Case studies & non-highway applications; Success and failure from real practice

Experiences from cold recycled materials used in asphalt bases: a comparison between five European countries

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Abstract

The application of reclaimed asphalt is becoming increasingly important in the European Road Network. The demand for more environmentally friendly methods to construct pavements is growing constantly. Most developed countries are seeking new ways to consume less energy and virgin materials and produce less CO2-emissions and less waste. Beside the conventional recycling options (i.e. hot asphalt mixtures), cold recycling is becoming more popular and have been successfully applied in numerous road structures. However, the guidelines on when and how cold recycling can and should be applied differ from country to country. Structural design and mix design are also different in the European countries. A comparison of the use of cold recycling in road construction indicates that some countries are ahead of others and that comparing methods and approaches could be beneficial for all. In this paper, experiences and results are compared from five European countries. Each country presents 2-4 road sections where cold recycled materials are included in the asphalt base layer and where test results are available. Structural design, mix design, traffic loads and test results are compared to assess the success each road and study what could be learned for future constructions.

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1. INTRODUCTION

The demand for better and more environmentally friendly materials is constantly increasing. More pressure is put on road administration and contractors to reduce energy consumption and CO_2-emissions in the transport system. One way to decrease the environmental impact from road constructions is to implement reclaimed asphalt (RA) when designing roads. Beside conventional recycling options (i.e. hot asphalt mixtures), cold recycling (CR) has shown to be a promising alternative for application in the different asphalt pavement layers [1,2]. Because cold recycled materials (CRM) can be mixed at ambient temperatures, CR has high potential to significantly lower the energy consumption. It also has the advantage of enabling remixing the RA with additional virgin bitumen at mobile asphalt plants which reduces the transports of the RA and thus reduces the CO_2-emissions. Additionally, using RA reduces the need for extraction of virgin materials and reduces waste. When using cold recycling, a large part of the input material, often up to 100%, constitutes of reclaimed material with less sensitivity to RA properties compared to conventional hot recycling [3,4].

Therefore, in several countries structures with cold recycled materials were built. In many cases, these structures were used as test roads, because of lacking experiences in these materials. The applied procedures vary considerably regarding applied methods of mix design, especially applied binder (bitumen and cement) content and structural design of pavements [5,6]. With introduction of EN-standard for asphalt concrete with bitumen emulsion (EN 13108-31), harmonized mix design procedures were introduced in 2019. Despite the formal instruments for wider application of these technologies are available, the lack of knowledge about these materials works against their practical application, especially because the mechanical properties of cold recycled materials vary from these of hot-mix asphalt. The objectives of this paper are: to compare the long-term performance of pavements constructed with CR base layers; to estimate their expected service lifetime and to identify best practices aimed at improving the confidence in these relatively new types of materials. In order to cover relevant European climatic conditions, road sections in Sweden, UK, Germany, France and Italy were selected.

This study summarizes the properties of the assessed structures regarding road type (traffic loading, climatic conditions), service lifetime, mix design of the CR layer and structural design considering the service performance of the roads. From these data estimates about the expected service lifetimes ss well as about best practices for the application of CRM will be derived.

2. STUDIED ROAD SECTIONS

For each mentioned country, 2-4 road sections were selected, where cold mix asphalt has been included in the base layer, most of them with reclaimed aggregates. The road section names, in which country they belong, and their construction year are presented Table 1. Traffic load data in the form of annual average daily traffic (AADT) and the number of heavy vehicles (>3.5 t) per day are also presented in the table. It can be noted that traffic data for two of the Italian roads have been reported as 80 kN equivalent single axle loads (ESALs), whereas no AADT has been reported for the French roads. Also, for the Swedish road section *Lexby*, no counting of vehicles has been performed but it is a small municipality road with very low traffic and almost no heavy lorries.

Table 1. Road section names and their construction years are presented along with their annual average daily traffic and the number of heavy vehicles (>3.5 t).

Country	Road name	Construction year	AADT	Heavy vehicles per day
Germany	B52	2009	26000	3900
	L52	2011	1500	60
	L386	2007	7000	490
Italy	SP18	2008	5000	250
	SS38	2007	30000	1850
	A14	2007	Note 1	Note 1
	SS286	2016	Note 2	Note 2
UK	A21	2002	47714	11700
	A46	2006	19192	3664
	A38	2004	37000	3700
Sweden	Rv95	2014	3136	380
	E45	2012	1233	333
	Lexby	2012	<1000	~0
France	RD26	2011	No data	25-50
	RD44	2008	No data	100-150

Note 1: $5.0 \cdot 10^6$ 80 kN ESALs per year [7]
Note 2: $0.85 \cdot 10^6$ 80 kN ESALs per year [8]

3. PAVEMENT DESIGN

3.1. Structural design

Comparing different design procedures between the participating countries in this study shows that there are three general approaches on how to design the pavements. Germany and Italy apply an empiric catalogue system where the pavement designer adds and subtracts thickness from the different layers depending on the traffic loading classes, subground bearing capacity and climatic conditions. In the UK, a nomogram system with fitted functions to identify the total asphalt thickness of the pavement is employed. Sweden and France both use mechanistic-empiric design methods where software is utilized to calculate the maximum strains a construction is exposed to when a certain structural design is chosen and comparing these strains to the maximum allowed.
European countries differ significantly regarding the use of CRM and the guidelines around it. The Italian design guide for northern Italy [9] include chapters about designing with CRM. German general design guide [10] does not include CRM although a helping guideline document does. The Swedish guidelines [11] do not give any specific details about using CRM but merely state that CRM may be applied if the quality of the mix can be considered the same, or higher, compared to conventional hot mix asphalt (HMA). In the UK, CRM may be applied in pavement design in two ways, either if the CRM is placed immediately above the foundation and covered by a bituminous surfacing, or by being applied as a substitute for conventional HMA for inlay treatments, where a significant proportion of the existing pavement remains to form a part of the rehabilitated pavement [12]. In France, grave emulsion is a standard road material [13], however prepared without the addition of reclaimed asphalt.

The structural design for the 14 studied road sections is illustrated graphically in Figure 1 together with the given layer thicknesses. The structural design is presented down to the cold recycled base layer. The road sections have different conditions regarding underlying unbound granular base layer and/or subbase layers but those are not presented in this paper.

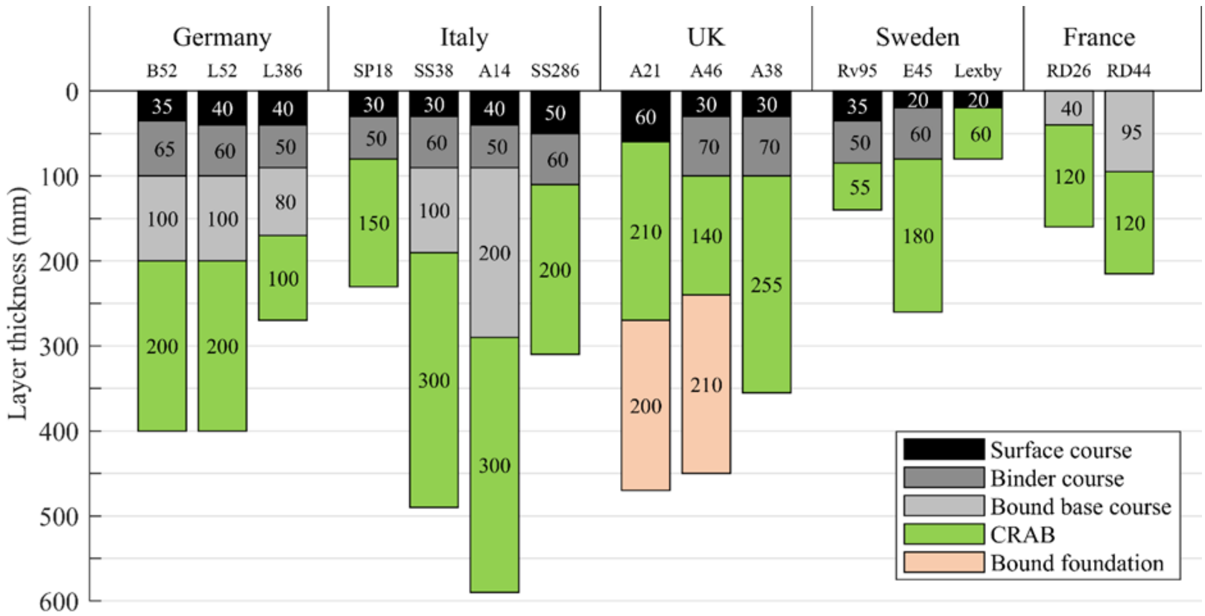

Figure 1. Layer thicknesses for the 14 studied road sections illustrated as a bar diagram.

It can be noted that the thinnest constructions are found in Sweden and France and the thickest in Italy, Germany and the UK. This partly reflects the traffic volumes but also the different design methods of the countries [14].

3.2. Mix design

The mix designs of the CR materials, which were applied in the studied road sections, differ greatly. Reclaimed material percentage, binder materials, binder content are all parameters that vary greatly among the identified road sections. Although the intention was to identify road sections where CR had been implemented, some of the included sections have no recycled material but are still studied in this paper as cold mix asphalt projects. On the other hand, both German and Italian road sections have 100 percent reclaimed aggregates. The percentage of the input stone material that contained of reclaimed asphalt is given in Table 2.

Table 2. Percent (by weight) of the input material in the asphalt base layer that is reclaimed material.

	Germany			Italy				UK			Sweden			France	
	B52	L52	L386	SP18	SS38	A14	SS286	A21	A46	A§(	Rv95	E45	Lexby	RD26	RD44
RA content (%)	100	100	90	20	34	50	100	-	73	88	30	0	30	0	0

No data on the RA percentage are given about the UK road section A21, that is because no mix design is available for this site.

It is shown that the particle size distribution of the ingoing materials is similar for most materials included in this study. In Sweden, one road section had a large stone skeleton with a high percentage (65%) of the ballast in the fraction 16-32 mm. The stone skeleton is created to carry the very heaviest vehicles, up to 90 t on that particular road. Besides the Swedish road, the two German road sections L52 and L386 and one of the Italian sections stand out by having a portion of larger aggregates, 10-11% of the material in the fraction 31.5-63 mm, included in the CRM. The particle size distributions for all road sections where the gradation curves were available are given Figure 2. The curves in Figure 2 are color coded so that each color is represented by one country.

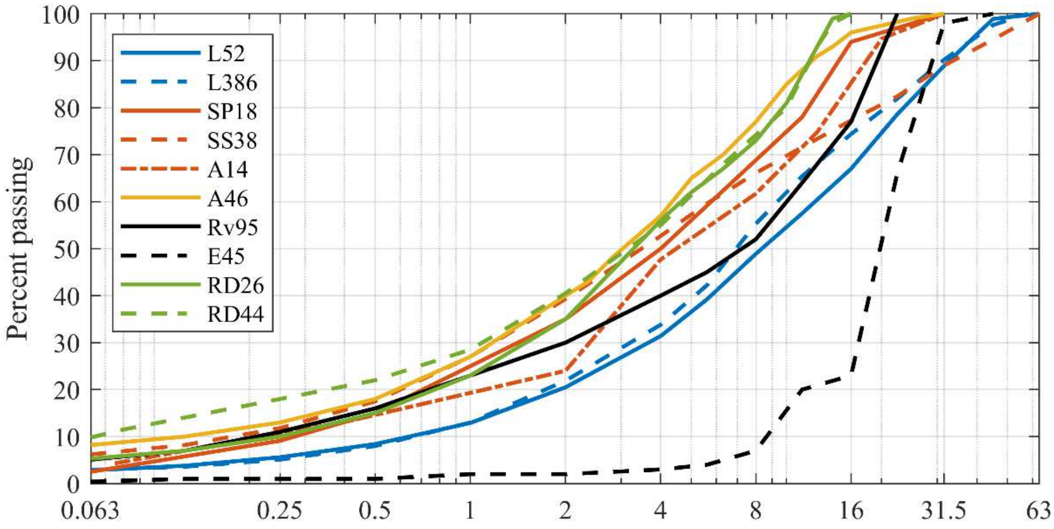

Figure 2. Particle size distributions for the recycled material layers.

In most road sections, cement is added to the CRM to stabilize the mix; however, in the Swedish and French roads no cement was added.

Bitumen emulsion was added to the mix for all studied road sections but the UK roads. For A21, no mix design was available and therefore no information can be given on that mix. On the UK road section A46, foamed bitumen was used with 3.5% of the mix by weight. Five percent fly ash was also included in this mix. For all other road sections, bitumen emulsion was included in the mix with proportions according to Table 3. Both the bitumen emulsion and the residual bitumen according to recipe are given in the table.

Table 3. Cement and bitumen content in the different mixes.

	Germany			Italy				UK			Sweden			France	
	B52	L52	L386	SP18	SS38	A14	SS286	A21	A46	A38	Rv95	E45	Lexby	RD26	RD44
Cement content (%)	4.0	4.5	3.5	2.0	2.0	2.0	2.0	-[3]	1.5[1]	1,5[1]	0	0	0	0	0
Bitumen emulsion content (%)	4.0	2.5	3.0	4.0	3.0	3.0	4.0	-[3]	-[2]	-[2]	4.8	4.2	4.8	7.0	6.7
Residual bitumen (%)	2.4	1.5	1.8	?	1.8	1.8	2.4	-[3]	3.5	3,0	4.6	2.8	3.0	4.0	4.1

[1] Five percent fly ash was also added to the A46 mix.
[2] The bitumen content specified for the UK road section A46 and A38 regards foamed bitumen.
[3] CRM with foamed bitumen, Mix design details unknown.

4. LONG-TERM PERFORMANCE OF CRM STRUCTURES

In this chapter, results regarding the studied road sections are presented. Different countries have different test methods and different procedures on when and where tests were executed. The presented results will thus vary from country to country. All presented results from the different test methods regard the CRM unless anything else is explained.

4.1. German road sections

From an optical survey, B52 shows no distress. No cracks nor excessive rutting or unevenness could be detected. In its early life, L52 suffered from transversal cracks on the surface. The reason for the cracks was believed to be a high cement content, causing shrinkage cracking after the surface layer was constructed. However, the layers above the CRM were exchanged above within the cracked zones and a new surface layer was paved. No new cracks have occurred. At L386, some minor cracks have been identified at intersections.
Elastic moduli have been calculated using falling weight deflectometer (FWD) data for different dates along individual sections of the studied German road B52. Note that the B52 road section is divided into three parts where the first and third parts were constructed using bitumen emulsion and the second part using foamed bitumen. B52 (2) and B52 (3) also had a 20 mm thinner asphalt base layer compared to B52 (1). During nine years f service, the central deflection shows a continuous decrease. The thicker section (1) shows the lowest deflection, whereas the section with foamed bitumen shows the highest.

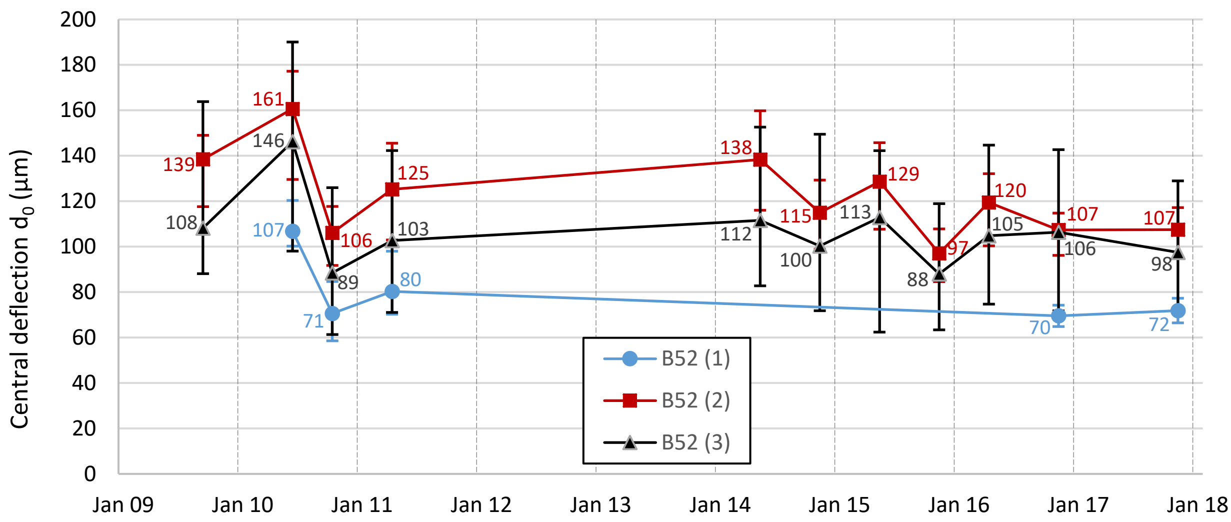

Figure 3. Central deflection in falling weight deflectometer measurements.

Indirect tensile strength (ITS) has also been determined on laboratory specimens after curing in 5 °C for 7 and 28 days for all German road sections and on core samples extracted in the field from the B52 and L52 roads. The ITS values are presented in Table 4. It can be noted that the evaluated average ITS values from the cores were higher than the corresponding values from the laboratory specimens from laboratory specimens for all examined road sections.

Table 4. Indirect tensile strength (ITS) evaluated on laboratory specimens and core samples.

	B52 (1)	B52 (2)	B52 (3)	L52	L386
ITS lab. specimen – 7 days (MPa)	0.66	0.50	0.66	0.54	0.67
ITS lab. specimen – 28 days (MPa)	0.93	0.85	0.93	0.75	1.13
ITS from cores – mean value (MPa)	1.08	0.99	1.21	1.38	-

4.2. Italian road sections

No distress has been reported on the Italian road sections. Different tests have been performed on the mixes and the roads. Indirect tensile stiffness modulus (ITSM) and/or ITS have been determined on laboratory specimens and core samples from three of the four roads. The obtained results from these measurements are presented in Table 5 together with the curing conditions and temperatures when the measurements were performed.

Table 5. ITS and ITSM results from laboratory specimens and core samples from three Italian roads.

		SP18	A14	SS286
Laboratory	ITS (MPa)			0.40
	Curing cond.			3 days @ 40 °C
	ITSM (MPa)	4479	4245	3242
	Curing cond.	3 days @ 40 °C	28 days @ 25 °C	3 days @ 40 °C
Core samples	ITS (MPa)			0.71
	ITSM (MPa)	4592 @ 20 °C		

For the SS38 the stiffness moduli have been back-calculated from FWD data yearly, for eight years after construction. The back-calculated moduli have been shifted to represent the stiffness at a reference temperature of 20 °C. The results are presented in Figure 4 where the modulus can be seen to increase during the first six years to then decrease again. In the short and medium term, stiffening due to the curing process and the aging of the emulsion residual binder is clearly visible. In the long term, the damage due to traffic loading and environmental effects prevails, leading to the stiffness decrease.

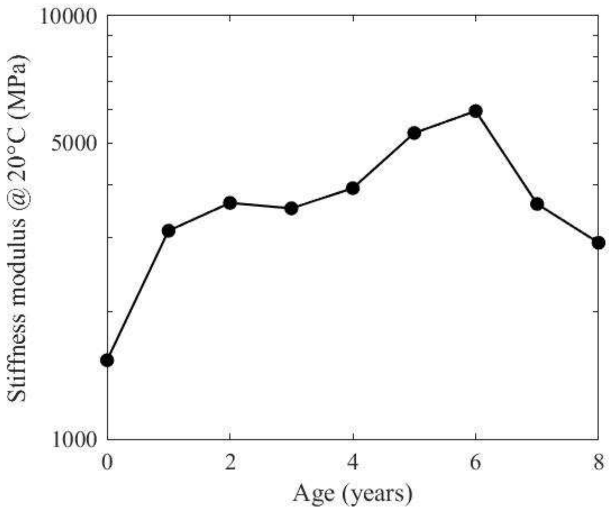

Figure 4. Stiffness modulus development eight years after construction calculated from FWD data.

Additional testing on the A14 road section was made through ITSM measurement on laboratory specimens up to four weeks after construction. The ITSM increased almost linearly when it was measured after 7, 14, 21 and 28 days. The specimens were cured at 25 °C and the ITSM measured at 20 °C showing results of 2600, 3429, 3688 and 4245 MPa, respectively.
Finally, stiffness moduli for the CRM of the SS286 road section were measured before laydown of the surface layer using FWD and on cores extracted on the same day. The modulus back-calculated from FWD, translated to 20 °C and 10 Hz was 6358 MPa at. The modulus measured in the laboratory on the extracted cores, at the same temperature and frequency, was higher probably because of scale effects (the FWD measurement involve large portions of pavements and thus may include micro or macro defects).
More detailed information about the Italian road sections SP18, SS38, A14 and SS286 are given in [2], [15], [7] and [8], respectively.

4.3. UK road sections

The UK results consist of various examinations performed on the two test road sections. On the A46, cores were extracted during April 2019 in order to determine the ITSM of the CRM. Twelve cores (six couples) were extracted. Unfortunately, one of the core samples was too damaged to test when it arrived at the laboratory. The evaluated stiffnesses from the cores are given in Table 6. The core with the ID "A46_06" had a lower stiffness modulus compared to the other cores. However, the sample appeared to miss the CR layer and reminded of a conventional HMA. Each core with a diameter of 150 mm was tested twice over two different diameters where the mean value is given as one test result for each core sample in Table 6.

Table 6. Indirect tensile stiffness modulus measurements on the UK road section A46.

Core ID	Location (m)	ITSM #1 (MPa)	ITSM #2 (MPa)	ITSM overall mean (MPa)
A46_01	+875	6 697	6 479	6 588
A46_02	+925	5 399	5 347	5 373
A46_03	+975	5 102	5 197	5 150
A46_04	+1500	Sample too damaged to test		
A46_05	+1580	5 267	4 895	5 081
A46_06	+1660	3 736	3 625	3 681

Regarding the A21 road section, no coring has been performed since no distress has been identified. However, with more than 47 000 daily vehicles and no visible distress, the road is in good general condition. During a traffic speed survey performed in September 2018, rut depth was measured along a number of road sections of different lengths, and the results are given in Figure 5.

The plots show that the rut depths are below the threshold values for road category 2 (11 mm) for the northbound lane (Figure 5a) and road category 1 (6 mm) for the southbound lane (Figure 5b) [14].

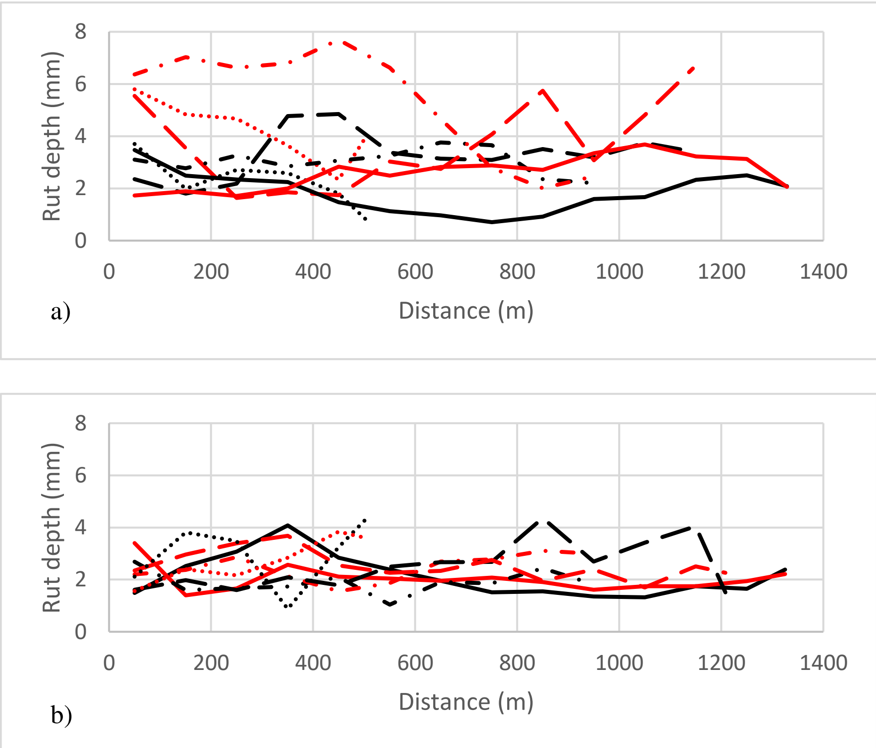

Figure 5. Rut depth on a) northbound and b) southbound lanes on the UK road section on A21. Black lines represent left wheel track while the red lines represent the right wheel track.

4.4. Swedish road sections

Stiffness moduli measured on core samples from the Lexby road show values of 1886, 1378 and 586 MPa at 5, 10 and 20 °C, respectively. These figures can be compared to test results from a conventional base layer material without CRM, where corresponding moduli were 3057, 1542 and 736 MPa.

Falling weight deflectometer data from Rv95 clearly indicate a weaker construction where the CRM is applied compared to a conventional construction using HMA. On this road, a reference section was constructed close to the test section. The structural designs were identical except for the bitumen bound base layer. In Figure 6, the deflection basins from FWD tests performed two successive years at different temperatures on these two road sections clearly indicate a weaker construction where CRM was included in the base layer. The absolute deflections indicate a weaker subground below the conventional construction compared to the CR test section (larger absolute deflections). However, the large deflection difference between 0 and 1200 m in the CR test section implies a weaker construction. This is the case both in 2015 and 62016, indicating a stronger superstructure for the conventional construction compared to the CRM.

On the other hand, core samples were extracted and moduli measured during the autumn of 2015. The moduli of the base layers consisting of conventional HMA and CRM were tested to 5906 and 5965 MPa, respectively. The CR can thus be concluded to give comparable results to conventional HMA.
Regarding the E45 road section, cores were extracted in order to perform tests on them. However, the stability in the large stone mastic was so poor that no tests could be made.
The Swedish road sections Rv95, E45 and Lexby are described more in detail in [17,18,19], [17,20,21] and [17,22], respectively.

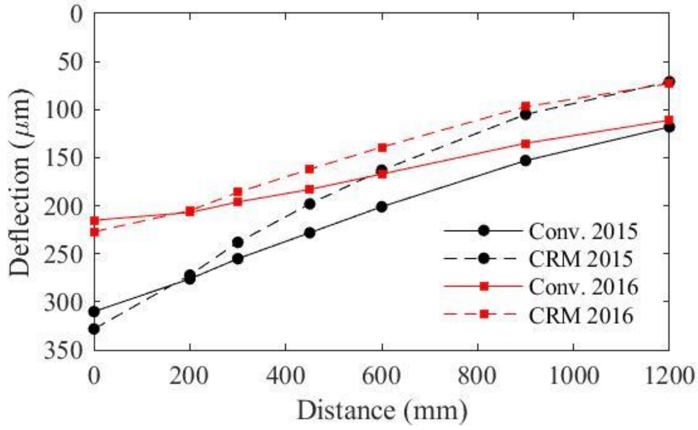

Figure 6. Deflection basins from two successive years, showing both the tested CRM construction and a conventional reference construction.

4.5. French road sections

A visual inspection from RD26 showed no distress in 2016. An inspection of the RD44 made 2018 showed a few visible cracks. Three test methods have been applied on the CRM to determine stiffness moduli on the French roads RD26 and RD44: indirect tensile strength modulus (ITSM), two point bending test (2PBT) and direct traction test. Results from these tests are given for RD26 and RD44 in Table 7 and Table 8, respectively.

Table 7. Moduli for the French road section RD26 determined through three different test methods. All moduli are given in MPa.

	ITSM (MPa)	2PBT (MPa)	Direct Traction (MPa)
11 months	1500		1400
16 months	2050		1250
20 months	3250		2000
25 months	3000		
35 months	3050	2450	

Table 8. Moduli for the French road section RD44 determined through three different test methods. All moduli are given in MPa.

	ITSM (MPa)	2PBT (MPa)	Direct Traction (MPa)
5 months	3250		
14 months	3080	1964/2495	2028
24 months	3990	2656/3800	2799
31 months	3840	2528/3500	3065

5. DISCUSSION

In total 14 road structures in five countries containing cold recycled base layers were assessed for this study. These structures differ considerably regarding traffic loading and location (climatic conditions) as well as regarding the applied design approaches.

In Figure 7, the total thickness of bound layers within the assessed sections are plotted versus the average daily traffic. The structures can be separated into two groups. The sections in Sweden, France and Italy show the same systematic thickness increase with increased traffic loads, except of one structure from Sweden (Rv95). On the other hand, the sections of Germany and UK are paved in similar thickness, where the traffic doesn't significantly affect the chosen thickness of bound layers. Regarding the mix design for the CRM layers, UK and German sections show a considerably higher content of cement or other hydraulic binders within the mix. This results in higher stiffness of the CRM layer which can be an explanation for the differing pavement design approach compared to the other sections, in which the cement content varies between 0 and 2 %.

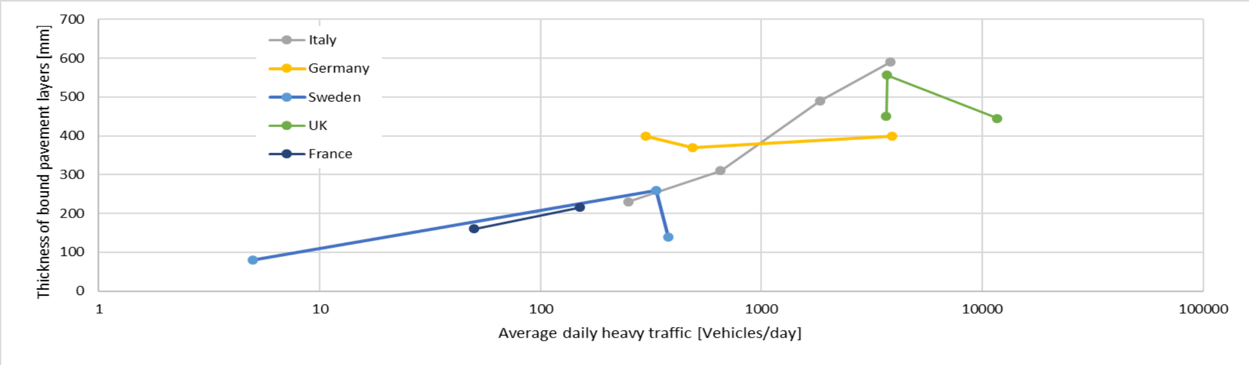

Figure 7. Total thickness of all bound layers plotted against amounts of heavy traffic for each of the studied road sections.

Regarding the long-term-performance of the assessed structures, most of them doesn't show any distress of surface properties after trafficking of between 2 and 17 years. One section (German L52) showed transversal cracks shortly after construction. These were interpreted as shrinkage cracks which can be explained by comparably high cement content applied. However, after rehabilitation of the cracked regions down to the CRM layer as well as the laying of a new surface course, no considerable distress is visible for 8 years.

The similarity of pavement design as well as the general identified success of the structures identify, that the applied methods for pavement design seems to result in durable structures.

Regarding mix design, the assessed CRM layers show a large variety in terms of proportion of reclaimed asphalt materials within the mixture. Whereas in Sweden and France the bitumen emulsion base layers were prepared without the addition of reclaimed asphalt, the RA content reaches 100 % for some German and Italian structures. On the other hand, the applied (residual) bitumen content in Sweden and France is higher compared to the other countries. One explanation can be that the bitumen of the RA allows the reduction of adding new binder because of already existing covering of the aggregates. However, in Germany, Italy and UK, cement is added to the mix as an active filler helping for the mixing of the material with bitumen emulsion or as an additional rigid binder. At higher cement contents this results in stiffness values which are higher than usual asphalt mixtures (compare Table 6) or which even result in shrinkage cracking (German L52). However, the lack of mineral binder within the mixture may result in lower bearing capacity compared to conventional hot-mix asphalt structures, as indicated by the section Rv95 (Sweden).

Nevertheless, CRM layers show an increasing stiffness during service life, as shown by stiffness values obtained in French structures (Table 7 and 8) as well as by decreasing deflections in FWD measurements in German and Italian structures (Figures 3 and 4). This further remakes the importance of the curing process and thus the difference between short-term and long term-properties must be always addressed for CRM.

6. CONCLUSIONS

In order to identify the expected service lifetime of road structures with base layers composed of cold-recycled materials, fourteen road sections from five European countries have been studied for this paper. Cold paving methods have been applied for the bitumen bound base layers in all these projects. In 11 of the 14 project, reclaimed asphalt has also been included as aggregates.

The mix design differs significantly among the studied objects. While Germany and Italy have constructed roads with 100 percent RA in the base layer, both France and Sweden have no, or a low percentage, RA in theirs. Germany, Italy and the UK also use cement in their CR layer. Sweden and France do not add any cement in their mixes but apply higher bitumen contents on the other hand. The higher content in cement resulted in early-life shrinkage cracking in one of the structures, which could be maintained successfully without rehabilitation.

Despite the varied mix designs of the structures, the pavements show very similar design approaches regarding total thickness versus traffic loading. Here, the structures with CRM layers again can be divided into a group with high cement content and one with low or without any cement. The generally good condition of the roads show, that the applied design approaches resulted in successful pavement structures.

Therefore, suitable mix and pavement design procedures can be applied in different European climatic regions to pave road structures by cold recycled materials without disadvantages in service lifetime and therefore in road maintenance needs.

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