, the thickness of all structures is lower compared to English or German designs. However, these CRAB structures are based on top of a cement stabilised layer, which gives higher bearing capacity. Generally, the same differences between the actual pavement structure thickness and the designed ones are identified also with the Italian method with the B52 as an exception. In three cases (SP18, SS268, A46) the difference between pavement thickness and re-designed thickness is lower than ± 2 cm. Four of the pavements (L52, L386, SS38, A14) seem to be over-designed according to all design procedures applied. Three of these structures are identified by a very low crack condition value and nearly show no crack damage at all. The exception for this conclusion is section L286, where cracking could be observed in some specific spots and which originally showed transversal cracking shortly after construction and which was maintained.

Within the validation process a theoretical structural performance parameter (SW_B) was calculated according to a German guideline document (FGSV, 2019) according to a structural number approach. Therefore, the required thickness (DIerf.) of the bound layers was calculated by considering the traffic loading and the bearing capacity of the unbound subbase. This thickness was compared to the “active” thickness (DIvorh.) of the assessed pavement structure, where the actual thicknesses of the structural layers are reduced according to the age of the layers. Afterwards, the theoretical structural life (t_{sl}) was calculated and was compared to the service life according to the different national standards (see Figure 11).

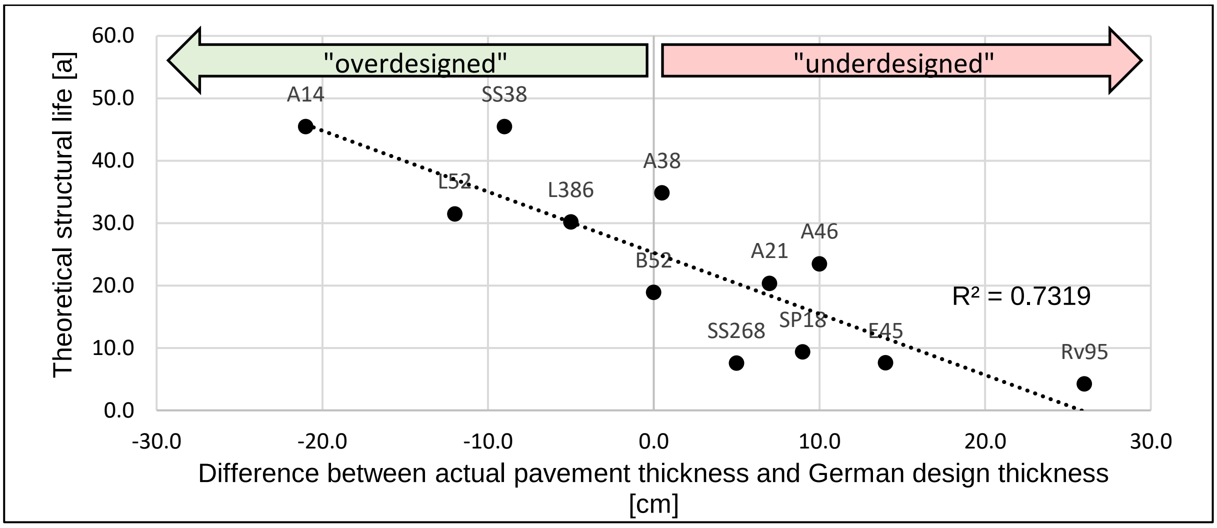

Figure 11. Effect of over- and under-design according to German design principles to the theoretical structural service life for the assessed CRAB pavements.

From the general assessment of the pavement design procedures for standard flexible pavements in Germany, Italy and UK (empirical) and France and Sweden (empiric-mechanistic), it could be learnt, that different approaches for considering traffic loads and subground bearing capacity are applied. However, all procedures seem to be based on similar principles, which indicate a common origin. However, the design procedures cannot be compared to each other directly.

Therefore, no common empirical design proposal can be given which would be applicable in all European countries. However, the comparison between the traditional HMA structures to CRAB structures give an indication for the expectation in cold recycled asphalt mixtures as base layer material. From these observations in the theoretical pavement design procedures, it can be concluded that CRAB base layers can be generally applied in flexible pavements instead of HMA base layers. Because of the usually reduced stiffness of these materials, the asphalt base layer thickness should be increased by a specific factor. When comparing the individual approaches, a factor of 1,5 seems to be feasible. If a subbase layer is added, e. g. by a cement stabilisation of existing granular material or by a lime stabilization of existing clayey subground, an asphalt layer thickness increase of 20 % is proposed (see Table 10).

Table 10. Applied and proposed thickness adjustment factors for the total asphalt layers for exchange of HMA base layer by a CRAB layer.

	SWE	FRA	UK	ITA	GER
According to Design guides	1,0	1,65	1,1 – 1,2	1,4 – 1,8	1,5 – 2,0
According to model pavements	1,0	1,2	1,0 – 1,4	1,2	1,5 – 2,0
Proposal	1,5 (1,2, when stabilised subbase is added)				

2.5. Demonstration structure

The objective of Work Package 6 (WP6) was to demonstrate the applicability of the cold recycling technique and to characterise the short-term development of the CRM layer properties, with particular attention to the influence of climate conditions on the curing process.

The CRABforOERE test section was built in the Republic of San Marino along a four-lane urban highway, characterised by an annual average daily traffic of 4000 veh/day, with 10 % of heavy vehicles. The works were part of the annual maintenance plan of the State-owned Enterprise for Public Works (AASLP).

The rehabilitated pavement structure included a 10 cm binder layer built using a CRM produced in a central plant and a 4 cm AC wearing course. In part of the test section (Subsection 1) a 15 cm cement-treated base made with recycled aggregates was also built, below the CRM layer. The thickness of the bound layers (29 cm) was comparable to those found for the mixtures investigated within WP2 and WP5 (Figure 12a). The CRM had a grading distribution close to the maximum density and was obtained by mixing 92% of RA aggregate, 4% of sand and 4% of filler. The dosage of bitumen emulsion was 4,5% (2,7% of residual bitumen), the dosage of cement was 2,0% and the total water content was 5,0%. The composition was comparable to those found for the mixtures investigated within WP2 and WP4 (Figure 12b).

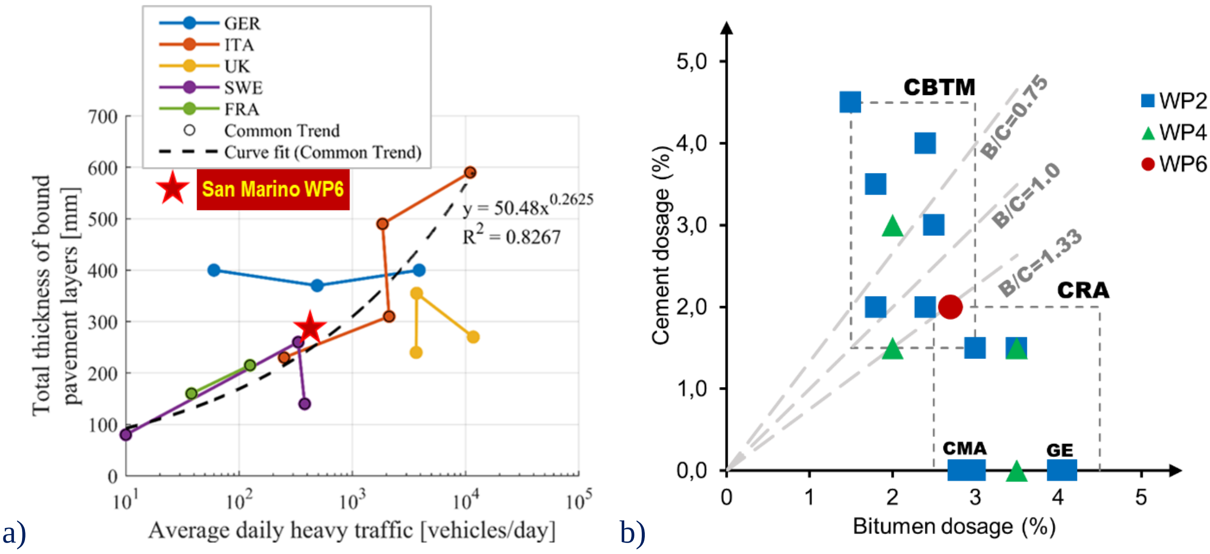

Figure 12. Characteristics of the demonstration structure a) structural design; b) mix design.

2.5.1. Construction and instrumentation

The demonstration structure was built in July 2020, starting with the milling of the existing distressed pavement. The CRM binder layer was enclosed within two bituminous membranes: the prime coat laid on the top of the underlying cement-treated base (Figure 13a) and the tack coat laid before the construction of the AC wearing course. The paving operations were carried out using the same equipment normally used for hot paving (Figure 13b).

During construction, six moisture and temperature sensors were installed within the CRM binder layer (Figure 13c) and connected to a data logger mounted at roadside (Figure 13d). The collected data are transmitted to a remote server from which they can be accessed using a web application.

Figure 13. Construction and instrumentation of the pavement: a) prime coat applied on the cement-treated base; b) laydown of the CRM layers; c) sensors installed at the centre of the traffic lane; d) data logger.

2.5.2. Laboratory and field testing

Figure 14a compares the evolution of the stiffness modulus of gyratory-compacted (GC) specimens and of cores extracted from the pavement after 22 days, both subjected to laboratory curing at 25 °C. The higher stiffness of the GC specimens is due to their lower voids (13,8 %) with respect to the cores (16,5 %). However, the stiffness evolution of the cores and GC specimens was similar. The plot also highlights the stiffness of the cores sampled after 305 days of field curing. Although the curing conditions were different, this value is comparable to that of the cores sampled after 22 days and cured in laboratory. This confirms that the curing temperature affects mainly the initial curing rate, whereas its effect on the long-term stiffness value is lower.

Figure 14b shows the effect of temperature on the FWD back-calculated modulus (E1) of the bituminous layers (40 mm of AC surfacing + 100 mm of CRM binder layer). As it can be observed, the values are compared to those measured in the laboratory at the frequency of 10 Hz on CRM specimens and AC cores. The temperature sensitivity of E1 sharply increased above 25 °C and was mainly due to the temperature sensitivity of the AC mixture. On the other hand, the temperature had a limited effect (less than 10%) on the E1 values measured between 15 °C and 25 °C.

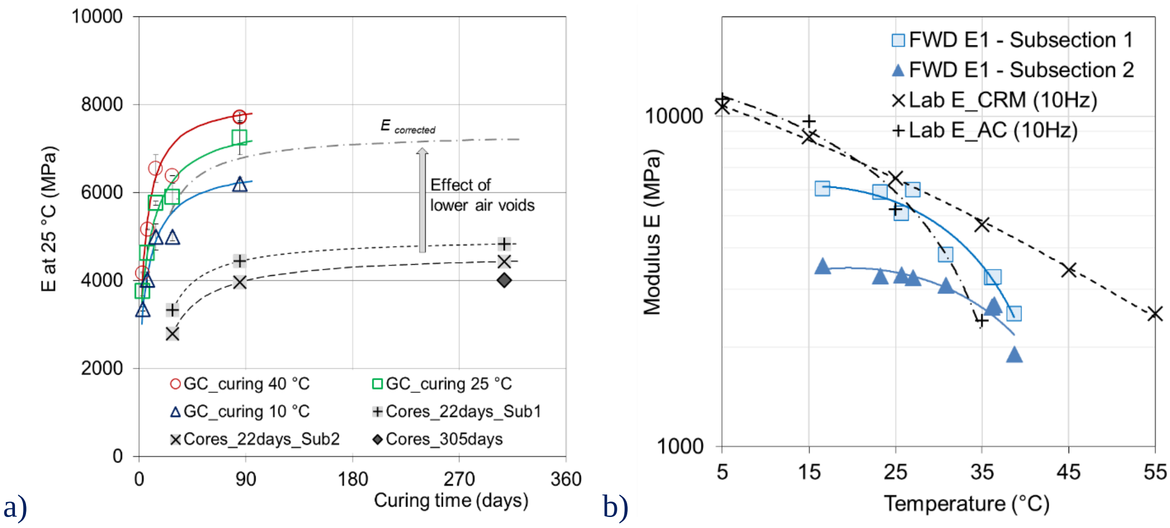

Figure 14. Results of laboratory field tests: a) stiffness evolution of CRM ; b) comparison between laboratory-measured stiffness of CRM and AC and back calculated stiffness of surface layer (AC+CRM).

2.5.3. Moisture and temperature monitoring

Figure 15a shows the temperature measured by the sensors in the first curing year (7th July 2020 - 7th July 2021). The air temperature was generally lower than those measured within the CRM binder layer, except for the winter months, from November 2020 to March 2021, when the two temperatures were practically the same. Wider daily excursions were measured during the summer months.

Figure 15b shows the trend of the gravimetric water content of the CRM layer calculated staring from the volumetric water content measured by the sensors and applying the maximum (2122 kg/m3) and the minimum (2081 kg/m3) bulk densities measured on the CRM cores. During the measurement year, the average GWC gradually increased from about 4,0% to about 4,5%. Such long-scale variation of the water content probably reflects the gradual transition towards equilibrium conditions with the moisture of the soil surrounding the pavement.

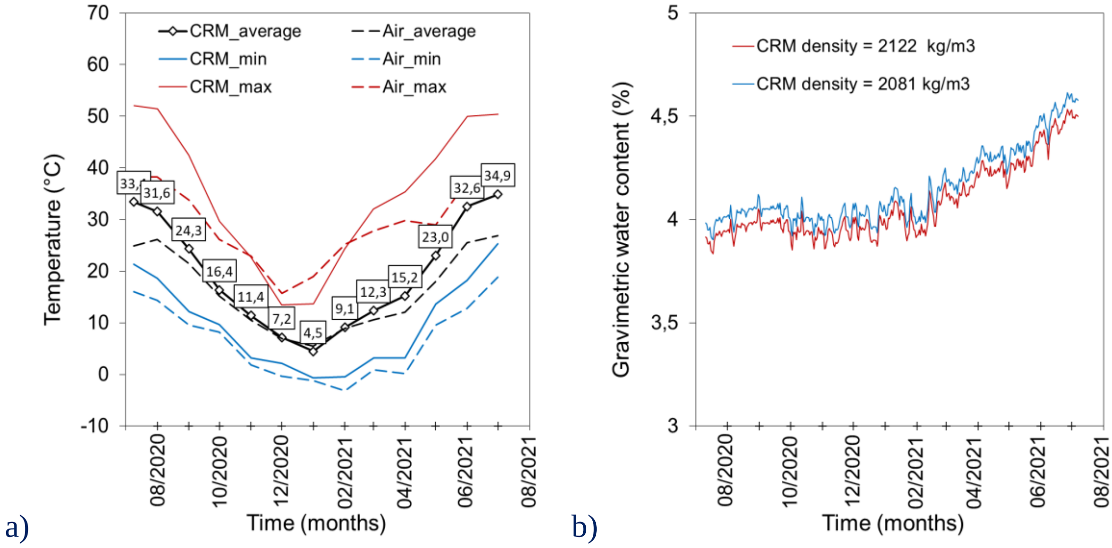

Figure 15. Results of field monitoring: a) Temperature ; b) Gravimetric water content.

2.5.4. Conclusions

The activities carried out within WP6 lead to following conclusions:

- The compaction energy required by the construction specifications (100 gyrations) overestimated the actual compaction energy applied in the field. Consequently, the cores extracted from the pavement had higher voids and lower stiffness with respect to the gyratory-compacted specimens. However, considering the difference in voids level, field and laboratory curing led to similar stiffness evolutions.
- At high temperatures (above 25 °C) the back-calculated modulus of the surface layer (AC wearing course + CRM binder) was temperature-dependent. However, at intermediate temperatures (15 – 25 °C), the temperature-related variation of the modulus was less than 10 % suggesting that, in such conditions, correcting the layer modulus to consider the temperature effect could not be necessary.
- Comparing the FWD measurements (in the same temperature range) performed 22 days and 371 days after construction, the stiffness of the surface layer had a limited increase (less than 10 %). This is because the high pavement temperatures during the first three weeks led to a sort of “accelerated” curing.
- The daily average temperature of the CRM layer ranged from 4,5 °C (January 2021) to 34,9 °C (August 2021). The daily maximum temperature exceeded 50 °C in the summer months (from June to August), whereas daily minimum fell slightly below 0 °C only in January and February 2021. These were almost optimal conditions for the development of the material properties.
- The water content of the CRM layer remained almost constant (about 4%) until March 2021, and then slightly increased. This behaviour can be explained considering that the upper and lower surfaces of the layer were sealed using bituminous coats and that, in the long-term, the moisture of the pavement must reach an equilibrium with the surrounding soil. These curing conditions could be simulated in the laboratory by sealing the specimens using, for examples, plastic bags.

- The pavement section was opened to regular traffic less than two days after the construction of the CRM layer and, after one year, it doesn't show any distress.

2.6. LCA

The aim of Work Package 7 of the Crab4Oere Project, is to evaluate the benefits of using cold recycled materials (CRM), produced at ambient temperature, rather than using hot recycling techniques, limiting the investigation to the production of the pavement materials/products (A1 – A3).

The study has been carried out on the basis of two case studies representative for two different production scenarios: in-plant recycling (Republic of San Marino) and in-situ recycling (Germany).

For each case study, results have been analysed in order to address which life-cycle stage between material supply, transport and manufacturing is the most impactful. Furthermore, a sensitivity analysis on the transport distances was undertaken assuming distances up to 200 km.

Finally, for each case study, the investigation also focused on the effect of using different CRAB mix designs by varying the range of cement, bitumen emulsion and water within typical ranges indicated within the other deliverables of the project.

The following "flowchart" provides a summary of the processes followed for the LCA study.

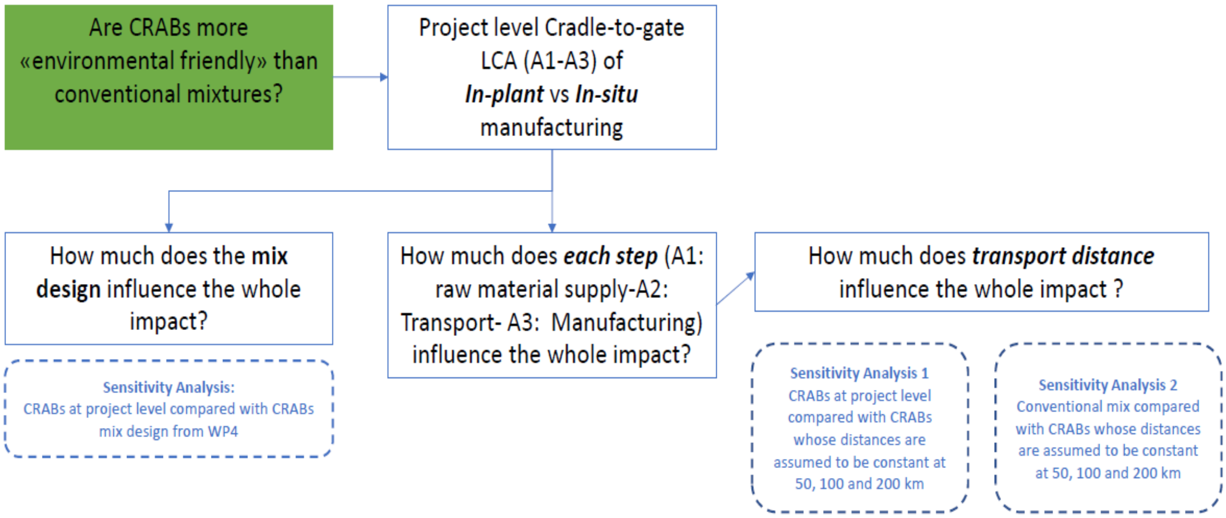

Figure 16: Flowchart indicating analysed LCA processes.

The data collection has been carried out with the support of the partners. Primary Data was used when available, secondary data was taken mostly from GaBi database. The LCIA methodology chosen was EF 2.0. The whole exercise was carried out according to the following reports, communications and frameworks:

- JRC (2016). Guide for interpreting life cycle assessment result, EU Joint Research Centre technical report.
- EN 15804:2012 + A1:2019. Sustainability of Construction works. Environmental Product Declarations. Core Rules for the product category of construction products.

- EN ISO 14040 (2006). Environmental management – Life Cycle Assessment – Principles and framework
- EN ISO 14044 (2006). Environmental management – Life Cycle Assessment – Requirements and guidelines
- PavementLCM. Guidelines, created within the project funded by CEDR.

Following results were identified within the LCA study:

- The research shows that regardless of the manufacturing process (A1-A3), the environmental impact of all investigated CRABs is at least 40% lower than a conventional HMA in almost all the impact categories, see Figure 17.
- CRAB materials seem to be more environmental friendly than HMA, both for in-situ recycling (base course) and in-plant recycling (binder course). In fact, all the impact categories, for both case studies with CRABs, have an environmental impact for the relevant indicators (climate change, acidification, eutrophication, photochemical ozone formation, resource and energy use) at least lower than 40% in relation to HMA. This can be explained by the following:
    - CRABs are produced at ambient temperatures, hence, their production needs less energy than a conventional HMA;
    - CRABs contain a much higher amount of RA, a component with 0% of embodied environmental impacts;
    - CRABs manufacturing requires lower amounts of materials to be transported at the manufacturing site, which in turns corresponds to a significant lower number of trips, hence an overall reduced impact of the transport phase (A2).
- The hotspot analysis showed that the most impactful stage is the acquisition of raw materials, in particular bitumen and cement, for CRAB (at least 80% of total emissions for both CRABs). Hence, in order to further reduce environmental impacts of this technology, CRAB material producers should focus on identifying materials whose extraction and/or supply is less impactful.
- Sensitivity analyses revealed that transport distances, related to material supply and CRAB manufacturing, do not play the same main role as they typically have with the environmental impact of conventional HMA.
- In general, appreciable emissions savings (at least 40%) can be observed for both case studies using CRABs. Hence, CRABs are less impactful than conventional HMA regardless of the manufacturing process and mix design formula.

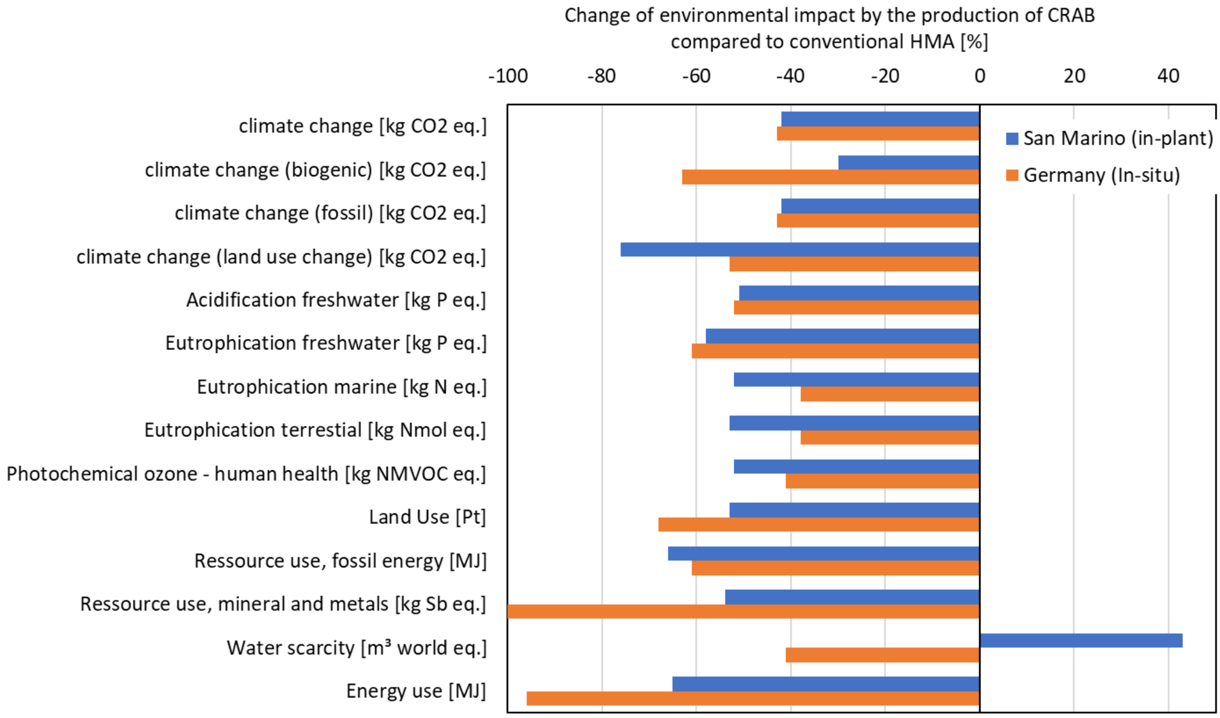

Figure 17. Change of environmental impact parameters by use of CRAB compared to conventional HMA as results from the case studies in San Marino and Germany.

3. Recommendations for the possible ways forward

3.1. Mix design and material properties of CRM for CRAB

From the research results reported in detail in deliverable reports D2 to D6, it could be concluded, that a seven-step approach is required for the mix design of CRM:

1. Sampling of RA
2. RA assessment
3. Grading of mix granulate
4. Compaction water content
5. Binder and binder content selection
6. Laboratory mixing, compaction and curing
7. Specifications on void content, strength (ITS), stiffness, water sensitivity

3.1.1. Sampling of RA

Due to the usually very high proportions of RA within the mix granulate of CRAB, special care is to be taken for sampling. According to international experience, the requirement regarding homogeneity is equal to what is usually experienced for RA use in HMA (hot recycling). Therefore, the sampling rules specified in EN 13108-9 (section 5.4 to 5.6) can be applied to RA for the use in CRAB in the same way.

When CRM is produced within a stationary asphalt mixing plant, reclaimed asphalt shall be pre-processed by crushing and sieving in order to obtain homogeneous stockpiles of RA. Usually, the required properties of the RA are measured periodically.

When CRM is to be produced from RA obtained from specific road sections with mobile mixing plants or by in-situ recycling, the assessed RA samples shall be representative for the entire road section. Here an intensive re-assessment of the road structures which will be milled is important to identify changing structural properties within the length but also width of the pavement, as these will also affect the composition of the resulting RA.

3.1.2. RA assessment

The RA aggregate to be used in CRM should be assessed following the same general scheme adopted for assessing natural aggregate as described, for example, in European standards like EN 13043 or EN 13242. The properties listed in Table 3 can be measured using the same testing procedures usually adopted for natural aggregates, except that drying should be carried out at lower temperature (e.g. 40°C) in order to avoid the softening of the aged bitumen. The acceptance ranges for natural aggregate adopted in each country appear to be applicable also to RA aggregate. Clearly the application type (foundation, base or binder course) must be considered.

For mix design of CRM, it is essential to determine at least the particle size distribution (black curve) and the water absorption on representative RA samples. The first is needed to correctly design the grading of the mix granulate, the second is needed to correctly evaluate the design water content of the mixture and the need for a water addition in the recipe. For the same reason, in the mixing phase of CRM, both in-plant and in-place, it is essential to constantly monitor the water content of the aggregate (RA and natural).

When only cationic bitumen emulsion is used as recycling agent, measuring the reactivity of the RA using the rise in pH test, will help in selecting the most appropriate emulsion formulation.

However, when cement is used, it will control the reactivity of the mix granulate and using an emulsion with high mixing stability (Class 10 breaking behaviour) is recommended.

The Fragmentation test can be used within in-place recycling projects as a quality-control tool to obtain a quick assessment of the aggregate stability and homogeneity during construction.

3.1.3. Grading of mix granulate

In all assessed specifications, the mix granulate shall meet a dense mix composition. As freshly milled reclaimed asphalt usually has low contents of fines (< 0,063 mm) and fine particles (< 2 mm), usually fine natural aggregate and/or fillers are added to the mixture in order to achieve a favourable gradation with a maximum grain size between 10 mm to 20 mm for based course mixtures.

3.1.4. Compaction water content

In general, the sequence of incorporation of the components and the mixing duration must reproduce the aspect intended by the mix designer. A study of the compatibility of the components must be carried out to enable the coating quality, the mix consistency and its cohesion have to be checked. This also makes it possible to set the optimum water content and to evaluate the formula sensitivity to avoid mix behavior that is too liquid or too dry. This laboratory approach is necessary but will require to be completed with the plant one to set the mix design.

For evaluating the added water content for the mix preparation, the moisture of aggregate and the bitumen emulsion water content are subtracted from the optimum water content

3.1.5. Binder and binder content selection

Cold mixes are characterized by their short-term evolutionary behaviour. Such a property is initiated from manufacturing stage by adding bitumen emulsion and – if required – additional binders or active fillers, like cement. This development, which depends on the mix design and the climatic conditions of the worksite, results in a more or less rapid increase in cohesion of the loose mixture. Workability depends on the friction contact of the mixture and on evolution of the cohesion within the mixture (aggregates, bitumen content, water content, emulsion/aggregate reactivity). Controlling the mixtures' workability is a major issue for transport, laying and compaction. The cohesion increase shall be initiated by compaction of the layer and additionally is supported by traffic loading. Depending on the target traffic and the type of mixture targeted in the pavement structure, the grade of the bitumen within the emulsion, the bitumen emulsion content as well as the addition of cement needs to be defined.

For pavements with moderate and high traffic loading, following binder contents are recommended:

- Cement: 1,5 %-2,5 %,
- bitumen/cement ratio: 1 – 1,5 (residual bitumen from a slow-breaking bitumen emulsion or foamed bitumen).

For pavements with low traffic loading also mix designs without any cement additions is applicable. However, in this case the compatibility between bitumen emulsion and mix granulate has to be carefully assessed in order to achieve the desired emulsion breaking process.

3.1.6. Laboratory mixing, compaction and curing

Various laboratory mixers were identified as suitable for producing CRM in laboratory scale.

The effect of the applied compaction procedure is lower compared to the effect of achieved void content. Therefore, the laboratory compaction shall result in similar compaction success as site compaction. Therefore, the applied compaction energy in most nationally applied laboratory compaction procedures shall be adjusted.

In situ curing depends on the regional climate of the pavement location and weather conditions. The structure of the roadway and road traffic also play a role in the mixture curing. It will change depending on the formulation and the specifics of the worksite. Therefore, a perfect simulation in the laboratory is illusory. However, a curing procedure integrating temperature, humidity and duration must be chosen at least by relying on the modulus values of the mix on site. Curing conditions (temperature, moisture) affect the evolution kinetics of strength and stiffness of the specimens. Until additional knowledge regarding the curing process is achieved, the laboratory curing procedure shall be similar to site conditions. In order to achieve some harmonisation, following procedures are proposed:

- for high temperature conditions (southern Europe): Curing at 40 °C for 3 days
- for low and intermediate temperature conditions (northern Europe): Curing at 20 °C for 28 days

The moisture during curing shall be selected according to the site and construction conditions:

- In case of a quick covering of the CRAB with seal or a surface or binder asphalt layer within 24 h, the curing shall be done in sealed conditions (e. g. in a plastic bag).
- In case of several-days drying of the CRAB layer without cover, the laboratory curing shall be conducted at unsealed specimens.

3.1.7. Specifications on void content, strength (ITS), stiffness, water sensitivity

Due to the wide varying compaction, curing and test parameters applied within existing mix design procedures, no commonly applicable specification values can be identified from the conducted studies. However, following strategy is recommended for the mix design of CRM:

Based on the selected mix granulate and cement content (see 3.1.3 and 3.1.5), the bitumen emulsion content shall be varied in at least three stages. After compaction, the void content shall be lower than 15 %. If this is not reached, the mix granulate composition needs adjustment. After curing, strength (e. g. indirect tensile strength according to EN 12697-23) and water sensitivity (EN 12697-12) shall be assessed. The applicable bitumen emulsion content shall be selected according to the resulting values.

3.2. Pavement design for flexible pavements with CRAB

The assessment of the existing CRAB pavements showed that observed surface conditions in CRAB pavements can be linked to their structural design properties (structural thickness, subbase layers) and service lifetime. In general, the pavement's performance was identified as suitable and no higher risk of premature failure compared to traditional asphalt pavements could be identified.

From the assessment, a pavement design "rule of thumb" could be derived, which would allow the application of national empirical pavement design procedures. Here, the HMA base layer can be changed to a CRAB layer by considering a higher layer thickness:

- $h_{CRAB} = 1{,}5 \cdot h_{HMA\ base}$, or
- $h_{CRAB} = 1{,}2 \cdot h_{HMA\ base}$, when a cement stabilization is applied below the CRAB.

Generally, mechanical-empirical design procedures can be applied for pavements including CRAB layers. For CRM complex modulus can be assessed according to EN 12697-26, which was proven for tests according to annexes C, D and F.

4. Conclusions

Compared to the usually applied hot-mix asphalt pavements, the use of cold recycled asphalt base layers (CRAB) in flexible pavements is less common in road construction. However, several European countries have a long experience in these materials, which are usually composed of high contents of reclaimed asphalt (> 75 %), bitumen emulsion and cement. The analysis of national specification documents as well as of existing pavements with CRAB identified a wide range of mix and pavement designs applied but also commons in the used design methods. The existing pavements with CRAB perform very similar to asphalt pavements composed of hot-mixed asphalt base layers even at high traffic loading. At the same time, the production of cold recycled materials (CRM) will result in a reduction of at least 40 % of environmental impact factors, including global warming potential (-42 % of CO_2-eq.), acidification of freshwater (-51 % of P-eq.), eutrophication of freshwater (-58 % of P-eq.) or fossil energy resources (-61 %). The assessment of 17 existing CRAB pavements allows the conclusion, that these benefits are not reduced by higher maintenance demands of the pavements, if feasible mix and pavement design principles are followed.

Especially the mix design procedures applied for optimising the properties of CRM needs some European harmonisation in order to facilitate their application. Regarding the pavement design rules, a simple and conservative "rule of thumb" was proposed, which will allow the application of CRAB layers in road construction and rehabilitation projects.

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