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Design of flexible pavements with cold recycled asphalt bases: Comparison of five national approaches

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Abstract

The Application of reclaimed asphalt is becoming increasingly important in the European Road Network. Beside the conventional recycling options (i. e. hot asphalt mixtures), cold recycling has been successfully applied in numerous road structures within the secondary and the main road network. However, the standard design procedures for common pavement materials as well as the approaches for cold recycling differ from one country to another. The comparison of five national pavement design procedures shows, that different design approaches may result in similar pavement structures for standard road materials (here: hot asphalt mixtures). The available specifications for pavement design with cold recycled materials indicate generally a surplus of thickness compared to standard structures. This varying surplus in thickness indicates different safety conditions applied in the analysed countries. In order to validate the existing pavement design procedures for cold recycling materials, two options will be followed. On the one hand mechanistic pavement design is applied which allows the calculation of required layer thicknesses. On the other hand, pavement design based on empirical values can be used.

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1. Introduction

Because the European Road Network is almost complete, the maintenance of the existing roads will cover an increasing rate of the future investments into road infrastructure. The vast majority of the roads are constructed with asphalt pavements, where the usual maintenance procedure is the removal of the entire asphalt structure or the upper layer(s) from it and the paving of new asphalt mixture on the remaining structure. As a consequence, the increasing age of the road network results in increasing amounts of reclaimed asphalt (RA).

Cold recycling (CR) of RA is a procedure, by which high recycling rates of usually ≥ 75 % are reached with less sensitivity regarding RA properties (Mollenhauer & Simnofske, 2015) compared to other recycling options (i. e. in hot asphalt mixtures). CR has been successfully applied in numerous road structures within the secondary (Bocci et al. 2014) and the primary road network. Because the mixture is produced at ambient temperature, the main energy demanding process for asphalt production – the heating and drying of aggregates – is reduced significantly.

Despite the available practical experience with cold recycled materials (CRM), the failure modes are not yet fully understood. This can partly be explained by the frequent application within the secondary road network with comparably low traffic volume as well as with low expertise and need in maintenance and durability assessment. The mechanical properties of CRM are well-researched in laboratory-based projects. As a result, usually lower stiffness and strength properties are assessed compared to hot asphalt mixtures (HMA). Therefore, available pavement design procedures based on fatigue failure criteria usually applied on hot asphalt mixtures result in thick required base layers and therefore are not practically applicable (Radenberg et al. 2015) and don't comply with the practical experience made with these pavement materials. Therefore, the practically applied pavement design procedures vary considerably and range between the same thickness estimations as for hot bituminous materials (e. g. in Switzerland) to thickness-increase factors of e. g. 50 % (Bocci et al. 2010) compared to standard hot asphalt mixtures.

One reason for these caution-driven design estimations lies within the time-dependent change of material strength during curing which results in increasing bearing capacity of Cold Recycled Asphalt Bases (CRAB) structures over months or even years (Serfass, 2010, Godenzoni et al 2018). International experiences show applicability of CRM even in highly-trafficked highway structures (Wirtgen 2015). For these pavement designs the failure criteria applied within pavement design are permanent deformation, shear strength and fatigue cracking (Asphalt Academy 2009, Liebenberg and Visser, 2004).

As the mechanical design approaches are not yet fully accepted and failure modes for cold recycled materials are not implemented within the procedures, existing empirical pavement design methodologies in several countries were compared. As already the standard design procedures applied for conventional pavement materials (especially HMA), vary considerably from one country to another these approaches are compared in a first step. Afterwards, special approaches for cold recycled materials are introduced. For comparing the design procedures both for pavements with base layers from HMA and CRM, empirical and mechanical pavement designs from five selected European countries covering the range of climatic conditions within Europe are applied for eight common model pavements with varied traffic and subground conditions. From these results the expectations on CRM in comparison to HMA are assessed.

2. Empirical pavement design procedures

2.1. Applied national pavement design specifications

The pavement design procedures applied within Europe differ considerably. In order to compare the structural design of CRAB as applied in various countries, firstly the commons of the design approaches are discussed. The designs applied for standard asphalt base layers, as well as unbound base and cement stabilised base layers are used as reference for comparison of the structures with CRAB layers.

Current pavement design guidance in UK is regulated by Highway Agency's (HA) Design Manual for Roads and Bridges (Highways Agency, 2006), (Highways Agency, 2006) (Highways Agency, 2004). It provides the procedure of standard design methods in detail (Thom, 2008).

Regulations from the Swedish Transport Administration are specified in the TRVK Väg (Trafikverket, 2011) and state that pavement design should be made by limiting horizontal strain at the bottom surface of the bottom bound bitumen layer and vertical strain at the top surface of the subground. Additional requirements regarding minimum thicknesses for the different layers must also be fulfilled.

In Italy, the only official reference document available on pavement design is a pavement catalogue, "*CATALOGO DELLE PAVIMENTAZIONI STRADALI*", published in 1994 by the National Research Council (CNR) (Consiglio Nazionale Delle Ricerche, 1995). The catalogue was developed using the design method described in the "AASHTO Guide for Design of Pavement Structures". Besides the CNR catalogue, a draft specification document for cold recycled materials , which also considers the different climate conditions in Northern Italy, is applied (Provincia Autonoma di Bolzana - Alto Adige, 2016).

In Germany, the pavement design procedure is specified in RStO 2012 (FGSV, 2012). The procedure considers the mechanical properties of applied road materials, which themselves are specified in mix design standards, as well as environmental conditions. The specifications for pavement design considering CRM are given in M KRC (FGSV, 2005).

The French pavement design method for road pavements is described in the French standard NF-P 98-086 (2011), which describes the application of a multi-layer elastic pavement model for pavement calculations. Primarily the calculated stresses and strains in the pavement layers are compared with acceptable values, which are mainly function of the number of ESALS and pavement layer properties.

2.2. General pavement structures

Within Europe almost each country has different approaches for pavement design procedure. However, despite varying tools for considering traffic loading and subground conditions, the general pavement designs are similar with increasing stiffness, bearing capacity and resistance against cracking and/or permanent deformation from the bottom to the top of the pavement. Table 1 shows the general pavement structures and applied technical terms from the four selected European countries covering the range of climatic conditions within Europe.

On top of the existing subgrade of low bearing capacity (e. g. clay), a first subbase layer (1) is constructed either by applying a granular base layer or hydraulically bound layer, later often mixed in place. The subbase layer (2) is applied in order to provide increasing bearing capacity as well as to allow for frost-resistant and water-draining pavement bases.

The base layers provide the required bearing capacity and can be composed of granular, hydraulically bound or asphalt base layers. The asphalt surfacing is composed of an asphalt binder layer topped by a surface course, providing high resistance against permanent deformation by high vertical stress below the wheel paths as well as suitable road surface characteristics.

2.3. Design parameters

2.3.1. Traffic loading

The calculation procedures for considering traffic load are similar from one European country to the other. Table 2 gives an overview about various input parameters, which are applied within the national guidelines. The basic value considering traffic loading is the number of standard axle loads during aspired service life of the pavement. As standard axle load 8,2 t (UK, IT), 10 t (SWE GE) or 13 t (FR) is applied and design lives are 30 years (SWE, IT, GE, FR) or 40 years (UK). All calculations take the average daily traffic volume (ADT), the proportion of heavy lorries and the road type into account.

Table 1. National terms and applied materials for pavement layers according to national pavement design guides

Layer type	UK[1]	SWE[2]	ITA[3]	GE[4]	FR
Surface layer	"Surface course" (asphalt)	"Slitlager" (asphalt)	"Tappeto di usura" (asphalt)	"Deckschicht" (asphalt)	"Couche de roulement"(asphalt)
Binder layer	"Binder course" (asphalt)	Bindlager (asphalt)	"Strato di collegamento" (asphalt)	"Binderschicht" (asphalt)	"Couche de liaison" (asphalt)
Base layer 2	"Base" (asphalt, hydraulically-bound or granular)	"Bundet bärlager" (asphalt)	"Strato di Base" (asphalt)	"Tragschicht" (asphalt)	"Couche de base" (asphalt, hydraulically bound or granular)
Base layer 1	-	"Obundet bärlager" (granular)	"Misto cementato" (hydraulically-bound)	"Tragschicht" (hydraulically bound, granular)	-
Subbase layer 2	"Sub-base" (hydraulically-bound, granular)	"Förstärkningslager" (granular)	"Misto granulare" (granular)	"Frostschutzschicht" (granular)	"Couche de foundation" (asphalt, hydraulically bound or granular)
Subbase layer 1	"Capping" (hydraulically-bound, granular)	"Skyddslager" – granular	"Strato antigelo" (granular)	"Bodenverfestigung" In-place hydraulically bound	"Couche de forme" (hydraulically bound, granular)
Subgrade					

[1] (Highways Agency, 2006), [2] (Trafikverket, 2011), [3](Consiglio Nazionale Delle Ricerche, 1995), [4] (FGSV, 2012)

Table 2. Compilation of input parameters regarding traffic load

	UK	SWE	ITA	GE	FR
Standard axle load [t]	8.2	10	8.2	10	13
ADT	✓	✓	✓	✓	✓
Proportion of heavy lorries	✓	✓	✓	✓	✓
Design period [a]	40	30	30	30	20 / 30
Traffic increase	✓	✓	✓	✓	✓
Road type factor	✓	✓	✓	✓	✓
Lane width	x	✓	✓	✓	✓
Percentage of vehicles in the heaviest loaded lane	✓	x	x	✓	✓
Reference velocity factor	x	✓	x	x	x
Longitudinal slope	x	x	x	✓	x

2.3.2. Subground conditions

The procedures for considering the individual subground bearing capacity vary within the pavement design specifications. In Germany, a minimum value for the subground bearing capacity is defined in terms of a deformation modulus $EV_2 \geqslant 45$ MN/m². In case the soil conditions don't suit this requirement, the subground is stabilized by cement to form a first subbase layer.

Other design approaches have a higher flexibility regarding varying bearing capacities of the natural ground and provide foundation classes according the available bearing capacity, in terms of resilient modulus Mr, CBR-ratio or surface modulus, see Figure 1. In case of low bearing capacity of the natural soil, cement or lime treatment can be used to improve the soil properties.

In addition, the frost sensitivity of the subground is considered according to the German, Swedish and French design guides. According to the soil parameters (especially grading), the soil is classified in three (GER, FRA) or four (SWE) frost sensitivity classes according to the danger of frost heave in winter conditions. The frost sensitivity class of the soil determines an additional thickness parameter for the pavement (usually a granular frost-protection layer).

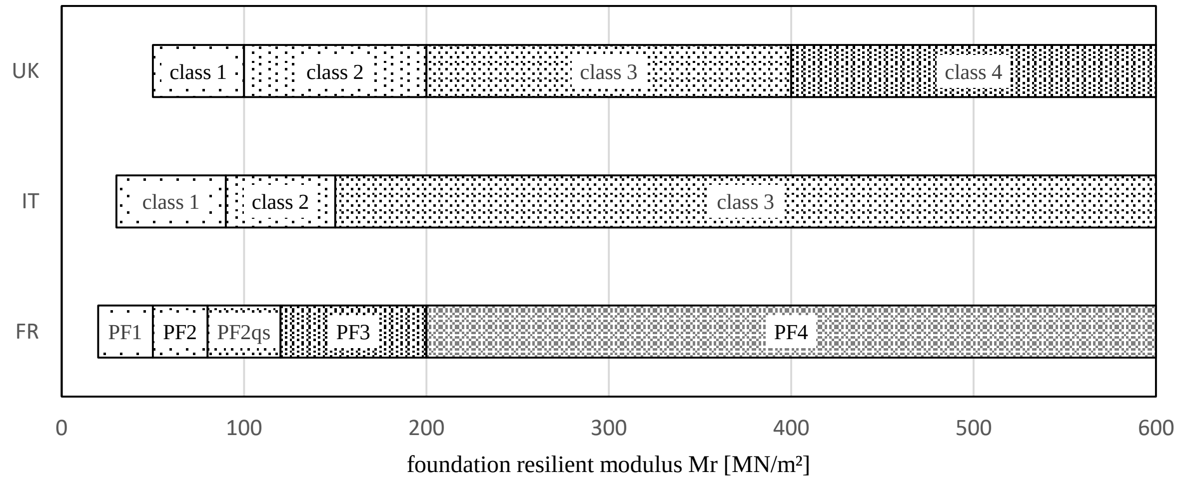

Figure 1.Applied foundation bearing capacity classes in Italy (CNR-Catalogue), UK and France according to resilient modulus

2.3.3. Climatic conditions

The climate condition is considered differently from country to country. But in most of the guidelines a landscape with different climate zones (frost zones) is applied. The German and Swedish guidelines have landscape zones which define three (GER) or five (SWE) climate zones for considering the frost depth during wintertime, compare Figure 2. The Italian pavement catalogue "*CATALOGO DELLE PAVIMENTAZIONI STRADALI*" explicitly refers to climatic conditions typical of Central Italy, whereas according to the Northern Italian design guide the altitude above the mean see level is considered, see Table 3. Within the UK and France, the mean annual frost index is the basis for assessing the frost depth.

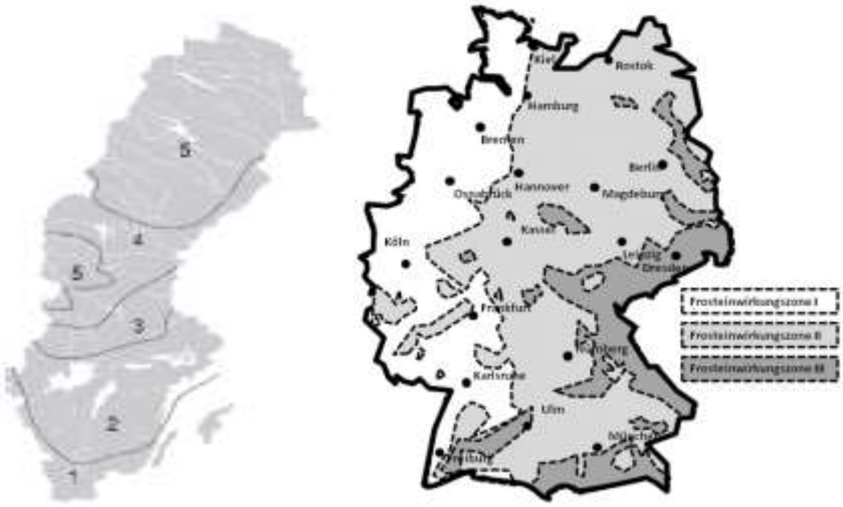

Figure 2. Climatic zones for considering frost depth in Sweden (left) and Germany (right)

Table 3. Italian climate areas according to BZ-catalogue (Provincia Autonoma di Bolzana - Alto Adige, 2016)

Climate area	Altitude [m]	Hottest monthly average temperature [°C]	Coldest monthly average temperature [°C]
1	up to 500	23.1	0.9
2	500 to 1000	21.0	0.1
3	1000 to1500	17.9	- 0.1
4	over 1500	15.8	- 1.5

2.4. Design procedures

The study of the different pavement design procedures makes clear, that there are three different fundamental approaches to dimension a suitable pavement. The United Kingdom use nomograms with deposited functions to design the total asphalt thickness. The layers below will be defined by using nomograms depending on the foundation class of the natural ground. The guidelines from Italy and Germany use a systematic catalogue to design pavements. In Sweden and France, a mechanistic-empirical design procedure is applied based on multi-layer theory, considering the resistance against fatigue cracking at the bottom of the bound layers and against permanent vertical deformation at the top of the subgrade.

As a common for all procedures, the total thickness of the pavement in order to prevent frost heave is calculated considering climatic parameters as well as soil composition. Whereas in Sweden and Germany, the required thickness can sum up to 80 cm, in UK, a thickness of 45 cm (35 cm in coastal regions) is applied.

2.4.1. Catalogue systems

The empirical pavement design procedures applied in Italy and Germany are based on a design catalogue. Suitable pavement structures are defined for given traffic loading classes, subground bearing capacities as well as applied base layer materials. In France, a catalogue also exists in addition to the mechanistic-empirical design procedure (SETRA-LCPC, 1998), and provides pre-calculated design solutions for some standard types of pavement structures, for different traffic classes and subgrade bearing capacity levels.

2.4.2. Nomogram system

In contrast to the catalogue system, the guidelines of the United Kingdom apply nomograms with deposited functions to identify the total asphalt thickness of the pavement. For this procedure the number of equivalent standard axle loads on the pavement during the design period as well as the present foundation class are used as input parameters. Figure 3 shows the design thickness for flexible pavements. After calculating the traffic load, the relevant foundation class is linked (1). The required total thickness of the asphalt layer depends on the used asphalt base layer material (2). Besides, the design procedure allows to replace the asphalt base by an HBM base (hydraulic-bounded-material).

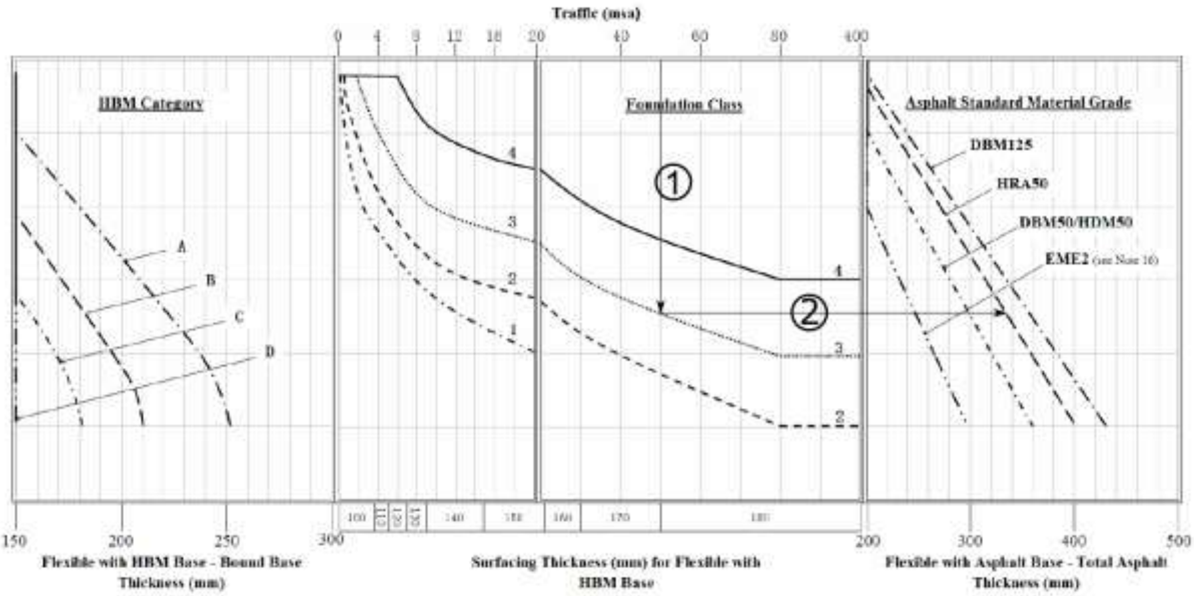

Figure 3. Design Thickness for Flexible Pavements (Highways Agency, 2006)

2.4.3. Mechanistic-empirical design procedure

Within Swedish and French design procedures, a software, based on elastic multilayer theory, is used to calculate the resulting stresses and strains within the pavement. The stiffness parameters for the road layers are chosen according to the relevant pavement material. Subground stiffness is varied according to the temperature during the year and the frost susceptibility conditions (in Sweden) or rather according to the long-term bearing capacity class of the subgrade. Within the pavement design procedure, the layer thicknesses are set to limit the vertical stress on top of the subground surface in order to withstand the actual number of loading cycles during the pavement design life. Further, the horizontal strain at the bottom of the asphalt base layer, or the horizontal stress at the bottom of the hydraulically bound base layer, is limited in order to avoid fatigue cracking.

3. Design of pavements with cold recycled materials (CRM)

The use of CRM is not standard in most European countries. Therefore, it is not considered in pavement design procedures or only handled rather roughly. As an alternative, mechanistic pavement design procedures have to be applied when nonstandard road materials are applied.
For Italy, the design standard for northern Italy contains structures with cold recycled materials (Provincia Autonoma di Bolzana - Alto Adige, 2016):

- asphalt concrete for surface, binder or base layers (*usura, binder, base*) all manufactured with SBS modified binder;
- CRM base layer with SBS modified bitumen emulsion (*base a freddo con emulsione di bitume modificato*) and cement

- CRM base layer with foamed bitumen or bitumen emulsion (*base a freddo con bitumen schiumato o emulsion bituminosa*) and cement
- Cement- or lime-stabilized foundation layers (*Fondazione stabilizzata a calce e/o cemento*) which are produced in-place.

All layers are designed according to individual technical specifications for materials and construction works. The use of a CRM base layer is often coupled with the cement- or lime-stabilized foundation layer. This is an effective way to limit the tensile strain in the CRM base layer and thus increase its long-term performance. Moreover, according to Italian specifications, the application of CRAB requires the construction of a trial section in order to test the Contractor organization, the mixture compactability and its mechanical properties. Since the trial section involves an additional cost for the Contractor, the use of CRAB is often limited to medium or large projects.

Similarly, CRM are not included within the German pavement design guide (FGSV, 2012). However, a guideline document for cold recycled materials contains suitable pavement structures including CRM base layers formally composed of tar-contaminated asphalt material. Compared to other mix designs, the German CRM are mixed with high bituminous and cementious binder contents.

According to the Swedish guidelines, there are no special requirements when using cold recycled material. The goal when using CRM is that the CRAB layer should be equally good or better than the conventional asphalt base layer. Therefore, an individual assessment is needed to determine when the CRM meets the requirements and can be considered to be of the same quality as the conventional HMA.

In the United Kingdom cold recycled materials can be utilised in a pavement structure in two ways (Merrill, Nunn, & Carswell, 2004):

- The cold recycled material forms the layer immediately above the foundation and is covered by a bituminous surfacing.
- Bitumen bound cold recycled material can be used as a substitute for conventional hot mix material for inlay treatments where a significant proportion of the existing pavement remains to form part of the rehabilitated pavement.

The French pavement design method does not define a specific design procedure for pavements with cold mix layers. The method only proposes specific mechanical performance classes for cold bituminous mixes (called Grave-Emulsions or GE). These mixes do not contain any hydraulic binder. Three types are considered, depending on the content of bituminous binder:

- Type 1 is used for profiling works. Their maximum grain size can be 10 or 14 mm.
- Types 2 and 3 are used for base layers. Their maximum grain size can be 10, 14 or 20 mm.

In order to compare the different design procedures with and without cold recycled base layer materials, model pavements are design based on common traffic load conditions as well as subground bearing capacities.

4. Comparison by model pavements

In the following section, the described pavement design procedures are applied on example structures, which are defined by common traffic loads and subground conditions. For each structure, pavement designs are compared for a standard pavement structure with a conventional asphalt base layer as well as a structure with CRAB. The conditions for the four example pavements are given in Table 4. The marginal difference between all example pavements is the number of vehicles, the lane width, the traffic increase and the subground conditions. Pavements 1 and 2 should simulate medium traffic loads with high or rather low bearing capacity of the subground. Compared to this, pavements 3 and 4 simulate low traffic conditions.

Table 4. Traffic loads and subground conditions for example pavements

	Traffic loads	Subground condition
Pavement 1	Medium traffic condition: • Average daily traffic on 1 lane: 4500 vehicles/day • proportion of heavy lorries: 3 % • lane width: 3,0 m • Traffic increase: 2 %/year	High bearing capacity: • CBR: > 15 % • M_R = 120 MN/m²
Pavement 2		Low bearing capacity: • CBR: 10 % • M_R = 50 MN/m²
Pavement 3	Low traffic condition: • Average daily traffic on 1 lane: 450 vehicles/day • proportion of heavy lorries: 3 % • lane width: 2,6 m • Traffic increase: 1 %/year	High bearing capacity: • CBR: > 15 % • M_R = 120 MN/m²
Pavement 4		Low bearing capacity: • CBR: 10 % • M_R = 50 MN/m²

As a result, Figure 4 shows the resulting pavement structures according to the different pavement design procedures, for pavement 1. The structures vary considerably in total thickness.

For Germany, considering the high bearing capacity of the subground, no granular subbase layer is required for frost protection or increasing bearing capacity. The total hot-mix asphalt thickness sums up to 22 cm. When CRM is used as an additional base layer below the HMA base layer, a total thickness of the bituminous structure of 32 cm is required, composed of 12 cm HMA and 20 cm CRM.

As result from the Italian design, total asphalt thickness sums up to 22 cm, including a base asphalt layer of 14 cm and a granular base layer is required. When a base layer of CRM is used instead of HMA, the base layer thickness is increased to 16 cm, and the asphalt surfacing from 8 to 10 cm. In addition, the unbound base layer has to replace by a foundation layer to ensure a sufficient bearing capacity.

In Sweden a mechanistic-empirical design is applied considering the actual stiffness properties of the pavement materials. As CRM is not specifically described, the same properties as for HMA base layers were applied which results in the same structural thickness of the pavement layers. In total the asphalt layers sum up to 14 cm based on 8 cm granular base and 42 cm granular base layer applied below all flexible road structures.
The UK design approach results in a total asphalt thickness of 28 cm containing an HMA base layer with a thickness of 16 cm. When CRM as alternative to HMA, is used as bituminous base layer, a thickness of 29 cm is required.

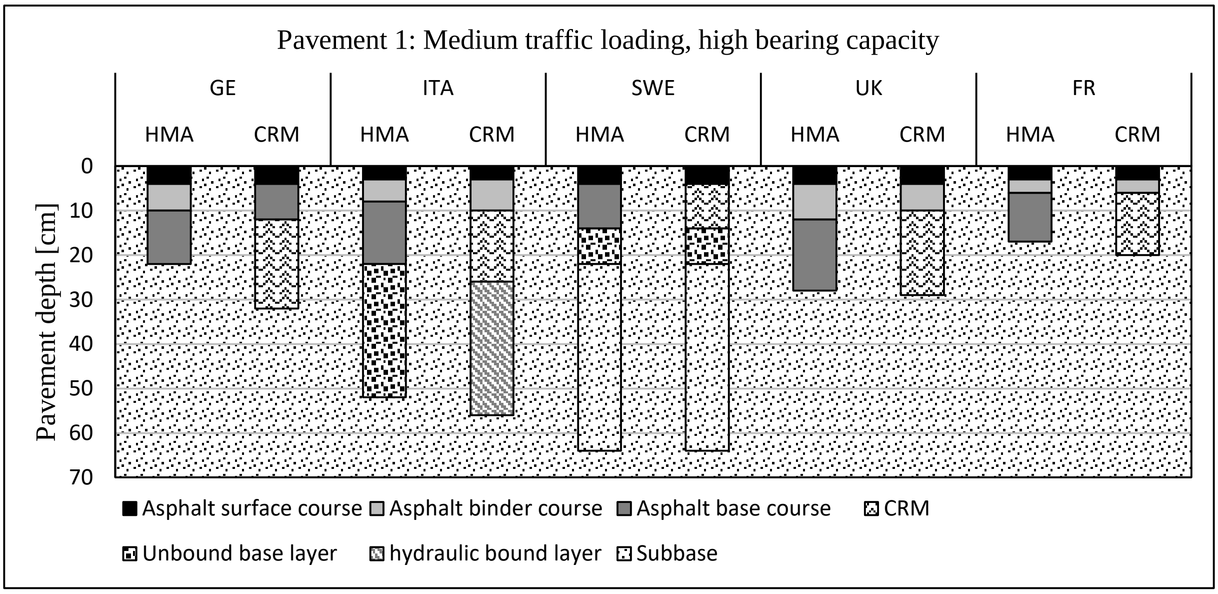

Figure 4. Resulting designs for model pavement 1 (medium traffic loads, high bearing capacity)

The design according the French procedure results in a total thickness of 17 cm containing an HMA surface layer with a thickness of 6 cm and a base layer with a thickness of 11 cm. If the pavement contains CRM, the thickness of the base layer with Grave emulsion increases up to 14 cm.
For the other model pavement structures described in table 4, the resulting total bituminous layer thicknesses are summarised in Table 5. Firstly, it can be observed, that the HMA pavement structures according to German and Italian pavement design result in similar HMA layer thickness. The pavements according to UK design have higher asphalt thickness, whereas Sweden and France pavements are designed with a thinner asphalt 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 more or less comparable structures. Obviously, the different calculation approaches were originally designed on a common basis.

Considering a novel pavement material (cold recycled material), different safety levels were applied for introducing them into the pavement structures. Further, the pavement materials, here stated as CRM as simplifications vary considerably in mix design regarding applied binder content and binder types which also can be an explanation of the large variety.

Table 5: Structural bituminous bound layer thickness for model design pavements and differences between CRM and HMA

Pavement	Asphalt layer thickness	GER		ITA		SWE		UK		FR	
		HMA	CRM	HMA	CRM	HMA	CRM	HMA	CRM	HMA	CRM
1	Thickness	22	32	22	26	14	14	28	29	17	20
	Δ [cm]	+10 cm		+4 cm		+0 cm		+1 cm		+3 cm	
	Δ [%]	+45 %		+18 %		-		+3 %		+17 %	
2	Thickness	22	36	23	-	14	14	30	33	22	22
	Δ [cm]	+14 cm				+0 cm		+3 cm		+0 cm	(+ granular subbase)
	Δ [%]	+64 %				-		+10 %		-	
3	Thickness	14	24	10	-	4,5	-	21	28,5	1,5(1)	13,5
	Δ [cm]	+10						+7,5 cm		+12 cm	
	Δ [%]	+43 %						+ 36 %		-	
4	Thickness	14	28	10	-	4,5	-	23	31,5	1,5(1)	13,5
	Δ [cm]	+14						+8,5		+12 cm	
	Δ [%]	+100 %						+37 %		-	

(1) For this very low traffic level, the French method allows to use structures with only a bituminous surface dressing, and granular base and subbase as structural layers. This explains the very low bound layer thickness.

5. Conclusions

Various national empirical pavement design procedures covering the range of climatic conditions within Europe were compared on basis of common traffic and subsoil conditions. As a result, it is shown that different design approaches may result in very similar pavement structures. Regarding the first experiences with empiric design of pavements containing cold recycled materials, different safety considerations can be identified.

For identifying suitable pavement design approaches for these materials two options will be followed. Within mechanistic pavement design, stiffness and strength parameters of CRM are assessed which allow the calculation of required layer thickness. However it has to be ensured, that applied failure models are actually relevant for these kind of not-fully bound pavement materials. The evolution of their properties with time also needs to be taken into account.

On the other hand, existing pavements with CRM base layers can be monitored in order to assess long-term performance. This will allow to validate the empirical pavement design procedures and identify possible changes.

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