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## REDUCING RESOURCE CONSUMPTION AND CARBON DIOXIDE FOOTPRINT USING FOUNDATION LAYERS FOR ROAD PAVEMENTS

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**Keywords:** *foundation layer, cold mixtures, CO<sub>2</sub> emissions, CO<sub>2</sub> footprint, bitumen emulsion, foamed bitumen, cement, uniaxial cyclic compression test, strain rate, inflection point, creep curve, GWP*

### ABSTRACT

Sustainability aspects are becoming increasingly important in the successful planning of road construction projects. Particularly in the case of large projects, such as the system of public-private partnerships, concepts are required for both reducing CO<sub>2</sub> emissions and making the greatest possible use of the road construction materials. The aim must be to create a quality infrastructure that is based as far as possible on the use of secondary raw materials and has the smallest possible CO<sub>2</sub> footprint during manufacture and installation.

One way to achieve these goals is to design the so-called "foundation layers". These consist almost entirely of recycled building materials (RC-materials), which, if possible, accrue in the same project, are produced with as little primary energy as possible, and can be produced within the construction site environment. Cold construction methods with mobile central mixing plants are suitable for this purpose, which can produce paving mixtures based on foamed bitumen that neither have a complete coating – as is the case with asphalt mixtures – nor do they have a rigid superstructure with the risk of reflection cracking due to extensive use of cement.

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This paper describes the technical conception of these foundation layers, presents the current status of regulation creation in Germany, and makes a recommendation on how these layers should be evaluated in the context of sustainability. The determination of the CO<sub>2</sub> footprint of the secondary raw materials used plays a decisive role in the practical applicability.

## 1. Introduction

The so-called hybrid construction method, in which structures with bituminous and/or hydraulic binders are used on top of or below each other, has meanwhile become widespread in Germany. Such solutions are increasingly being implemented as newly built pavements or by means of partly rehabilitation, particularly on highly congested motorways. An example of this can be the production of a concrete pavement on an asphalt base course or a concrete supporting structure with a thin asphalt superstructure. When planning large-scale projects, such as public-private partnership projects (PPP) in particular, it is becoming increasingly important to plan sustainable solutions.

Since a significant part of the German Autobahns is paved in asphalt, it is – above all – necessary to recycle the old asphalt on site for the new pavement structure. In order to minimize transport efforts, the recycling rate should be as high as possible. At the same time, the road construction should be built with the lowest possible energy consumption, which normally necessitates the usage of a cold process.

A further task arises from the increasing amounts of demolished asphalt, which is no longer suitable for reuse, e.g. as a result of greatly expanded oxidative aging. The utilization for these materials in hydraulically bound layers is limited. At the same time, it always harbors the risk that layers built on top of these structures will suffer reflection cracking after some time. The disposal of such substances as waste is generally uneconomical and harmful to the climate.

A layer has to be developed that mainly consists of the demolition materials that accumulate on the construction site – preferably asphalt. While certain processing steps are conceivable, due to the PPP projects running in construction phases over several years, there is not a sufficient possibility of homogenizing the processed materials over the entire section. So, while the mean level of the load-bearing capacity of the layer should definitely reach the level of a classified base layer, larger fluctuations in the layer properties – for example the load-bearing capacity – must be expected. These layers are therefore referred to as foundation layers in contrast to the classified base layers.

So far only hot mixed foundation layers, cold recycling layers or cold mixed base layers are known to the national German regulations. The production and installation of a foundation layer using a cold method was previously not regulated nationwide. Due to the lack of a set of rules and the corresponding practical experience, such layers are still not considered in the German standardization regulations, but instructions for the production and construction of centrally mixed foundation layers with foamed bitumen or emulsion are underway. A prerequisite for producing a uniform quality of the layer(s) is, in addition to extensive preliminary investigations, the use of suitable and efficient machine technology with regard to dosing, mixing and installation.

<b>Nomenclature</b>	
LC	load cycle
B	number of load cycles
GWP	global warming potential
CO <sub>2</sub>	carbon dioxide
EPD	environmental product declaration
RC	recycled
RAP	reclaimed asphalt pavement
PPP	public-private partnership
EPD	environmental product declaration
FGSV	German Road and Transportation Research Association
FU	functional unit
wt. %	weight percentage
CO <sub>2</sub> eq.	carbon dioxide equivalent

## 2. Concept for a foundation layer using a cold method

### 2.1. Concept for a foundation layer

A number of regulations refer to concepts of layers similar to the cold foundation layer developed here. Table 1 shows the most important features of some sets of rules for the new development.

**Table 1. Comparison between different concepts**

	<b>Cold foundation layer</b>	<b>Cold recycling layer</b>	<b>Base course below asphalt or concrete layers</b>
Regulation	In development	M KRC [6]	M VB-K [7]
Type of layer	Foundation layer	Foundation layer	Base course
Binding agent	foamed bitumen cement DIN EN 197-1:2011-11	foamed bitumen from 50/70 or 70/100 pen grade cement [1] base course binder [2]	foamed bitumen from 50/70 or 70/100 pen grade cement [1] base course binder [2]
Recycling construction materials	RAP without limitations, preferably not suitable for hot reuse	(existing pavement, milled)	tar-containing road construction materials, RAP according to [8]
Building material mixture	RAP supplementary material bituminous binder hydraulic binder (max. 1 wt.%) water	Milled existing pavement supplementary material bituminous binder hydraulic binder water	tar-containing road construction materials RAP supplementary material bituminous binder hydraulic binder (1-2 wt.%) water
Specifications building material	max. aggregate size 22 or 32 mm < 0,063 mm: 3-12 wt. %	max. aggregate size 32 or 45 mm < 0,063 mm: max. 5 wt. %	max. aggregate size 32 mm < 0,063 mm: 4-9 wt. %
Laboratory samples	modified Proctor	according to [6], app. 6 („Duriez“)	according to [7], app. 2 („Duriez“)

Production	(mobile) mixing plant with double-shaft compulsory mixer (KMA)	mill recycler, mix paver	mixing plant with double-shaft compulsory mixer (KMA)
Paving	road paver	mill recycler, mix paver	road paver with high pre-compaction
Indirect tensile strength (dry)	> 0,225 N/mm <sup>2</sup> (4d)	0,50 – 0,80 N/mm <sup>2</sup> (7d/C)	0,60 – 0,80 N/mm <sup>2</sup> (7d)
Indirect tensile strength (wet)	> 0,175 N/mm <sup>2</sup> (5d) decrease < 25 %	decrease < 30 %	

As shown in Table 1, there are different construction types being quite similar to the developed cold foundation layer. However, there are significant differences. The material used for producing and constructing the cold recycling layer according to [6] (second column) is generated by milling and crushing the existing pavement. It is possible to add supplementary material and most machines can realize a homogenization in lateral direction. However, there are changes in composition in correspondence with the structure of the old pavement in longitudinal direction, which are inevitable.

The method for base courses according to [7] (third column) was mainly developed to safely recycle materials with significant tar amounts, which must be covered against dilution by water and have to be treated only by a cold method. Therefore, the addition of significant cement rates is mandatory. These layers tend to develop stronger hydraulic bonds, which subsequently increases the risk of having reflective cracking after some time. These cement rates are also compulsory to reach the specifications for indirect tensile testing. Classified base courses need a more homogeneous and higher-level bearing capacity than foundation layers, as they normally have to take over other tasks in a pavement.

## 2.2. Production and construction of a cold foundation layer on site

As already explained, there is no actual valid regulation in Germany describing production and paving of a cold foundation layer as defined in this paper. Nevertheless, there are several standardization efforts on the way. The experiences from test constructions and intensive laboratory testing for this layer type have been the basis for a draft regulation, which is actually being discussed within several working groups of the German Road and Transportation Research Association (FGSV). The process is underway and will eventually lead to a publication of such a regulation shortly.

The milled asphalt material, which is produced from the old pavement on site, has to be used for production as part of large-scale projects. It is necessary to determine the aggregate size distribution in order to derive the need to add additional materials (e.g. sand). The water content has to be determined as well. The material mixture is produced in the intended composition using a mobile cold recycling mixing plant with a twin-shaft compulsory mixer. This should have two separate dispensers for the starting materials.

Supplementary material must be added depending on the composition of the mixed aggregates. This may be made up of several components that are either available pre-mixed on site or have to be added individually to the mixing process as different components.

The mixture components are added in the following order:

- first mixed aggregates, then hydraulic binder as well as added water and possibly adhesion promoter (if not present in the binder),

- then the foamed bitumen is sprayed evenly in the mixing chamber during the mixing process and worked in homogeneously.

If bitumen emulsion is used, no foamed bitumen is produced in the last step, but the emulsion is injected and mixed homogeneously. It is advisable to determine the mixing time with test mixtures. A longer storage of the material after mixing is not possible.

The mixture is mixed with the various components and binders in the cold mixing plant and homogenized. The paving mixture can then be loaded onto transport vehicles by means of a conveyor belt and transported to the construction site. The mixture is paved with a conventional road paver. The layer, including the edges, is compacted immediately after installation, using rollers that are as heavy as possible. When using foamed bitumen, the layer can usually be used by machines after 24 hours; when using emulsions, longer periods should be planned.

### 3. Materials and method

#### 3.1. Production of the test specimens

After mixing, cylindrical proctor specimens with a diameter of 100 mm were produced with four different combinations of foamed bitumen and cement and five combinations of bitumen emulsion and cement (Table 2).

**Table 2. Comparison between different concepts**

Variant	Bitumen		Cement	Water
	Type	[wt.%]	[wt.%]	[wt.%]
1	Foamed bitumen	2,2	0,7	0,7
2	Foamed bitumen	2,2	1,0	1,0
3	Foamed bitumen	2,4	0,7	0,7
4	Foamed bitumen	2,4	1,0	1,0
5	Bitumen emulsion	2,0	0,7	0,7
6	Bitumen emulsion	2,4	0,7	0,7
7	Bitumen emulsion	2,4	1,0	1,0
8	Bitumen emulsion	2,2	0,7	0,7
9	Bitumen emulsion	2,2	1,0	1,0

All specimens were  $60 \pm 1$  mm high and were compacted in two layers at 25 strokes. The drop weight was 4,5 kg falling from a height of 45 cm. Three specimens were examined for the 7- and 28-day value respectively. The proctor compaction process was according to [3]. The test specimens were then stored in their Proctor molds in a drying cabinet at room temperature. On the following day (approx. 20 hours after production) the formwork was removed and the test specimens were wrapped in moist cloths and stored in the drying cabinet at room temperature for 7 or 28 days respectively.

(a)



(b)



**Figure 1. Test specimen with foamed bitumen (a) and test specimen with bitumen emulsion (b)**

### **3.2. Uniaxial cyclic compression test**

To evaluate the stability against permanent deformation (also known as rutting stability) of the different variants presented above, the uniaxial cyclic compression test was used. This test is conducted following the German standard [9]. The deformation resistance of the specimens was measured over a cycle of 10 000 load pulses at a temperature of 50 °C. The test is conducted by applying a compressive load (0,35 MPa) on an asphalt specimen with a diameter of 100 mm and a height of 60 mm. In this test, a haversine load/pulse is applied in 0,2 seconds and then left to recover for 1,5 seconds. A small load (0,025 MPa) is applied permanently to the specimen, mainly to avoid impacting the specimen with each pulse. Each cycle is registered and plotted in a deformation-time diagram, building a creep function (creep curve) for the material (Fig. 2). The test is terminated after 10 000 load cycles or when the elongation exceeds 80 %, depending on which criterion is reached first.

The creep curve can be separated in three phases. In the first phase, there is a strong initial deformation with progressively decreasing deformation rate (consolidation). In the second phase, the deformation rate is almost constant (constant volume deformation). The course of the impulse creep curve in phase 2 is of particular importance for the evaluation of the deformation resistance. The strain rate at the inflection point  $\epsilon_w^* [\% \cdot 10^{-4}/n]$  is used as the decisive characteristic parameter. The associated characteristic variables strain at the inflection point  $\epsilon_w$  and number of load cycles at the inflection point  $n_w$  are shown at the end of the experiment ( $n = 10\ 000$ ). Finally, a third phase can occur, in which the deformation increases progressively (initial and progressive structural destruction of the specimen). For asphalts with high deformation resistance, phase 3 of the impulse creep curve does not normally occur until the defined end of the test.

This test delivers two main properties that allow comparing different mixtures: the load cycles at the inflection point ( $n_w$ ) and the strain rate at the inflection point ( $\epsilon_w$ ). The test is determined using the strain rate curve derived from the impulse creep curve. The strain rate of the inflection point corresponds to the minimum of this curve which can be determined mathematically.

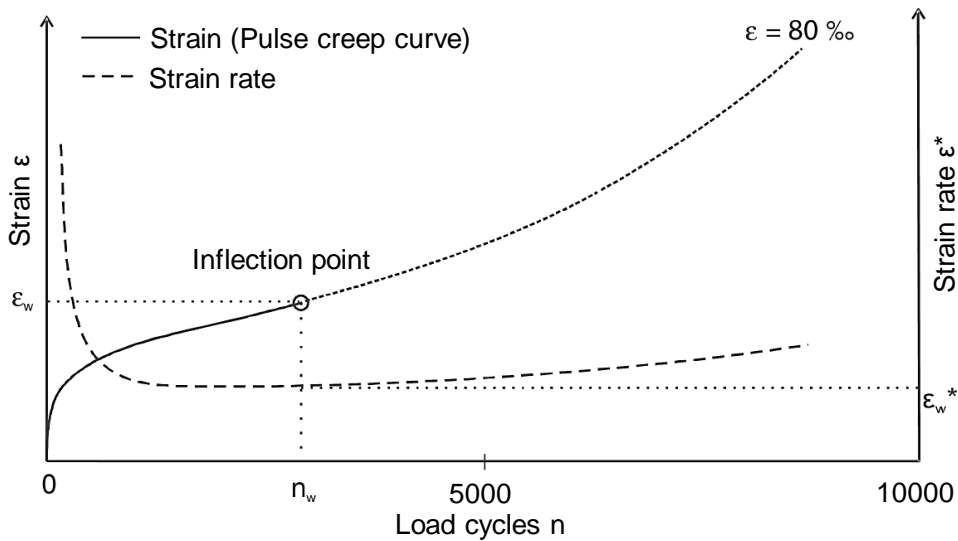


Figure 2. Impulse creep curve with inflection point according to [9]

## 4. Results and Discussion

### 4.1. Stability against permanent deformation

As mentioned in the previous section, the uniaxial cyclic compression test was used to evaluate the stability against rutting of nine different variants. There are still no characteristic values and requirements for the uniaxial cyclic compression test regarding foundation layers. However, based on the inflection point and the course of the strain rate, conclusions can be drawn about the flexibility.

#### **VARIANT 1: Test specimens with 2,2 wt.% foamed bitumen and 0,7 wt.% cement**

After 7 days of storage, the tests stopped after a few hundred pulses, as the maximum strain of 40 ‰ was reached. In this respect, it was not possible to show a meaningful progression as a pulse creep curve. After 28 days of storage, the test specimens were already very porous as the binder content was too low, so that only two specimens could be tested, since they broke during stripping.

#### **VARIANT 2: Test specimens with 2,2 wt.% foamed bitumen and 1,0 wt.% cement**

After 7 days of storage, the tests stopped already after several hundred pulses. No statements could be made about the inflection point of the pulse creep curve. However, the test usually ran over the full 10 000 load cycles with the specimens stored for 28 days. The deformation resistance was very high, which was due to the higher proportion of hydraulic binder (cement).

#### **VARIANT 3: Test specimens with 2,4 wt.% foamed bitumen and 0,7 wt.% cement**

The higher amount of foamed bitumen has a significant effect on the deformation resistance. After 7 days of storage, the test specimens already went through several thousand

load cycles before the maximum strain of 40 % was reached. This shows an increase in deformation resistance compared to the test specimens with less foamed bitumen. After conducting the tests with the specimens stored for 28 days, this statement could only be confirmed.

**Variant 4: Test specimens with 2,4 wt.% foamed bitumen and 1,0 wt.% cement**

In general, the evaluation of the results indicate that the specimens with a cement content of 1,0 wt.% are significantly better in terms of deformation resistance. The results showed, that foundation layers that are only based on bituminous binders are not suitable. However, a higher cement value should not be selected, because the mixture for a foundation layer should react flexibly in order to avoid later occurrence of reflection cracks.

**Variant 5: Test specimens with 2,0 wt.% bitumen emulsion and 0,7 wt.% cement**

The first material mixture with bitumen emulsion contained a lower proportion of binders compared to the other four variants. Thus, it was evident, that the low amount of both binders negatively affects the deformation resistance. In some cases, the test specimens already reached the maximum strain of 40 % after only 100 load cycles. This was especially evident for the test specimens after 7 days of storage. The tests of the specimens after 28 days of storage did not show better results as well. It was stated that the adhesion of the individual aggregates was not optimal.

**Variant 6: Test specimens with 2,4 wt.% bitumen emulsion and 0,7 wt.% cement**

A clearly higher deformation resistance was found to exist due to the higher bitumen emulsion amount. It should be noted here that the inflection point of the strain occurred significantly later when testing the 7 day-stored specimens than the 28 day-stored specimens and the strain at the inflection point was significantly higher.

**Variant 7: Test specimens with 2,4 wt.% bitumen emulsion and 1,0 wt.% cement**

With an increase of hydraulic binders amount while keeping a high bitumen emulsion content at the same time, the deformation resistance increased too. The inflection point occurred at over 9000 load cycles for the 7-days-specimens and had a low elongation of over 11 % in the inflection point but there was a very high variation of the results. The inflection point occurred much earlier for the 28-days-specimens.

**Variant 8: Test specimens with 2,2 wt.% bitumen emulsion and 0,7 wt.% cement**

The proportion of asphalt granules was lower than in the previous test series. It was attempted to make the void content smaller. This series of tests resulted in a very high deformation resistance. However, large variations were found to exist here.

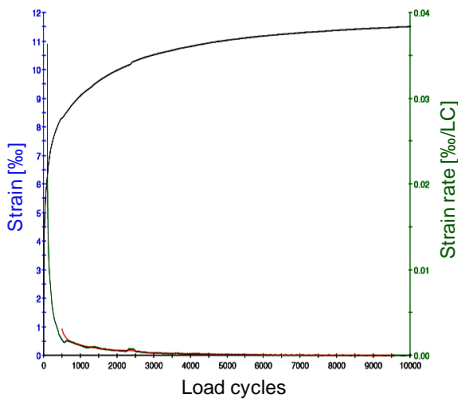
**Variant 9: Test specimens with 2,2 wt.% bitumen emulsion and 1,0 wt.% cement**

This mixture proved to be highly resistant to deformation. The inflection point occurred after 9000 load cycles for both 7-days and 28-days-specimens. This means that phase 3 of the pulse creep curve would begin very late.

Therefore, it can be recommended that the inflection point should occur in a range between 6000 and 7000 load cyclea and should exhibit an elongation of more than 20 %. The test specimens with less cement content confirmed this trend.

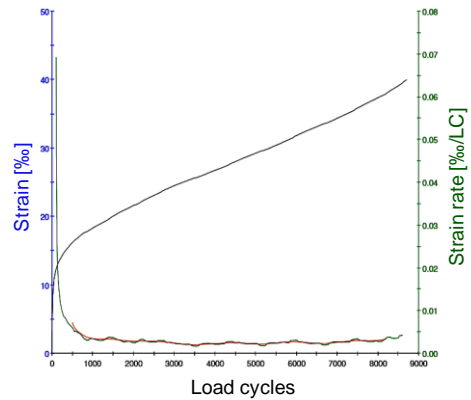
a

Load cycles at the inflection point	nW		9187
Strain at the inflection point	EW	%	11
Strain rate at the inflection point	EW*	%/10 <sup>4</sup> n	0,609375



b

Load cycles at the inflection point	nW		3497
Strain at the inflection point	EW	%	26
Strain rate at the inflection point	EW*	%/10 <sup>4</sup> n	21,44381



**Figure 3. Uniaxial cyclic compression test for a specimen with 2,4 wt.% bitumen emulsion and 1,0 wt.% cement stored for 7 days (a) and for 28 days (b)**

## 4.2. Environmental impact assessment

A short sustainability evaluation is presented in this section. Only the environmental dimension was considered for this evaluation and the analysis, based on [4], includes solely the life cycle phase A1, which is the raw material extraction and processing. This is because including further phases would have required making too many assumptions and would have not been purposeful. One of the main problems of these types of assessments is the lack of data on materials and processes in the road construction sector.

For the analysis, secondary data from an open access German dataset [11] was used. This databank has data available that considers the German context. For the bitumen emulsion, data from a publicly available environmental product declaration [10] of bitumen emulsion was taken. The foam bitumen was modelled as the combination of bitumen and water bit, while the bitumen was modelled using the publicly available life cycle inventory on bitumen provided by [5], and the information on the water was taken from [11] database. The analysis consisted in using the mixture recipes and evaluating the environmental impact that each mixture has on the global warming potential indicator (GWP in kg CO<sub>2</sub> eq.) from a resource perspective. A functional unit of 1,0 m<sup>2</sup> was used for the analysis. Considering a layer thickness of 15 cm, this is equivalent to 0,15 m<sup>3</sup> of mixture. All nine variants presented in this manuscript were considered in the analysis. An additional variant (variant 0) was used as a reference. The reference mixture is a gravel base layer (max grain size of 32 mm), which is the standard foundation layer used in Germany.

The results of this short environmental impact assessment are shown in Table 3. As can be seen, the reference mixture has the highest impact on the GWP of all variants. Evidently, this is mainly due to the use of virgin aggregates, which allows concluding that the use of reclaimed asphalt has a very positive environmental impact despite the usage of a binding agent (either foam bitumen, bitumen emulsion and/or cement). Additionally, the results show that the higher the bitumen content as well as the cement concentration, the higher GWP, whereas the cement has a higher impact with a concentration increase.

**Table 3. Results of the short environmental impact assessment (FU: 1,0 m<sup>2</sup> – 0,15 m<sup>3</sup>)**

Variant	Bitumen (Foam/Emulsion)		Cement	Aggregates	GWP
	Type	[wt.%]	[wt.%]		[kg CO <sub>2</sub> eq.]
0 (Reference)	–	–	–	Virgin Aggregates	15,23
1	Foamed bitumen	2,2	0,7	75 % RAP	9,92
2	Foamed bitumen	2,2	1,0	75 % RAP	10,77
3	Foamed bitumen	2,4	0,7	75 % RAP	10,09
4	Foamed bitumen	2,4	1,0	75 % RAP	11,28
5	Bitumen emulsion	2,0	0,7	75 % RAP	9,71
6	Bitumen emulsion	2,4	0,7	75 % RAP	9,90
7	Bitumen emulsion	2,4	1,0	75 % RAP	10,61
8	Bitumen emulsion	2,2	0,7	75 % RAP	10,72
9	Bitumen emulsion	2,2	1,0	75 % RAP	11,38

As mentioned previously, this short environmental impact assessment includes only the life cycle phase A1 (raw material extraction and processing). However, it is recommended that further phases should be included in future work.

## 5. Conclusions

After evaluating the results of the binder variations, it can be concluded that the paving mix should contain a cement content of 1,0 wt.%, since the resistance to deformation is higher. Moreover, the addition of bitumen emulsion is more appropriate for the paving mix for a foundation layer than foamed bitumen. The optimal percentage of bitumen emulsion has been found to be 2,4 wt.%. Over a longer period, the foundation layer can absorb strains, because of which reflection cracking will be avoided. However, the problem with the high void content still has to be solved. An open-pored asphalt layer could lead to fluctuations in the interlayer bond under corresponding loads. For this purpose, a better compaction at the construction site has to be foreseen. Despite the high void content, there is a high resistance to deformation due to both binders. A reduction of the void content could be achieved when using foamed bitumen. The reason for this is that the bond works better when the aggregate particles are closer together due to the point bonding function of the foamed bitumen. However, foamed bitumen at a higher binder content tends to be stiffer than the bitumen emulsion and therefore bitumen emulsion should be preferred for flexible foundation layers. A binder content of more than 2,4 wt.% should also be researched to obtain results in this respect. Recommended occurrence of the inflection point is between 6000 and 7000 loading cycles and should exhibit an elongation of more than 20 %.

The sustainability evaluation shows that the use of reclaimed asphalt has a very positive environmental impact in spite of using a binding agent (either foam bitumen, bitumen emulsion and/or cement). Additionally, the results show that the higher the bitumen content and the cement concentration, the higher the GWP, whereas the increased concentration of cement has a higher impact.

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# НАМАЛЯВАНЕ НА ПОТРЕБЛЕНИЕТО НА РЕСУРСИ И НА ОТПЕЧАТЪКА НА ВЪГЛЕРОДЕН ДИОКСИД ЧРЕЗ ИЗПОЛЗВАНЕ НА ФУНДАМЕНТНИ СЛОЕВЕ ЗА ПЪТНИ НАСТИЛКИ

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*Ключови думи:* фундаментен слой, студени смеси, CO<sub>2</sub> емисии, CO<sub>2</sub> отпечатък, битумна емулсия, разпенен битум, цимент, едноосово циклично изпитване на натиск, скорост на деформация, инфлексна точка, крива на пълзене, ПГЗ (потенциал за глобално затопляне)

## РЕЗЮМЕ

Аспекти на устойчивото развитие стават все по-важни за успешното планиране на проекти за пътно строителство. Особено при големи проекти, като например системата за публично-частните партньорства, са необходими концепции както за намаляване на CO<sub>2</sub> емисиите, така и за възможно най-пълноценно използване на материалите за строителство на пътища. Целта трябва да бъде създаването на качествена инфраструктура, която да се основава в максимална степен на използването на вторични суровини и да има възможно най-малък CO<sub>2</sub> отпечатък по време на производството и монтажа.

Един от начините за постигане на тези цели е проектирането на така наречените „фундаментни слоеве“. Те се състоят почти изцяло от рециклирани строителни материали (RC-материали), които по възможност произхождат от същия строителен обект, произвеждат се с възможно най-малко първична енергия и могат да се произвеждат на строителната площадка. За тази цел са подходящи методите на студено строителство с мобилни централни смесителни инсталации, които могат да произвеждат пътностроителни смеси на основата на разпенен битум, които нямат нито цялостно покритие, както е при асфалтовите смеси, нито твърдо горно строене, при което е налице риск от пукнатини поради широкото използване на цимент.

Настоящата публикация описва техническата концепция на тези фундаментни слоеве, представя текущото развитие на нормативни документи в Германия и прави препоръка как тези слоеве да бъдат оценявани в контекста на устойчивостта. Определянето на CO<sub>2</sub> отпечатък на използваните вторични суровини играе решаваща роля за практическата приложимост.

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