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Cold recycled asphalt for pavements with optimized resource and energy efficiency: proposal for harmonized mix and pavement design

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Abstract

The analysis of national specification documents on mix design for cold recycled materials (CRM) resulted in the proposal of a 7-step approach for optimizing the mixture composition. This procedure contains recommendations for sampling (1) and assessment (2) of reclaimed asphalt, design of the mix granulate grading (3) by adding fine natural aggregates, assessment of the water content (4), selection of bitumen emulsion and additional mineral binders (5), preparation of CRM mix and compaction and curing of specimens (6) and finally the prove of void content, strength and water sensitivity (7). For 17 existing flexible pavements with CRM base layers throughout Europe, a common pavement design strategy could be observed resulting in a durability similar to expectations on usual flexible pavements composed of hot-mix asphalt (HMA). A simplistic pavement design procedure is proposed.

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Keywords: Cold recycling; reclaimed asphalt; laboratorty compaction, curing and testing

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1. Introduction

Compared to the usually applied hot-mix asphalt (HMA) pavements, the use of cold recycled asphalt materials (CRM) in flexible pavements is less common in road construction. Because of high recycling rates as well as the mix production, laying and compaction at ambient temperature, CRM can be considered as energy efficient and environmentally friendly road material, if the pavements has a similar durability as conventional road structures. 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 (Mollenhauer et al. (2016), Godenzoni et al. (2016)). Recently, harmonized 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), which can encourage the application of these materials in countries with less experience in this field. However, CRM show systematically different material properties compared to conventional hot asphalt mixture especially in the short-term. For enabling the mixing, laying and compaction, a considerable amount of water is added to the mixture, which needs to be dried, drained and/or bond by mineral binders in order to achieve the required stiffness and strength properties in long-term (Graziani et al. (2018)). The in-situ development of the mechanical layer properties therefore highly depends on the actual weather conditions as well as the position of the CRM layer below and/or above other dense pavement layers. These conditions need to be considered during mix design and also pavement design.

Within collaborated research project “CRABforOERE”, funded by the Conference of European Road Directorates (CEDR), available mix and pavement design procedures were comparatively assessed in order to identify procedures which will help to introduce CRM into European pavement structures. Therefore, the mix and pavement design procedures of five European countries were analyzed for identifying common and different approaches and to validate these against local climatic and structural pavement conditions.

2. Existing CRM pavement structures and application of pavement design

In total 17 existing pavement structures with cold mix asphalt bases, most of which including recycled materials, were assessed regarding applied mix design, pavement structure and surface condition after several years of traffic loading. First, a high variability in mix design approaches for CRM applied in these countries in respect to content of bitumen emulsion, ranging between 2.5 % and 6.7 %, and addition of mineral binder, between 0 % and 4.5 %, could be identified. Generally, all structures showed a good pavement condition, however observed cracking could be related to low pavement thickness in one structure and shrinkage cracking due to high cement contents in another structure. Altogether, it could be found, that the applied thickness design is commonly dependent from the traffic loading similarly in the assessed countries. (Bjurström et al. 2020).

The pavement design identified within these CRM structures were verified against the empirical pavement design procedures applied usually for pavements with cold recycled asphalt base (CRAB) layers in Germany, Italy and the UK (Winter et al. 2020). Except of two German (in which tar-contaminated material was used as granulates) and one UK pavement (which was paved on top of a cement-stabilized layer), the applied CRAB pavements follow a similar overall design, in which the thickness of the asphalt layers (CRAB and HMA) depend from the traffic loading only. All assessed CRAB sections with traffic loading between some few (ten heavy vehicles) up to 11.000 heavy vehicles per day which were under traffic between 5 to 13 years of service didn't show substantial deterioration, except of two sections. In one German section, transversal cracking could be linked to shrinkage cracking due to high cement content in the CRM and one Italian section, which were actually designed as interim pavement structure, showed fatigue cracking. Using these data, Winter et al. (2021) could compare and validate the different approaches for pavement design applied in the five countries, ranging from empirical nomograph and catalogue solutions to empirical-mechanistic design procedures. From these assessments it could be concluded that the lower mechanical strength and stiffness of CRM layers compared to conventional HMA layers are usually compensated by applying higher pavement thickness, which vary with adjustment factors between 1.1 and 1.8, (see *Table 1*). From these results, a simplified pavement design procedure for the provisional application was proposed.

Table 1. Applied and proposed thickness adjustment factors for the total asphalt layers for exchange of HMA base layer by a CRAB layer.

Pavement design specification from country:	SWE	FRA	UK	ITA	GER
According to design guides	1,0	1,65	1,1 – 1,2	1,4 – 1,8	1,1 – 1,8
According to model pavements	1,0	1,2	1,0 – 1,4	1,2	1,1 – 1,8
Proposal for provisionally pavement design:	1,5 (1,2, when stabilized subbase is added)				

3. Methodology for proposal of harmonized mix design of CRM

The assessment of national specification documents for mix design, pavement design as well as the evaluation of the service conditions of the 17 existing road structures, which contain a CRM base layer, the wide range of mix designs regarding applied binder contents (bitumen and cement) could be confirmed, see also Table 2. The pavements applied in Sweden and France followed a cold mix asphalt "grave emulsion" principle with low or no addition of reclaimed asphalt (≤ 30 %) and without any mineral binder. In the structures evaluated in UK and Italy, moderate cement contents (1.5 – 2.0 %) and reclaimed asphalt (RA) contents of up to 90 % were applied in cold recycled asphalt mixtures (CRA). The mix designs applied in Germany could be characterized by cement-bitumen treated materials (CBTM) with cement contents of ≥ 2 % and high RA contents ≥ 90 %.

Table 2. Specified binder content ranges 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				

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 commonly applied test procedures for assessing the properties of natural aggregates according to EN 13043 or 13242 can be applied also for the assessment of RA. The tests procedures don't need any modification except for reducing the temperature for oven-drying to 40 °C.

In order to reach the specified grading curves, natural aggregates and filler (or eventually fly ash) is usually added to the RA granulates. According to most applications, the mix granulate follows a dense grading concept, which usually requires the addition of fine natural aggregates.

Based on these ranges of mix requirements, four CRM mixtures were defined for a comparability assessment of mix design procedures, see Table 3. Mixture A represents bitumen-stabilized material (BSM) usually applied in southern Europe, where the low cement content is added for controlling the emulsion breaking process, whereas mixture B can be defined as CBTM. Material C doesn’t contain any mineral binder and is used in France as “Grave Emulsion” (GE) and represents CRA which aims at similar long-term properties as conventional HMA. Mixture D represents a sealing cold recycled asphalt (SCRA) mix traditionally applied in western Europe for sealing tar-containing reclaimed road materials.

As all mixtures were composed using the same RA grading, they were mixed with a total water content of 4,5 %, containing the emulsion water as well as added water.

Table 3. Composition of assessed CRM materials.

Material		A BSM	B CBTM	C GE/CRA	D SCRA
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

A laboratory test program was applied on these mixtures to analyze the effect of the various compaction, curing and testing conditions applied according to the various mix design procedures applied on CRM. For compaction of test specimen, gyratory compaction (EN 12697-31) was applied, aiming at a target density, static compaction (EN 12697-56) with controlled compaction force and time and vibratory compaction with controlled time was applied. Whereas the specimens after gyratory compaction were unmoulded directly after compaction and before start of specimen curing, the specimens after static and vibratory compaction were kept 2 days in their moulds. In Table 4 the applied curing conditions, which were applied on mixtures A to D, are summerized.

Table 4. Summary of applied curing conditions.

Compaction procedure / curing time Curing temperature and humidity	Gyratory compaction (3 days, 28 days)	Static compaction (3 days, 28 days)	Vibratory compaction (3 days, 28 days)
20 °C, (70 ± 5) % RH (climate chamber)	A, B	B	
20 °C, (55 ± 15) % RH (room conditions)	A, B	B	A, B, C, D
40 °C, < 20 % RH (oven)	A, B	B	

After curing, the specimens bulk density was measured and the indirect tensile strength was tested according to EN 12697-23 with the test temperatures 5 °C (mixtures A and B) and 25 °C (all mixtures).

4. Results

4.1. Void content

The resulting void contents after compaction and curing of the specimens are plotted in Fig. 1. It can be observed, that the applied compaction procedures result in different levels of void content, where the gyratory specimens are better compacted compared to the applied static compaction and the vibratory compaction.

Further, an effect of curing temperature and duration can be observed. This can be explained partly by effects to the void structure during evaporation of the moisture or by cement hydration. However, curing conditions with long duration and high temperature will result in lower moisture content within the specimen which will reduce the bulk density of the specimen when assessed on moist specimen. Here, for the calculation of the void content, constant maximum density values were applied for each mixture sample, which were measured according to EN 12697-5 from one set of dry specimens, without considering the actual moisture content as well as possible change of mineral structure due to cement hydration. Unfortunately, the actual moisture of the specimens as well as individual maximum densities were not measured. This indicates, that some traditional test procedures have to be to extended for the application to cold recycled materials which contain a variable amount of moisture.

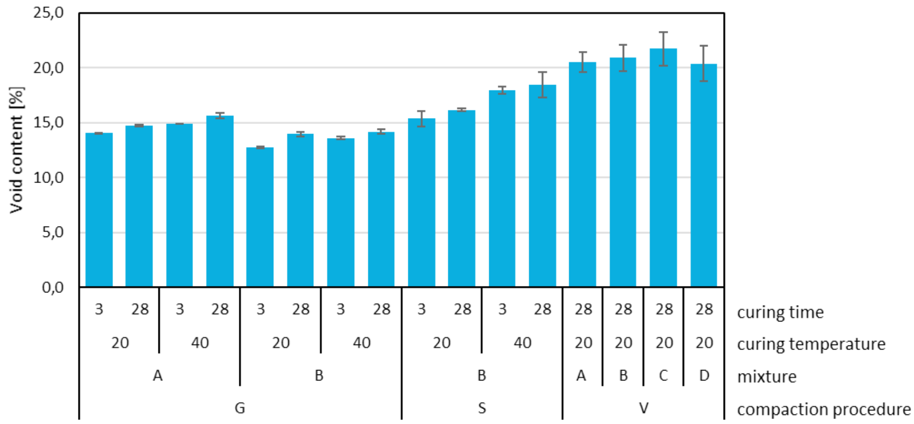

Fig. 1.Void contents of specimens after compaction and curing, calculated from measured bulk densities and calculated maximum densities of mixtures A to D according to their mix composition.

4.2. Indirect tensile strength

Most national specification documents contain maximum and some minimum requirements for the indirect tensile strength (ITS) of the compacted specimens during mix design. The various countries apply different test temperatures within these tests. The indirect tensile strength values obtained at 25 °C and 5 °C are shown in Fig. 2. All applied specimen preparation parameters affect the resulting ITS. With higher curing temperature and duration, higher ITS values are obtained. The higher the temperature and the longer the curing duration the more water is evaporated from the specimen, which results in an increase in strength.

The left diagram shows the ITS values obtained at 25 °C. When comparing the gyratory specimens (G), it can be observed, that the curing time affect the ITS of mix B stronger than the ITS of mix A. This can be linked to the higher cement content in mix B, where the short curing duration of 3 days won't result in the same hydration stage as curing 28 days. For the specimens obtained from static compaction (S), the temperature affect the strength less than the gyratory specimens. This is not linked to the compaction process itself, but to the fact, that the specimens were cured within their moulds for two days before demoulding and therefore are sealed and moisture cannot evaporate from the specimen. This explains the similar strength values obtained after 3 days of curing. When comparing the ITS of mixtures A to D after vibratory compaction it can be observed, that the high bitumen content in mix C will result in low ITS value. The addition of cement in mix D can again compensate this reduced ITS.

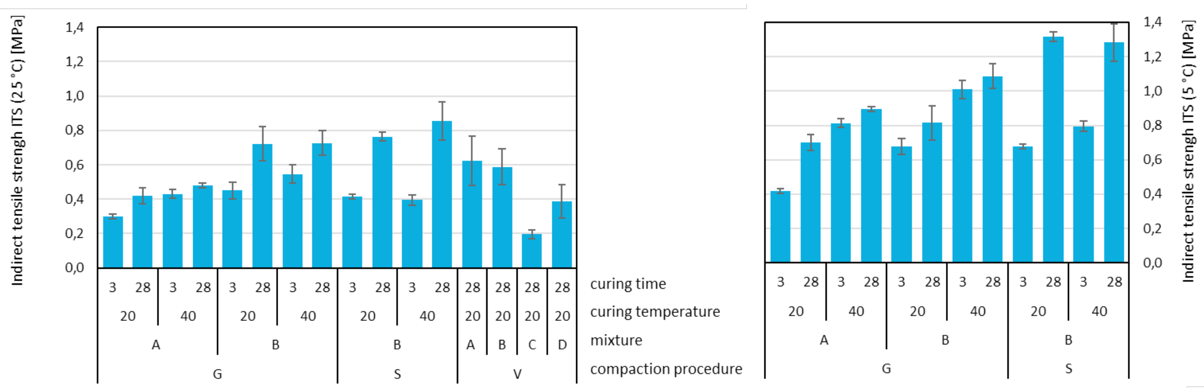

Fig. 2: Indirect tensile strengths, measured at 25 °C (left) and 5 °C (right) on specimens after varied compaction and curing conditions.

These curing effects are even more visible at the ITS values obtained at 5 °C. Obviously, the bitumen, which has a higher stiffness and strength at lower temperature, takes over a more distinct role for the overall material properties at the lower temperature compared to the temperature-independent cement bonds, which dominate the properties at 25 °C.

5. Conclusions for the implementation of design procedures for CRM

5.1. Conclusions from the laboratory mix design study

Following conclusions can be drawn from the results obtained in the laboratory assessment of varied CRM materials:

- The compaction procedure and applied compaction energy affect void content and mechanical properties.
- The compaction procedure is less important for the materials strength properties than applied curing conditions if similar void contents are achieved.
- The curing conditions time, temperature and moisture strongly affects strength and stiffness of CRM specimens.
- Accelerated curing at higher temperature is only possible when low cement contents are applied.
- First days of curing (here: 2) predominates long-term performance for CRM with cement.
- For selecting suitable 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 harmonization is recommended between the various national mix design procedures.

From these results as well as additional research obtained within CRABforOERE (CEDR, 2021) project and other studies, the following proposal for introduction of mix design and pavement design approaches for CRM layers in asphalt pavements are proposed.

5.2. Proposal for Mix and pavement design for CRM

5.2.1. Step 1: Sampling of RA

Due to the commonly very high proportions of RA within the mix granulate of CRAB, special care is to be taken for sampling. The requirements regarding homogeneity are equal to what is usually experienced for RA use in HMA (hot recycling). Therefore, the sampling rules specified in EN 13108-9 shall be applied to RA for the use in CRAB in the same way.

5.2.2. Step 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. 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 no cement or lime is used as secondary binder, 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.

5.2.3. Step 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), 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 and 20 mm for base course mixtures.

5.2.4. Step 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 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.

5.2.5. Step 5. Selection of type and content of binders

Cold mixes are characterized by their short-term evolutionary behavior. 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.

5.3. Step 6: Laboratory mixing, compaction and curing

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 harmonization, 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.

5.3.1. Step 7: Specifications on void content, strength (ITS), stiffness and 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 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.

5.3.2. Step 8: 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. 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.

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