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CoRePaSol
characterization of advanced cold recycling bitumen stabilized pavement solutions

Report on recyclability and multiple recyclability of cold-recycled asphalt mixes in cold and hot recycling

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CoRePaSol
Characterization of Advanced Cold-Recycled Bitumen Stabilized Pavement Solutions

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Executive Summary

The recycling of asphalt pavements in cold recycling mixtures is a widely applied and mostly approved procedure for full-depth rehabilitation measures. Whereas the mix design procedures for optimising the properties of cold recycled mixtures are well researched, the end-of-life strategies for these types of pavement layers are not known so far. However, the design of modern pavement materials has to consider end-of-life characteristics of the material in order to avoid costly and environmental hazardous disposal of these materials in future.

In order to assess the recyclability of pavement layers composed of cold recycled materials, a laboratory campaign was conducted on newly produced cold recycled mixtures. After the accelerated aging of the materials in laboratory their applicability in new road materials were evaluated. Therefore, two recycling options were analysed: cold recycling and hot/warm recycling.

Firstly, the recyclability in new cold-recycled materials was assessed. Here even three recycling cycles were evaluated in order to determine the multiple-recycling characteristics.

Secondly, the recyclability of cold-recycled material in new hot-mix and warm-mix asphalt was evaluated. One of the main goals of the performed studies was to check if the bituminous binder of the cold recycled mixture can be reactivated in new hot/warm-mix asphalt layers. This would enable the upgrading of cold recycled base layers even to continuously-bound asphalt base, binder and surface layers.

Following conclusions can be drawn from the results of the recyclability studies summarized in this deliverable report:

- Pavement layers consisting of cold recycled materials can be recycled both by cold recycling as well as hot/warm recycling at the end of their service life.
- When cold recycling is applied, the resistance against permanent deformation shall be evaluated in order to avoid mixtures with excess of total bitumen content.
- For the assessment of recyclability, it is recommended to obtain the mix granulate by crushing of prior compacted and laboratory aged specimens in order to simulate milling process on site.
- For hot recycling, reclaimed cold recycling mixtures can be handled in the same way as reclaimed hot mix asphalt. Cement included in the cold recycling mixture doesn't interfere with the recyclability of the bitumen.
- For warm recycling the applied study shows the applicability of reclaimed cold recycled material. However, as the reactivation of the binder in the reclaimed material depends on production temperature and mixing time, additional experiments are required in the future.
- Providing suitable aging properties, the bitumen "stored" in cold recycled mixtures can be recovered and reactivated again during hot recycling process.

1 Introduction

The recycling of asphalt pavements in cold recycling mixtures is a widely applied and mostly approved procedure for full-depth rehabilitation measures. Whereas the mix design procedures for optimising the properties of cold recycled mixtures are well researched, the end-of-life strategies for these types of pavement layers are not known so far. However, the design of modern pavement materials has to consider end-of-life characteristics of the material in order to avoid costly and environmental hazardous disposal of these materials in the future.

In order to assess the recyclability of pavement layers composed of cold recycled materials, a laboratory campaign was conducted on newly produced cold recycled mixtures. After the accelerated aging of the materials in laboratory their applicability in new road materials were evaluated. Therefore, two recycling options were analysed.

Firstly, the recyclability in new cold-recycled materials was assessed. Here even three recycling cycles were evaluated in order to evaluate the multiple-recycling characteristics.

Secondly, the recyclability of cold-recycled material in new hot and warm-mix asphalt was evaluated. One of the main goals of the performed studies was to check if the bituminous binder of the cold recycled mixture can be reactivated in new hot/warm-mix asphalt layers. This would enable the upgrading of cold recycled base layers even to continuously bound asphalt base, binder or surface layers.

2 State of the Art

The recycling of road material in new pavements is state of the art and proven practice since several centuries. For asphalt pavements the most common applied recycling procedures are hot recycling in new hot-mix asphalt as well as cold recycling in new road base layers with bitumen emulsion, foamed bitumen and/or hydraulically binders. In recent years also applications in warm mix asphalt are more common and seen as an alternative to HMA containing RAP. The procedures for recycling in these materials are widely well researched and described in several guidelines (e. g. Wirtgen 2012, Grilli et al. 2012 and further prescribed for the European harmonisation process in CoRePaSol project (Valentin et al. 2014).

Though, what have not yet been researched are the end-of-life characteristics of cold recycled materials. For hot recycling process, De Visscher et al. (2012) could show that the commonly approved hot recycling process can be repeated several times considering moderate contents (50 %) of reclaimed asphalt in new hot mixtures. The properties of the aged binder in the reclaimed asphalt can be levelled by new binders with reduced viscosity which results in new hot asphalt mixtures reaching similar quality compared to asphalt mixtures fully composed of new materials.

For cold recycling technology, this proof has been done not yet. The material performance of cold recycled mixtures depends besides the content and type of bituminous and mineral binders applied also on the composition of the mix granulated originating from the milled road (compare Simnofske et al. 2014). Here a significant effect of the content of reclaimed asphalt in the mix granulate on the mechanical properties could be analysed.

When cold recycling mixtures reach their end of service life, they need to be recycled in new pavement layers. For the applicability of these pavement materials in new cold recycled mixtures, the effect of combination of bituminous and hydraulic binders for the properties of the new material has to be checked. Further, multiple recyclability for cold recycling was not evaluated, yet.

On the other hand, cold recycling pavement layers still cannot be compared with hot-mix asphalt layers. Later reach lower void contents, higher stiffness and strength values and would allow reduced pavement thicknesses. Therefore, the recycling of reclaimed cold recycled layers in new hot/warm-mix asphalt can be an economically feasible method for reducing the demand for new bituminous binder in the future. Whereas so far this seems not to be necessary, the reduced availability of bitumen resources can lead to the demand of also upgrading former cold-recycling mixtures by hot recycling.

3 Experimental assessments

For the evaluation of the end-of-life-properties of cold recycled road materials two sets of experiments were conducted. Firstly, the multiple recyclability of cold recycled materials again in new cold-recycled mixtures was analysed at University Kassel (section 3.3). Secondly, the recyclability of cold recycled road base layer materials in new hot-mix asphalt was tested (section 3.4). In parallel similar testing has been conducted by CTU in Prague focusing on application of cold recycled, aged and crushed material again in a cold recycled mix. At the same time some variations of these cold recycled and aged materials were applied in hot and warm mix asphalt.

Therefore, in Germany two laboratory-prepared cold recycled mixtures were prepared in laboratory and artificially aged. These aged materials then were applied as reclaimed road mixtures for evaluating the recyclability properties. In the Czech Republic four different cold recycled mixes representing main combinations of used binders were prepared and artificially aged. Resulting material was used for one type of cold recycled mix with reduced bituminous emulsion content and in hot/warm asphalt concrete mixes applicable for wearing courses. The preparation of these simulated reclaimed materials is discussed in section 3.1.

3.1 Laboratory-simulated reclaimed cold-recycled mixtures, case study Germany

For the evaluation of the recyclability of cold recycled materials in new road layers, two cold recycled mixtures were prepared in the laboratory.

3.1.1 Source materials

The reclaimed asphalt material was obtained from a stockpile of granulated reclaimed asphalt located in an asphalt mixing plant in Rhünda (Germany). The source reclaimed asphalt is usually applied as RA in new hot-mix asphalt layers and represent typical milled and sorted reclaimed asphalt materials originating from German asphalt pavements.

The grading of the reclaimed asphalt granulate is plotted in Figure 1.

The reclaimed asphalt composition was analysed by extraction and recovery according to EN 12697-1 and -3. The binder content and bitumen characteristics were evaluated as followed:

- Binder content: 5.4 %
- Penetration (according to EN 1426): 23 1/10 mm
- Softening point (according to EN 1427): 63.5 °C

The applied bitumen emulsion was classified according to EN 13808 (2013) as a C60B1 and is a product typically applied for cold recycled materials. The characteristics of the bitumen recovered from the emulsion were as followed:

- Penetration (according to EN 1426): 78 1/10 mm
- Softening point (according to EN 1427): 46 °C

The hydraulic binder used in this study was a Portland cement CEM I 42.5 N according to EN 197.

3.1.2 Mix design of the laboratory-simulated cold-recycle mixtures

As plotted in Figure 1, the reclaimed asphalt granulates didn't comply with the minimum allowed content of fines according to the applied mix design requirements. Therefore, 5 % inactive limestone filler was added to 95 % of the reclaimed asphalt granulates.

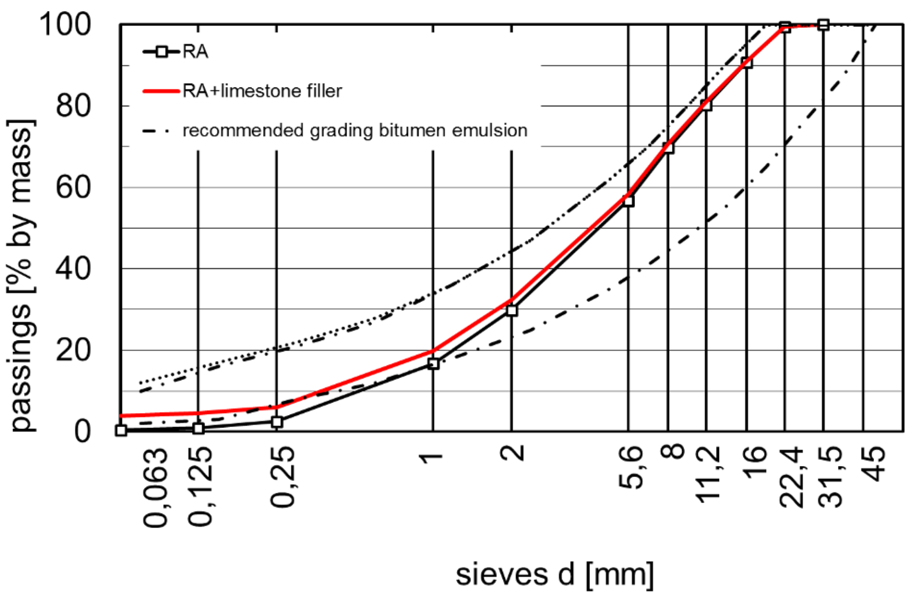


Figure 1: Grading of the reclaimed asphalt granulate and the applied mix granulate after addition of limestone filler with the grading envelope according to Wirtgen (2012)

The applied mix compositions of these simulated reclaimed cold recycled mixtures (RCRM) is summarised in Table 1:1.

Table 1: Mix composition of laboratory-prepared reclaimed cold recycled mixtures (RCRM)

Reclaimed cold recycled mixtures	Bituminous emulsion (in brackets: residual bitumen)	Cement	Reclaimed asphalt	Inactive limestone filler
RCRM 1	2 % (1.2 %)	-	93.9 %	4.9 %
RCRM 2	2 % (1.2 %)	3 %	91.1 %	4.7 %

Proctor test according to EN 18127 was applied to determine the water content for optimal compaction. The optimum fluid content of 7.8 M.-% could be determined from the point of intersection of Proctor curve and the curve of 65 % water saturation (compare Figu2). The added water content for preparing the cold recycled mixture was calculated according to (1) considering the emulsion water, the moisture of the mix granulates as well as the fluid effect of the emulsified bitumen. This resulted in an added water content of 6.2 %.

$$W_{water\ add\ em} = w_{OFC} - w_{air\text{-}dry} - w_{em} - 0.5 * PRB \qquad (1)$$

$W_{water\ add\ em}$ =	percentage of water to be added for BSM/BCSM with bituminous emulsion [%]
w_{OFC} =	optimum fluid content [%]
$w_{air\text{-}dry}$ =	moisture content of the mix granulate [%]
w_{em} =	water content from bituminous emulsion [%]
PRB =	percentage residual bitumen in emulsion [%]

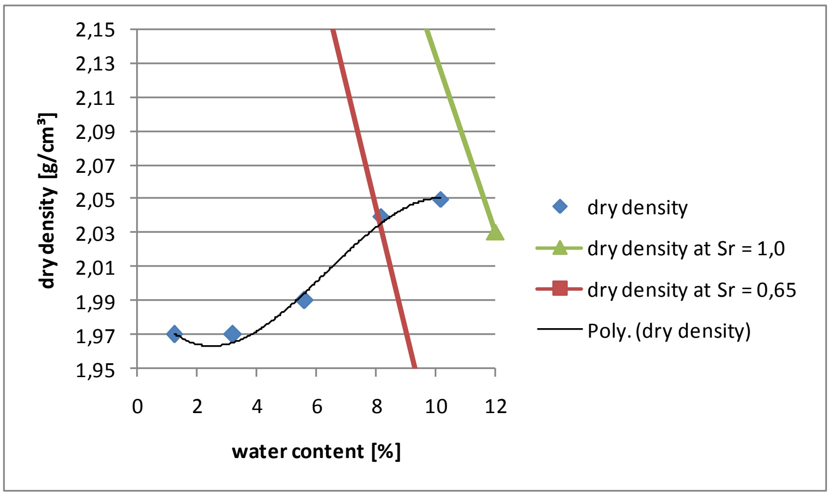


Figure 2: Results of proctor test for evaluation of optimum water content

3.1.3 Reclaimed cold recycled mixture preparation and conditioning

The cold recycled mix variations were produced using a Wirtgen compulsory pugmill mixer WLM 30. After pre-mixing of aggregates and cement for 1 minute, the water is added to the mixture and mixed additionally for 1 minute. After adding the bitumen emulsion into the mix, the mixing was proceeded for 1 minute. The mix was checked if the aggregates and binder were distributed homogenously and the aggregates were fully covered by bitumen emulsion.

For the simulation of long-term aging, an accelerated laboratory conditioning procedure as successfully applied on hot-mix asphalt (De La Roche et al. 2009, Mollenhauer et al. 2011) was conducted on the freshly prepared cold-recycling mixtures. Therefore, the cold recycling mixture was spread on a metal tray and stored for 10 days at a temperature of 85 °C in a ventilated oven. After conditioning the long-term aged cold recycling mixture was then granulated manually and used again as a granulated reclaimed material for the additional recycling procedures.

For evaluating the effect of compaction on the ageing properties as well as possible effects on the recyclability, cylindrical specimens (diameter 150 mm, height 80 mm) were compacted from the freshly produced cold recycled mix. The compaction was conducted by repeated static compaction with a double-plunger system with a maximum load of 50 kN. The compacted specimens were stored in their moulds at 20 °C, 80 % relative moisture for approximately 24 hours and demoulded afterwards. Then the same aging conditioning procedure was applied as for the spread mixture. After 10 days simulated aging at 85 °C, the specimen were cooled down to room temperature and crushed manually (compare Figure 3) by a metal rammer in a bucked in order to simulate the milling action on a jobsite.

The described ageing procedures were applied for the initial preparation of a cold-recycled road material at the end of its service life which afterwards will be used in cold and hot recycling procedures as well as for simulation a second and third recycling cycle for the cold recycled mixtures.

Figure 3: Breaking procedure for prepared specimens

3.2 Laboratory-simulated reclaimed cold-recycled mixtures, case study Czech Republic

Cold recycling is a term used for re-use of a material from existing pavement without heating the recycled material or any of added binders, as is common for traditional hot asphalt mixes. Group of these technologies became, not only in the Czech Republic but mainly abroad, a trend particularly in case of in-place cold recycling. This group of techniques is well-established standard described e.g. in Czech Technical Specifications of the Ministry of Transportation TP 208. It offers broad possibilities of application; from reconstruction of thin pavement layers to full-depth recycling of a pavement structure. With respect to evaluation of the possibility to re-use again once recycled material 3 different types of cold recycled mixtures were designed. They differ in the type of stabilizing agent/binder and their variable content in the mix as shown in table 3.

Table 2: Design of assessed cold-recycled mixes

Mix	RAP 0/22 Středokluky	Stabilizing agent content			Water
		Cement	Bituminous emulsion	Foamed bitumen	
A	91.0%	3.0%	3.5%	-	2.5%
C	94.0%	-	3.5%	-	2.5%
D	93.5%	-	-	4.5%	2.0%

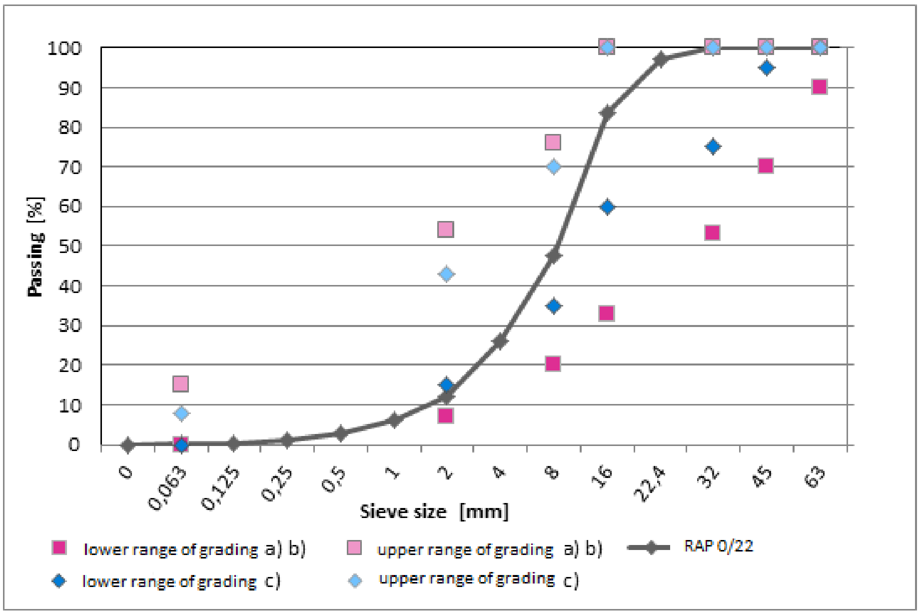
3.2.1 Input materials

For the design and experimental production of cold recycled mixtures reclaimed asphalt material (RAP) 0/22 mm from the Středokluky asphalt plant was used. Properties and composition of the RAP were analyzed in the laboratory and it included determination of bitumen content as well as of physical properties. Field tests i.e. Visual evaluation of the material allowed to determine if the RAP is active or inactive. This means assessment whether the RAP has definite own cohesion thanks to the contained binder. Extraction of the bituminous binder was done according to EN 12697 to reclaim aggregate from the RAP and to determinate the soluble binder content. Determination of the softening point is stated in the EN 1427 standard. The penetration test is defined in the EN 1426 standard. It is a very simple, but widely spread empirical test which is used for description of all bituminous binders. The needle penetration gives us one of the basic technical parameters of bitumen classification. Therefore the penetration test was used for the binder extracted from the used RAP. Gained characteristics of the RAP 0/22 mm, which were used for further mix designs are shown in Table 3.

Table 3: Characteristics of the RAP 0/22 mm from the Středokluky asphalt plant

Bitumen content (% by mass of RAP) according to the EN 12697-1	5,57 %
Softening point determined by the ring and ball method according to the EN 1427	77,4 °C
Penetration determined according to the EN 1426	14 dmm

Grading of the RAP from the Středokluky coating asphalt plant was determined according to the EN 933-1. A grading curve was plotted from the test results and the curve is shown in the Fig. 4 together with recommended requirements on grading envelope of cold recycled mixtures as specified in TP 208.



**Note: a) cement or other hydraulic binder, b) cement + bituminous emulsion/foamed bitumen, c) bituminous emulsion/foamed bitumen*

Figure 4: Grading curve of RAP 0/22

In compliance with the TP 208 a cationic bituminous emulsion of the C60B7 type was used for cold recycled mix design and its production, respectively. The pen grade bitumen 70/100 was used for production of foamed bitumen according to the EN 12591.

Further on, Portland cement (specified as CEM II/B-M (V-LL) 32.5 R), manufactured in compliance with the harmonized standard EN 197-1 was used as a hydraulic binder. Portland composite cement containing total amount of silica ash (V) and limestone (LL) between 21 % and 35 % by mass was selected. It belongs in the 32.5 strength class and has fast development of initial strengths (R). The specifications are given in the following Table 4.

Table 4: Technical parameters of the CEM II/B-M (V-LL) 32.5R Portland cement

Characteristic	Unit	Requirement according to EN 197-1	Average reached values
Beginning of hardening	Minutes	min. 75	180 - 240
Initial strength (2 days)	MPa	min. 10	16 - 22
Normalized strength (28 days)	MPa	32,5 - 52,5	43 - 49
Volume stability	Mm	max. 10	0 – 002
Sulfate content (e.g. SO_2)	%	max. 3.5	30 – 3.4
Chloride content	%	max. 0.1	0.03 - 0.07
Specific surface	$cm^2.g^{-1}$	N/A	3900 - 4400

3.2.2 Production of cold recycled mixtures

The WLM 30 mixing machine (Fig. 5 and 6) designed especially for laboratory applications was used for preparation of all designed cold recycled mixtures. It is a two-shaft drum mixer run by an electrical engine with forced circulation and mixing capacity of 30 kg. Materials are precisely mixed and without any lost due to the possibility to set different mixing periods and adjust number of revolutions.

Each component of the designed mixtures was, at first, weighted on laboratory scales with accuracy of 0.1 g. Then the reclaimed material, binder or water were dosed right into the drum mixer in the given order. A special device for producing foamed bitumen designated as WLB 10 S (Fig. 7) was used for production of cold recycled mixtures with foamed bitumen. This device allows setting different parameters for reaching the required result. The foaming procedure requires setting of parameters like bituminous binder temperature, content of added foaming water and air pressure during the foaming procedure of the bitumen.

Figure 5: two-shaft drum mixer WLM 30

Figure 6: Detail of the two-shaft drum mixer WLM 30

Figure 7: Laboratory device for production (generation) of foam bitumen

3.2.3 Manufacturing of test specimens and curing conditions

Requirements set for production of cold recycled mix specimens differ country by country according to existing national technical specifications. Usually, a static pressure or gyratory compactor is used for compaction; Marshall hammer is used rarely in Europe. The differences in manufacturing do not concern just the equipment used, but more likely size of the test apparatus, number of revolutions, number of strokes etc. Results presented further assume that all specimens were manufactured using a static pressure compaction. In compliance with the Czech specifications TP 208, a mixture is compacted by two pistons moving against each other. The pressure on a specimen is 5.0 MPa. When the load is applied, the vertical force needs to be balanced until it stabilizes at the value of 88.5 ± 0.5 kN for 30 seconds (for test specimens with 150 ± 1 mm diameter). Cylindrical test specimens with 150 ± 1 mm diameter and 60 ± 5 mm height were manufactured for each mixture using the mentioned compaction method. Bulk density was determined for each of the specimens (calculated from dimensions and weight) in order to get the required rate of compaction.

All three designed mixtures were observed to evaluate the effect of curing period and influence of environment where the specimens were stored. The curing conditions of cold recycled mix specimens are described in the TP 208 specifications. The document provides temperature, moisture and time necessary for storing test specimens. Using mixtures bound with bituminous emulsion or foamed bitumen (C and D mixture), test specimens are stored at 90–100 % relative humidity and temperature of (20±2) °C for 24 hours and then exposed to so called accelerated curing. This means that the specimens are moved to a heating chamber which keeps temperature of 50 °C for 72 hours. After elapsing this period the specimens are stored at 15 °C for at least 4 hours and then immediately tested for stiffness modulus. In the following cycle, the test specimens are exposed to ageing process in a heating chamber which keeps temperature of 85 °C for 9 days and then tested for stiffness modulus including indirect tensile strength at temperature of 15 °C (conditioning again for at least 4 hours). The ageing protocol was selected unanimously for the whole CoRePaSol project. In the case of cold recycled mixtures bound with cement and bituminous emulsion (A mixture), the test specimens were stored at 90-100 % relative humidity and temperature of (20±2) °C for 24 hours. Then the specimens cured at dry conditions with relative humidity of 40-70 % and laboratory temperature for additional 14 days. After this period the specimens are conditioned at 15°C for at least 4 hours and tested for stiffness modulus. Another ageing cycle follows like for C and D mixtures; the specimens are heated at temperature of 85 °C for 9 days, then the stored for 4 hours at 15 °C and immediately tested for stiffness modulus and indirect tensile strength.

Table 5: Laboratory curing condition and impact of ageing on test specimens

<table>
<tr><th rowspan="2">Variant of cold-recycled mixture</th><th>1st cycle</th><th>2nd cycle</th></tr>
<tr><th>Laboratory curing condition on test specimens</th><th>Impact of ageing on test specimens</th></tr>
<tr><td>Mix A</td><td>24 hours at moister content of 90-100 % and temperature of 20 ± 2 °C,
72 hours at moister content of 40-70 % and temperature of 50 °C</td><td>9 days at temperature of 85 °C</td></tr>
<tr><td>Mix C</td><td rowspan="2">24 hours at moister content of 90-100 % and temperature of 20 ± 2 °C
14 days of curing in dry conditions</td><td rowspan="2">9 days at temperature of 85 °C</td></tr>
<tr><td>Mix D</td></tr>
<tr><td colspan="3">Note: 90-100 % of relative humidity can be simulated by storing test specimens in sealed plastic bags. Relative humidity 40-70 % represents moisture content of a test specimen at regular atmospheric humidity in the laboratory in unsealed conditions.</td></tr>
</table>

Testing procedures including the ageing process in case of all prepared cold recycled mixtures enable simulating conditions of recycled pavement material at the end of its life-time. The test specimens exposed to the curing process, described in Table 5 were further quickly frozen and immediately crushed using a laboratory jaw crusher (see Fig. 8). This laboratory aged RAP was then used like a multiple recycled material in WMA and HMA mixes which are described in the paragraph 4.4. At the same time this material was used for designing cold recycled mixes with reduced content of newly added bitumen as well.

Figure 8: Crushing procedure for aged specimens

An illustration of multiple aged and crushed RAP is presented in the Figure 9.

Figure 9: Multiple aged and crushed RAP

3.3 Experimental design of multiple cold recycling German study

The aim of this study is to evaluate the end of life properties of pavement layers composed of cold recycled mixtures. As basis for the recyclability evaluations, three kinds of accelerated laboratory aged reclaimed cold recycled mixtures (RCRM) were used as described in section 3.1 (see also Table 1:1):

- RCRM1: 2 % bitumen emulsion, 0 % cement, aged as loose mix
- RCRM2: 2 % bitumen emulsion, 3 % cement, aged as loose mix
- RCRM3: same as RCRM 1 but aged as compacted specimens and crushed afterwards.

The first recycling stage for the virgin material is already represented by the described procedures for the preparation of the reclaimed cold recycled mixtures (RCRM).

For the evaluation of the second recycling stage, three cold recycled mixtures were prepared for which the binder content was varied. From each of these three mixtures, three cylindrical specimens (diameter 150 mm, height 80 mm) were compacted by double-plunger static compaction. After one day in the mould, the specimens were conditioned.

For the reclaimed materials based on RCRM1 and RCRM3, 1 %, 2 % and 3 % of bitumen emulsion were applied without the addition of cement. For these mixtures, the accelerated specimen conditioning for 3 days storage at a temperature of 50 °C was applied (Valentin et al. 2014).

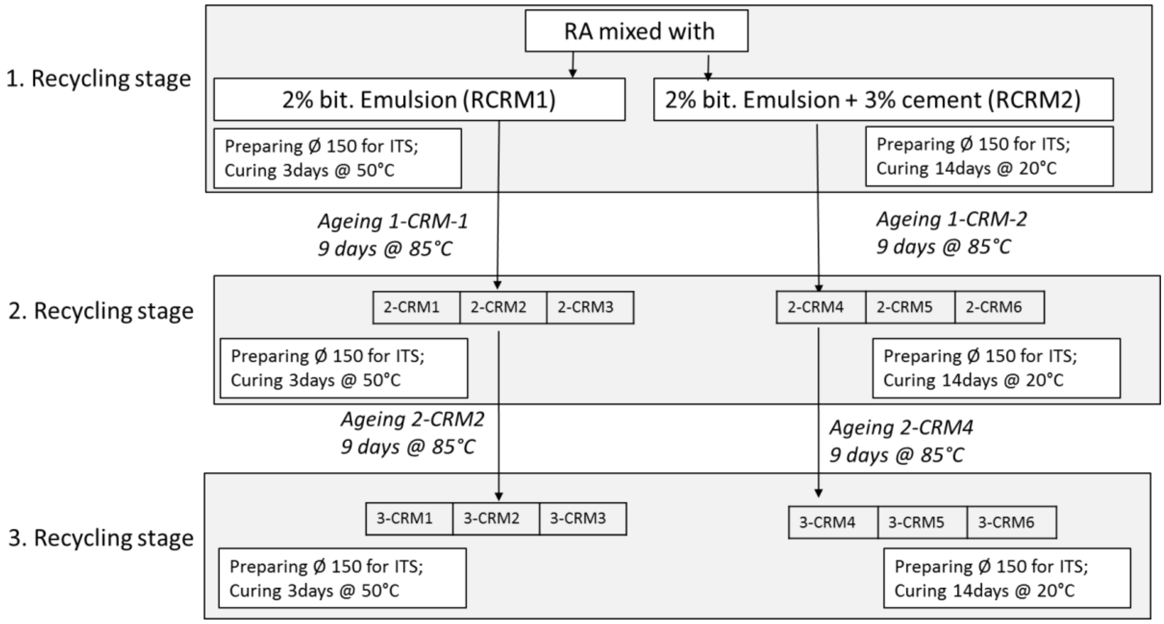


Figure 10: Experimental design of multiple cold recycling study for mix RCRM1 and RCRM2

For the cold recycled mixtures based on RCRM2, 2 %, 4.2 % and 6.7 % of bituminous emulsion as well as 3 % of cement were applied. For these mixtures, the demoulded specimens were stored at room conditions for 14 days before conduction of the mechanical tests.

From the mixtures with the lowest bitumen content, a larger quantity was prepared. These loose mixtures were conditioned according to the prescribed aging protocol (9 days at 85 °C in a ventilated oven), resulting in reclaimed cold recycled materials representing end-of-life material in the second generation (RCRM4 and RCRM5). Based on these mix granulates, again three cold recycled mixtures, representing the third recycling stage were prepared, where the same binder contents were added as in the second recycling stage.

For the study based on crushed specimen-aged mix granulate, mixtures with 2 % of bitumen emulsion and without cement were prepared in the second and third recycling stage.

The overall experimental study designs are plotted in Figure 10 and Figure 11. The labelling of the various mix samples prepared and tested in the study as well as the applied binder contents are explained in Table 6.

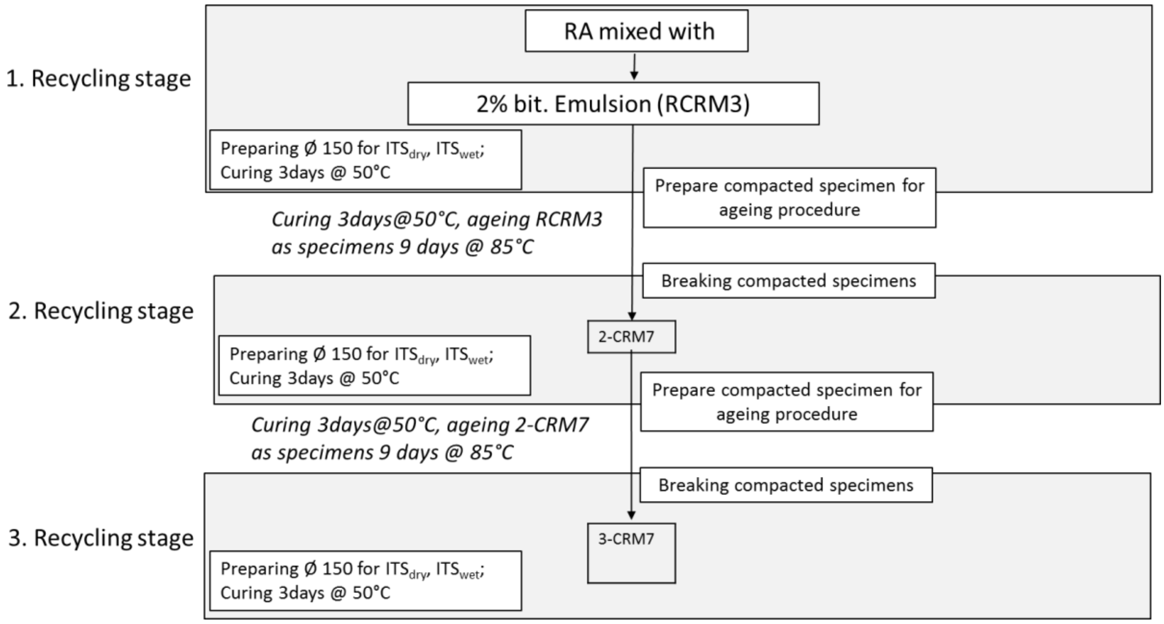


Figure 11: Experimental design of multiple cold recycling study for mix RCRM3

In order to evaluate the quality of the mix variations analysed, it is referred to Valentin et al. (2014). The indirect tensile strength of standard cold recycled mixtures as evaluated at 15 °C on specimens compacted statically in laboratory ranges between 0.40 N/mm² and 0.90 N/mm².

These reference indirect tensile strength values will be applied in order to evaluate the applicability of multiple recycled material in a new cold recycled mixtures.

Table 6: Labeling of mix samples prepared and tested in multiple cold recycling study

Recycling stage	Sample label	Mix granulate	Added bitumen emulsion content	Added cement content	Calculated residual bitumen content
1	1-CRM-1	RA	2 %	0 %	6.3
	1-CRM-2	RA	2 %	3 %	6.1
Simulated reclaimed aged cold recycled mixture	RCRM1	Aged 1-CRM-1			6.3
	RCRM 2	Aged 1-CRM-2			6.1
	RCRM 3	Aged 1-CRM-1 (crushed specimens)			6.3
2	2-CRM1	CRCM1	1 %	0 %	6.5
	2-CRM2		2 %	0 %	7.1
	2-CRM3		3 %	0 %	7.6
	2-CRM4	CRCM2	2 %	3 %	6.8
	2-CRM5		4.2 %	3 %	8.0
	2-CRM6		6.7 %	3 %	9.4
	2-CRM7	CRCM3	2 %	0 %	7.1
Simulated reclaimed aged cold recycled mixture	RCRM4	Aged 2-CRM-2			7.1
	RCRM5	Aged 2-CRM-4			6.8
	RCRM6	Aged 2-CRM-7 (crushed specimens)			7.1
3	3-CRM1	CRCM4	1 %	0 %	7.3
	3-CRM2		2 %	0 %	7.9
	3-CRM3		3 %	0 %	8.4
	3-CRM4	CRCM5	2 %	3 %	7.4
	3-CRM5		4.2 %	3 %	8.6
	3-CRM6		6.7 %	3 %	10.0
	3-CRM7	CRCM6	2 %	0 %	7.3

3.3.1 Laboratory tests conducted in multiple cold recycling study

3.3.1.1 Preparation of cold recycling mixture, specimen compaction and curing

The cold recycling mixtures were prepared in a laboratory mixer, compacted by applying double plunger static compaction procedure with a maximum force of 49 kN. After one day the specimen were demoulded and conditioned according to the conditioning regime selected regarding the cement content in the mixture (compare 3.1.3):

- Mixtures without cement: 3 days @ 50 °C,
- Mixtures with cement: 14 days @ room conditions.

3.3.1.2 Bulk density, maximum density and void content

From the bulk density, which was measured on the specimens prepared in the 3 recycling stages before temperature conditioning for conducting the test and the maximum density calculated from the constituent densities, and material composition, the voids content was calculated.

3.3.1.3 Indirect tensile strength test (IDT)

The indirect tensile strength test (IDT) was applied in order to determine the strength of the compacted and cured specimen. Before the test, each specimen was temperature conditioned for 4 h at 15°C in a temperature cabinet. Afterwards it was placed between two loading strips. The bottom loading strip is raised with a rate of 50 mm/min resulting in a vertical compression stress loading of the specimen. This results in a horizontal tensile stress which results in the formation of a crack indicating the failure of the specimen. From the maximum force F_{max} recorded during the loading, the indirect tensile strength (ITS) was calculated according to (2).

$$ITS = \frac{2 \ F_{max}}{\pi \ d \ h} \qquad (2)$$

where ITS is the indirect tensile strength [MPa], F_{max} is the maximum force recorded during the loading [N], d is the specimen diameter [mm] and h is the specimen height [mm].

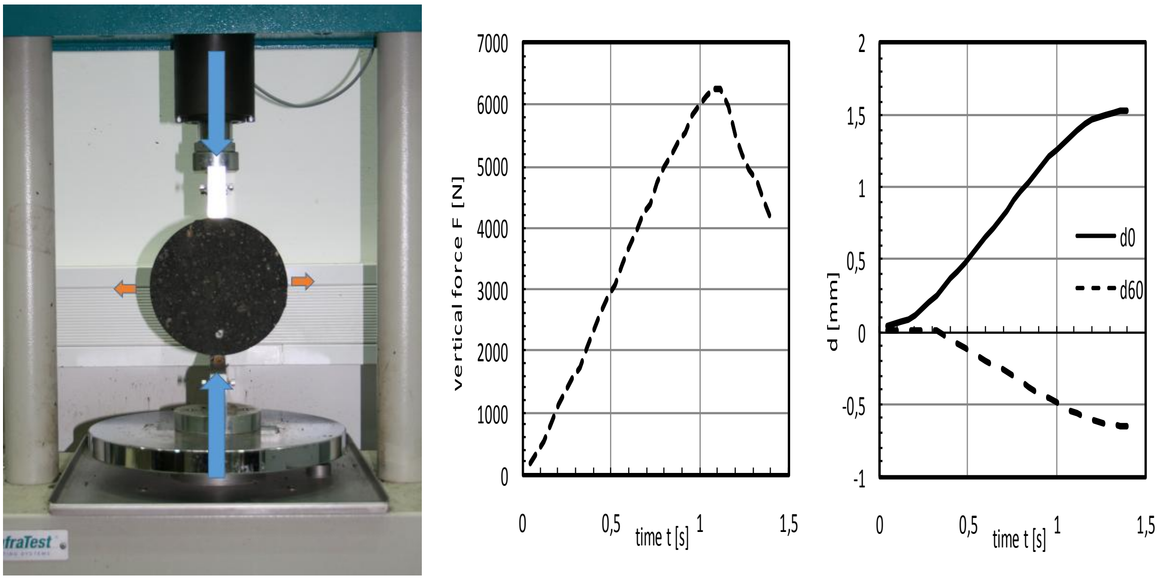


Figure 12: Indirect Tensile Strength Test

3.3.1.4 Moisture susceptibility

For evaluating the Moisture susceptibility of the compacted specimen, indirect tensile stress tests were conducted both on dry as well as on wet specimens, which were vacuum saturated and stored in a water bath at a temperature of 40 °C for 3 days (procedure according to EN 12697-12). After the water storage period, the specimens were temperature conditioned in a temperature cabinet to the test temperature of 15 °C and the indirect tensile strength was measured (compare 3.3.1.3).

3.4 Experimental design of multiple cold recycling Czech study

3.4.1 Laboratory tests conducted within the multiple cold recycling study

3.4.1.1 Preparation of cold recycled mixtures, specimen compaction and curing

In the Czech Republic based on the specifications given in TP 208, a mixture is compacted by two pistons moving against each other (compaction by static vertical pressure). The pressure on a specimen has to be 5.0 MPa. When the load is applied, the vertical force has to be repeatedly adjusted until it stabilizes at the value of 88.5 ± 0.5 kN for 30 seconds (for test specimens with 150 ± 1 mm diameter). Cylindrical test specimens with 150 ± 1 mm diameter and 60 ± 5 mm height were manufactured for each mixture using the described procedure.

3.4.1.2 Bulk density, maximum density and void content

For the determination of specimen bulk density for cold recycled mixes a standard test method for hot asphalt mixtures according to EN 12697-6 was used. Bulk density of each test specimen was determined from the weight and volume of the specimen. Weight (mass) of a specimen was gained by weighting dry specimen on air. The maximum density of a cold recycled mix was determined according to EN 12697-5 where test methods for hot asphalt mixtures are defined. Gained maximum density together with the bulk density is used for calculation of voids content for the compacted specimen. At the same time also other properties of compacted cold recycled mix can be calculated if related to volumetric properties. The determination of voids content of a cold recycled mix is defined in the technical standard EN 12697-8 and the calculation proceed from the two mentioned characteristics. Following equation can be used for calculating voids content:

$$V_m = \frac{\rho_m - \rho_b}{\rho_m}.100 \qquad (3)$$

3.4.1.3 Stiffness

Stiffness of asphalt mixtures is determined in order to find out the strain behavior of this pavement material. This helps to estimate behavior of the whole pavement structure. The EN 12697-26 standard prescribes possible test methods applicable for stiffness measurement depending on available testing devices and testing conditions. Amplitude of stress and strain together with phase angle between stress and strain are recorded during the test. The key principle of the test is to raise deformation of a specimen within its linear strain domain. This can be achieved by harmonized loading or by loading with constant strain. The standard describes test methods according to the modus of applied loading. The stiffness modulus, concerned in the analyses conducted within this study, was determined by the indirect tensile stress test on cylindrical specimens (IT-CY). Test specimen is exposed to loading dependent on sinusoidal amplitude which is constant in time. Applied force and phase angle are recorded.

Stiffness modules were determined in compliance with EN 12697-26 applying the IT-CY test method (repeated non-destructive indirect tensile stress test) determined at the temperature of 15 °C. Stiffness modules were determined on the designed (unaged) mixtures after the first cycle of their curing and then after ageing (at temperature of 85 °C after 9 days).

3.4.1.4 Indirect tensile strength

The indirect tensile strength test is conducted according to the standard EN 13286-42 and is partially modified according to the TP 208 specifications. The principle of the test is measurement of the acting compression force on a specimen including caused horizontal strain until the specimen breaks.

3.5 Applicability of hot recycling (German case study)

Hot recycling of reclaimed asphalt is widely applied in the asphalt industry. In daily practice, considerable amounts of reclaimed asphalt can be added to new asphalt mixtures without special testing of the resulting mixture. The resulting mixture which contains reclaimed asphalt has to meet the same technical requirements as asphalt mixtures with new constituent materials. The hot recycling process is widely applied because the bitumen in the reclaimed asphalt can – at least in accepted theory – be reactivated during the mixing process and therefore, the consumption of new binder can be reduced.

The current study was designed in order to evaluate if the bitumen bound in cold recycled mixtures also can be fully or partly reactivated by hot recycling process in future.

Therefore, four hot asphalt mixtures were designed with varied reclaimed asphalt content and with varied added bitumen contents. In the study, firstly the content of reclaimed asphalt was varied (15 % and 30 %). Furthermore, for later RA content the activity of the cold recycled bitumen was evaluated by varying the content of added bitumen.

Table 7 presents the mix variants containing an asphalt concrete mix AC 16 as applied for asphalt binder courses. Besides the reference mix (R), AC 16 variations containing 15 % or 30 % of reclaimed asphalt were prepared. For the larger RA content, the added bitumen content was varied by considering that all of the bitumen in the reclaimed cold recycled mixture (RCRM) can be reactivated during hot mixing process (V2), only 50 % of the RCRM binder is active (V3) or even that the whole bitumen as stored in the cold recycled mixture is lost for the hot recycling process (V4).

For the hot recycling study, the reclaimed cold recycling mixture RCRM 2 (compare **Ошибка! Источник ссылки не найден.**) was used. The cold recycled material was prepared with 2 % bituminous emulsion and 3 % cement. Specimens were compacted according to EN 12697-30 from the cold recycled mixture, cured for 14 days under room conditions and afterwards aged in laboratory for 10 days at 85 °C.

Table 7: Cold recycled mix options

Mix variants	Content of reclaimed cold recycled mixture (cured and aged)	Content of fresh bitumen	Considering bitumen content in cold recycling mixture
Reference (R)	0%	100%	-
V1	15%	100% - 100%RC	100%
V2	30%	100% - 100%RC	100%
V3	30%	100% - 50%RC	50%
V4	30%	100% - 0%RC	0% („Black rock“)

Afterwards the compacted specimens were crushed (compare 3.1.3).

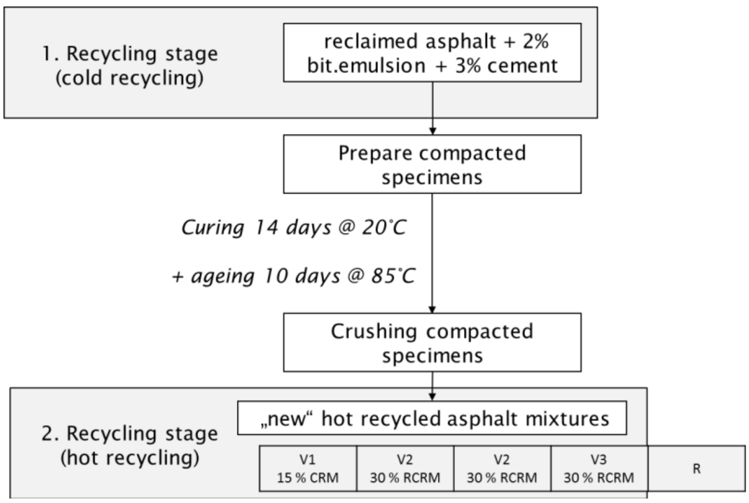


Figure 13: Recycling procedure and chosen stages

3.5.1 Source materials and mix design

For mixing AC 16 washed basalt aggregates and limestone filler was used. Figure shows the grading of the aggregates used as well as the grading of the aggregates recovered from the reclaimed cold recycled mixture (RCRM). Figure shows the grading envelopes for the applied AC 16 mix according to German specification document (FGSV, 2007) as well as the mix design grading applied in this study.

A bitumen content of 4.6 % in the reference mixture was fixed based on a mix design study. As a binder, a straight bitumen 50/70 was applied.

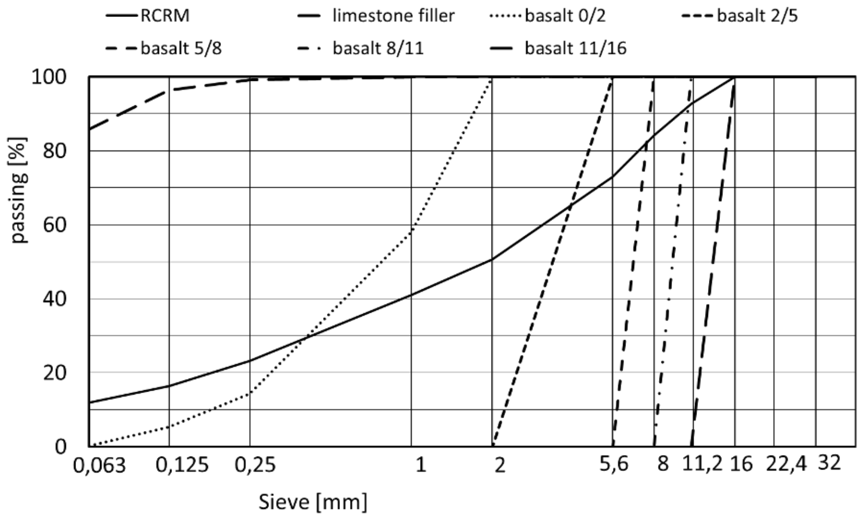


Figure 14: Grading of basalt aggregate and limestone filler

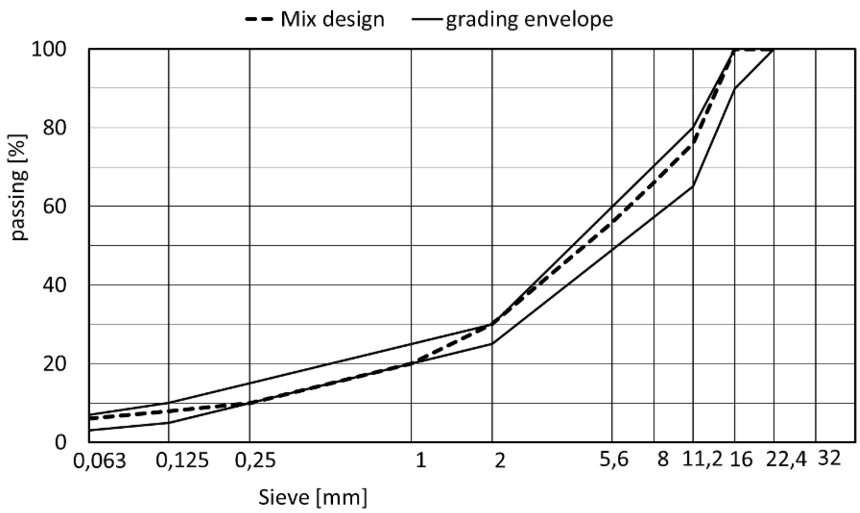


Figure 15: Mix design for AC 16 BS

3.5.2 Laboratory tests applied in hot recycling study

3.5.2.1 Bulk density and void content

The bulk density of asphalt specimens (ρ_{bssd}) was tested according to EN 12697-6, method B (4).

$$\rho_{bssd} = \frac{m_1}{m_3 - m_2} * \rho_w \quad (4)$$

m_1 Weight of dry specimen [g]

m_2 Weight of specimen under water [g]

m_3 Weight of dried specimen [g]

ρ_w Water density: 0,997 g/cm³

The void content according to EN 12697-8 was determined by the bulk density and the maximum density measured according to EN 12697-5:

$$V = \frac{\rho_m - \rho_b}{\rho_m} * 100 \tag{5}$$

ρ_m	Density of asphalt mixture [g/cm³]
ρ_b	Bulk density of bituminous specimen [g/cm³]

3.5.2.2 *Compactibility test*

For the evaluation of the compaction resistance, a specimen is compacted according to EN 12697-10 by applying 2 x 100 impacts. During the compaction process, the specimen height is measured. The recorded thickness reduction during the compaction process can be mathematically interpreted by an exponential function (6) where three physically relevant regression coefficients (t_0, t_∞, T) are evaluated. As example, Figure 16 shows the reduction of the specimen thickness during the compactibility test.

$$\frac{1}{t(E)} = \frac{1}{t_\infty} - \left[\frac{1}{t_\infty} - \frac{1}{t_0}\right] \cdot e^{-\frac{E}{T}} \tag{6}$$

t(E)	Specimen thickness in dependent of the compaction work E_2
E	Compaction work [21 Nm], number of compaction blows
t_∞	Minimum of specimen thickness [mm]
t_0	Specimen thickness [mm] at the beginning of compaction
T	Compaction resistance, determined by the change in specimen thickness

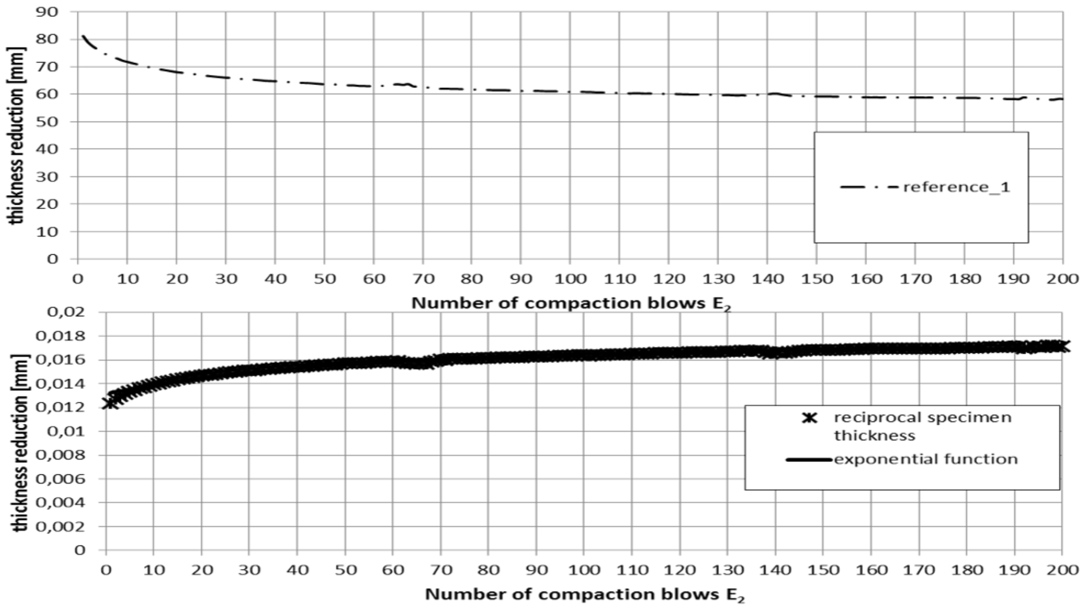


Figure 16: Specimen thickness development during impact compaction

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3.5.2.3 Wheel tracking test

For evaluating the resistance of an asphalt mixture against rutting, wheel tracking tests according to EN 12697-22 were applied using the small wheel tracking device. Asphalt slabs compacted according to EN 12697-33 and using the steel roller sector were fixed into the wheel tracking device (Figure 17Figure). During 20.000 wheel passes applied at a temperate of 60 °C, the rut depth was measured.

As a result, the rut depth and its slope after 20.000 wheel passes are evaluated.

Figure 17: Wheel tracking test setup

3.5.2.4 Indirect tension test

The indirect tension test according to EN 12697-23 was applied on impact compacted specimens in order to evaluate the specimens indirect tensile strength at a temperature of 15 °C. The specimen is placed between an upper and lower loading strip which are moved towards each other with a loading rate of 50 mm/min until failure of the specimen (compare Figure 12).

The indirect tensile strength (ITS) is determined from the maximum force F_{max} measured during the test (compare 3.3.1.3).

3.5.2.5 Resistance against frost/thaw

The resistance against moisture and frost of the hot mix asphalt was determined according to AASHTO T283. The asphalt specimens were prepared and compacted according to EN 12697-30 by applying 2 x 25 impact blows for reaching large void contents.

The specimens were water saturated by applying a vacuum down to 6.7 ± 0.3 kPa for 10-15 minutes. Afterwards the water saturated specimens were conditioned in a plastic bag with 10 ml water inside a cooling chamber at -18 °C for 16 h (+/- 1 h) and then in a water bath at 60°C for 24 h.

After water bath conditioning the specimen were temperature conditioned to test temperature for 3 – 4 h (test temperature = 15 °C) and indirect tensile test according to EN 12697-23 was conducted.

For evaluating the asphalt mix resistance against moisture and frost the indirect tensile strength ratio between moisture/frost conditioned specimen (ITS_{Ice}) and dry specimens (ITS_{dry}) is determined.

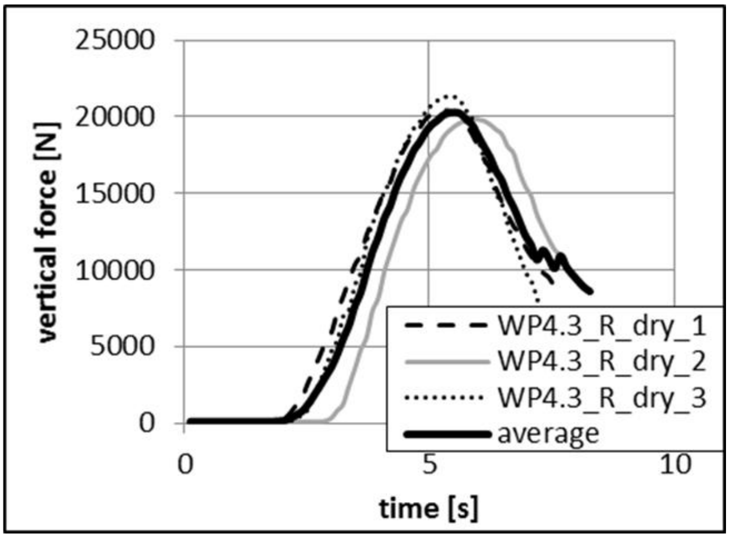

Figure 18: Indirect Tensile Strength Test

3.5.2.6 Moisture susceptibility

The moisture susceptibility of the hot mix asphalt was determined according to EN 12697-12. Therefore impact compacted specimen (2 x 25 blows) were prepared. Whereas three specimens were stored in dry conditions, three specimens were water saturated by applying a vacuum down to 6.7 ± 0.3 kPa for 30 minutes. Afterwards the specimens were conditioned in a water bath at 40°C for 68 - 72 h. After water bath conditioning the specimen were temperature conditioned to the test temperature (15 °C) of the indirect tensile test. For estimating the moisture susceptibility which is a measure to evaluate the adhesion between bitumen and aggregates, the ITS measured on wet specimens (ITS_{wet}) is compared to the indirect tensile strength of the dry specimens (ITS_{dry}) by calculating the ratio between these values.

3.6 Recyclability in hot and warm mix asphalt – Czech case study

This part summarizes the laboratory assessment conducted for asphalt recyclability of hot asphalt mixes according to the case study done in the Czech Republic. Within the testing done at the Department of Road Structures, CTU in Prague, firstly the influence of used RAP on mix properties was observed using a reference asphalt concrete mix ACO 11+ (AC for wearing course) with common distilled bitumen of pen grade 50/70 according to EN 13108-1. Marginally tests have been started for a standardized SMA 11+ mix with alternative designs containing up to 30 % reclaimed asphalt material (RAP). Beside of the reference ACO 11+

mix, several variants of same mix type were designed due to gained findings. Some of the alternative mixes contained low-viscous bitumen with addition of the Fischer-Tropsch paraffin (FTP) or market known surfactant Evotherm MA3. Both are commonly used WMA additives of known properties and influence on asphalt mix. From the point view of the laboratory tests, attention was focused on empirical and mechanical properties of experimentally produced mixes, e.g. voids content, moisture susceptibility, resistance to permanent deformation and determination of bending tensile strength (flexural strength). For all mixes gained data were analyzed and evaluated including comparison to the reference mix with findings presented in following sub-chapters.

A reference asphalt concrete mix ACO 11+ was designed in accordance with EN 13108-1. This mix was used as the basis for further assessments of possible reuse of once recycled asphalt material in a hot asphalt mix. In this case part of the aggregates was replaced by the RAP. In parallel other mix variants were designed focusing on reduced mixing and compaction temperatures containing suitable additives.

Evotherm MA3 was the first used additive. It is a surfactant used since several years for warm mix asphalts. It improves the lubrication effect between the aggregates coated by bitumen whereas this is possible for temperatures usually decreased by at least 30 °C. This can save more than 20 % of production energy, at the same time the RAP is not heated to very high temperatures which avoids additional ageing and deterioration of the bitumen in RAP. Decrease of working temperatures has a positive influence on production of GHG emissions as well. Evotherm ensures better process ability and adhesion of a binder to aggregate. The Fischer-Tropsch paraffin (FTP; Sasobit) was the second selected additive used for designing and producing an alternative AC mix. The reason for selecting FTP was that it is one of the most commonly used WMA additives. The mix contained 20 % of re-crushed RAP of 0/22 mm grading from cold recycled and artificially aged mixture marked SC (see the paragraph 4.2.1) Aggregate for the asphalt mix were from the Libodřice quarry (amphibolite). In the first step, grading curve of the RAP was determined to later design the AC mix composition which should be similar to the reference mix. Furthermore, bitumen content of the RAP was assessed by standard asphalt extraction procedure with determination of soluble binder content, in parallel grading of the cleaned aggregate used in the RAP could be analyzed as well. The grading curve of the mix with 20 % by mass of RAP was designed with respect to the final reference ACO 11+ (AC_{surf}) mix composition with 0 % of RAP. The FTP and Evotherm additives were dosed right into the binder. Doped bitumen was sufficiently blended (150 °C mixing with 300-400 revolutions per minute for 10-15 minutes) and then used for manufacturing the mix.

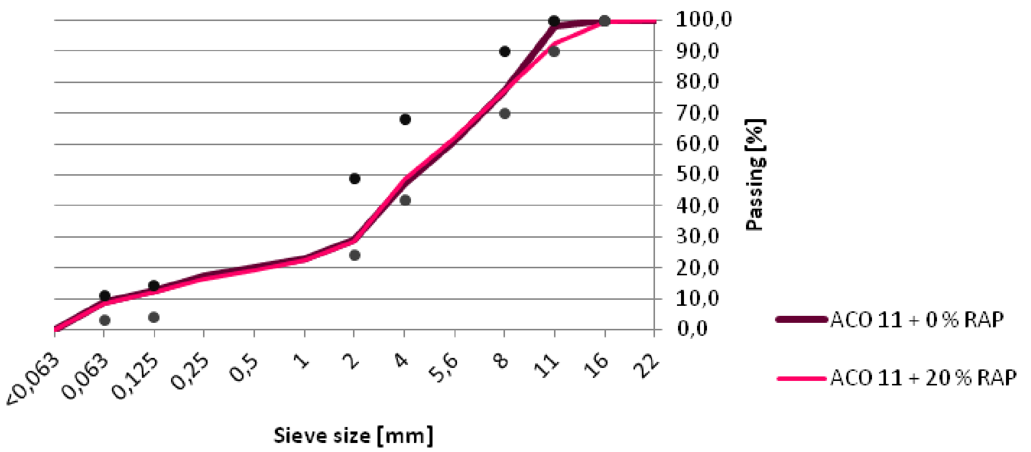

Figure 19: Grading curve of reference mix ACO 11 and mix variation containing 20 % RAP

The reference mix ACO 11+ was designed with optimal bitumen content of 5.2 % by mass of the mix. The mix variants with RAP contained only 3.6 % by mass of either bitumen 50/70 or one of the low-viscous binders prepared with distilled bitumen of 70/100 pen gradation. The reason for reduced bitumen addition was that already 1.6 % by mass of bitumen was already included in the added RAP calculated to 100 % of asphalt mix. The selected additives were dosed with different ratios – FTP was used with 3 % by mass of bituminous binder and Evotherm MA3 with 0.5 % by mass of the bitumen.

3.7 Recyclability in hot-mix asphalt – Portuguese case study

3.7.1 Introduction

In order to evaluate the recyclability of cold recycled mixtures with focus on experience and conditions typical for Southern Europe, a study was conducted in which performance related properties of a conventional Hot Mix Asphalt (HMA) using new aggregates, was compared to the ones obtained for the same type of mixtures, but incorporating 30 % of a cold recycled mixture (using bituminous emulsion).

3.7.2 Materials

For the production of a hot asphalt mixture, a typical mix design used in Portugal, mainly in wearing courses, was selected (AC14 surf PMB 45/80-60), being adopted the following composition:

- 21.0 % of basalt 10/16
- 31.4 % of basalt 4/12
- 19.1 % of basalt 0/4
- 19.0 % of limestone 0/4
- 4.8 % of filler
- 4.7 % of PMB 45/80-60

Figure 20 shows the grading curve of the adopted mix of aggregates, as well as the Portuguese required envelop for the referred type of mixture (AC14 surf).

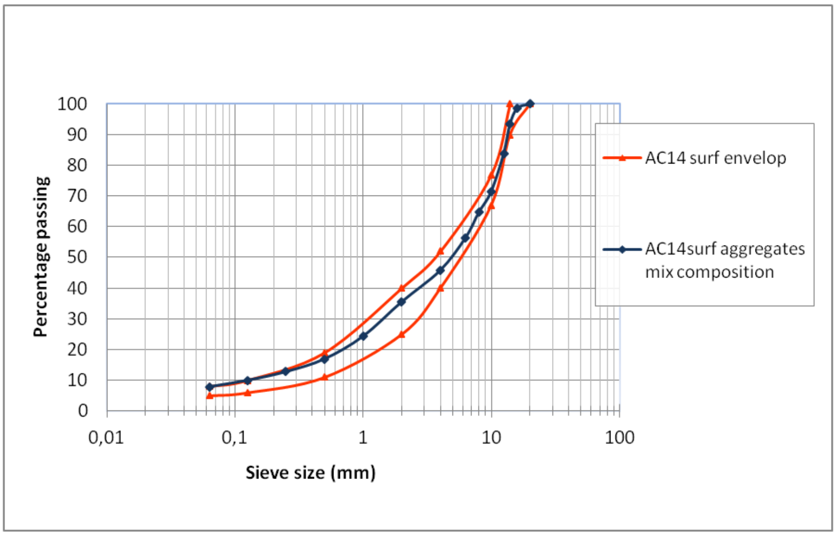

Figure 20: Mixture of aggregates curve and envelop for AC14 produced with virgin aggregates

In the framework of CorePaSol project, several cold recycled mixtures have been produced. Among these, CM-E4 mixture was selected to be used in this study. CM-E4 cold recycled mixture was produced using the following materials:

- 91.8 % of reclaimed asphalt (originated from the milling of the upper layers of a Portuguese National Road pavement, which recovered binder of 4.5 % showing penetration of 12 x 10-1 mm and a softening point of 73.4 °C);
- 2.8 % of filler
- 3.8 % of bituminous emulsion C60B5
- 1.6 % of added water

Test specimens produced with this mixture and further cured, were used in order to obtain cold recycled mixture to evaluate its recyclability. Specimens of fully cured CM-E4 mix were loosened, both by mechanical and manual procedures.

With respect to simulate freshly-milled reclaimed asphalt pavement (from a cold recycled layer), an accelerated ageing procedure was selected. Taking into account that this ageing procedure should simulate long term ageing, and that a homogeneous reclaimed material should be obtained in order to be re-used in the production of a new bituminous mixture, the following procedure was adopted: loose bituminous mix was spread on a tray and stored for 9 days in a ventilated oven at a temperature of 85 °C, according to a method that is further included in the newly proposed EN 12697-52.

The processed reclaimed “cold recycled” material (RCRm) used in this study was investigated for grading before (RCRm-Bit) and after bitumen extraction (RCRm-Bitout), as shown in Figure 21.

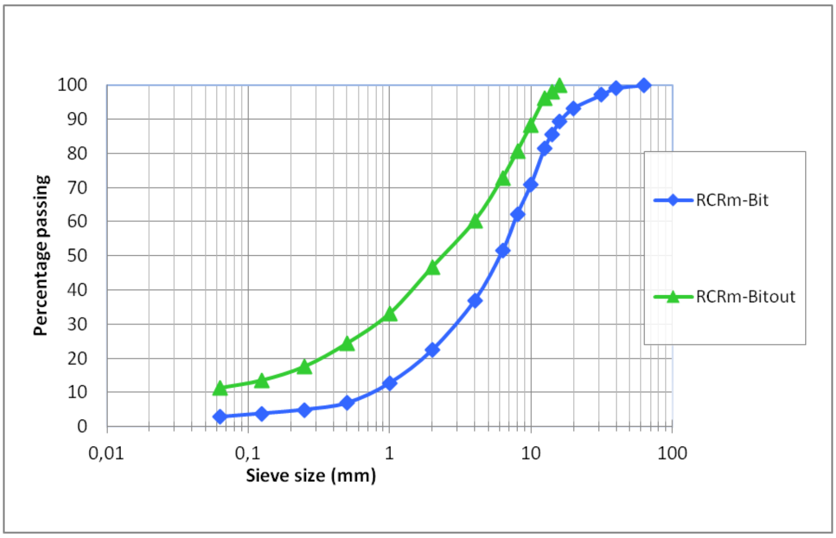

Figure 21: Reclaimed "cold recycled" material grading curves with bitumen (RCRm-Bit) and without bitumen (RCRm-Bitout)

The mix composition of the RCR material (CM-E4 fully cured and long-term aged) has supposedly the following composition:

- 93.4 % of mixture of aggregates (90.5 % of aggregate from the cold recycled RAP + 2.9 % of filler)
- 6.6 % of bitumen residue (4.3 % of old bitumen from the cold recycled RAP + 2.3 of residual bitumen from C60B5 emulsion)

For the mix composition of the hot recycled mix incorporating 30 % of RCRm (HRM30%RCRm), it was considered that only 50 % of the "aged" binder of the reclaimed material would behave as an active binder. As so, the following composition for the hot recycled mix was adopted (bearing in mind that a similar composition to the previously identified AC14 should be obtained):

- 30.0 % of RCRm
- 16.4 % of basalt 10/16
- 27.0 % of basalt 4/12
- 22.1 % of basalt 0/4
- 2.9 % of filler
- 3.7 % of PMB 45/80-60

The maximum density of the produced HMA was determined (EN 12697-5, method A), as shown in Table 8.

Table 8: Maximum density of cold recycled mixtures

Hot Mix Asphalt ID		AC14	$HRM_{30\%RCRm}$
Maximum density	ρ_{mv} **(Mg/m^3)**	2.667	2.628

With each one of the referred HMAs (AC14 and HRM30%RCRm), test specimens were prepared according to the shape and dimensions required for the test.

3.7.3 Laboratory tests

In order to assess performance related properties of the reference hot asphalt mixture (AC14 produced with new aggregates) and the hot recycled mixture (incorporating 30 % of "aged" cold recycled material), tests usually performed on conventional hot mixtures were performed equally in both mixtures. A synthesis of the main tests carried out to characterise both hot mixes were the following:

- Determination of void characteristics of bituminous specimens, according to EN 12697-8, including:
  - Determination of the maximum density (EN 12697-5, method A);
  - Determination of bulk density of bituminous specimen (EN 12697-6, Procedure B: Bulk Density — Saturated surface dry (SSD))
- Marshall tests, performed in accordance to EN 12697 34;
- Wheel tracking tests, performed in accordance to EN 12697-22, small size devices, procedure B, in air, at a temperature of 60 ºC;
- Water sensitivity tests, performed in accordance to EN 12697 12 (method A: ITT), at a temperature of 15 ºC.

The results obtained are further presented in section 4.5.

4 Results of the laboratory tests and discussion

4.1 Multiple recyclability in cold recycling – German case study

The following section discusses the results of the case study presented in chapter 3.3.

4.1.1 Results obtained on cold recycled mixtures without cement addition (BSM)

The results obtained on the cold recycled mixtures without addition of cement are summarised in Table 9.

Table 9: Test results obtained on samples based on reclaimed cold recycled mixture RCRM 1 without cement addition (bitumen stabilised materials)

Recycling stage	Specimen no.		Max. density [g/cm³]	Bulk density [g/cm³]		Voids content [%]		ITS_{3days} [MPa]	
				single value	Mean	single value	mean	single value	average
I	1-CRM-1	1	2.604	2.258	2.263	13.3	13.1	0.637	0.705
		2		2.268		12.9		0.743	
		3		2.263		13.1		0.736	
II	2-CRM1	1	2.593	2.169	2.169	16.3	16.3	0.826	0.803
		2		2.176		16.1		0.785	
		3		2.163		16.6		0.797	
	2-CRM2	1	2.595	2.193	2.186	15.5	15.8	0.800	0.823
		2		2.201		15.2		0.864	
		3		2.163		16.6		0.804	
	2-CRM3	1	2.568	2.181	2.185	15.1	14.9	0.882	0.840
		2		2.192		14.7		0.847	
		3		2.182		15.0		0.790	
III	3-CRM1	1	2.556	2.095	2.114	18.0	17.3	0.530	0.561
		2		2.125		16.9		0.575	
		3		2.121		17.0		0.577	
	3-CRM2	1	2.564	2.146	2.122	16.3	17.2	0.591	0.563
		2		2.131		16.9		0.558	
		3		2.088		18.6		0.540	
	3-CRM3	1	2.510	2.101	2.104	16.3	16.2	0.517	0.531
		2		2.093		16.6		0.521	
		3		2.118		15.6		0.555	

The void contents evaluated for the specimens from these BSM mixtures are plotted in Figure 22. With closer look to mixtures containing 2 % bituminous emulsion in all recycling stages (1-CRM1, 2-CRM2 and 3-CRM2) the void content increases from recycling stage to recycling stage (I stage = 13.1 %, II stage = 15.8 %, III stage = 17.2 %). This can be explained by the increased resistance against compaction in the mixtures. With the same compaction effort, in recycling stage 2 and 3 lower bulk densities can be achieved compared to the initial cold mix preparation.

Within the 2nd and 3rd recycling stage the average of voids content decreases with increased content of bituminous emulsion. This can also be observed with standard cold recycled mixtures.

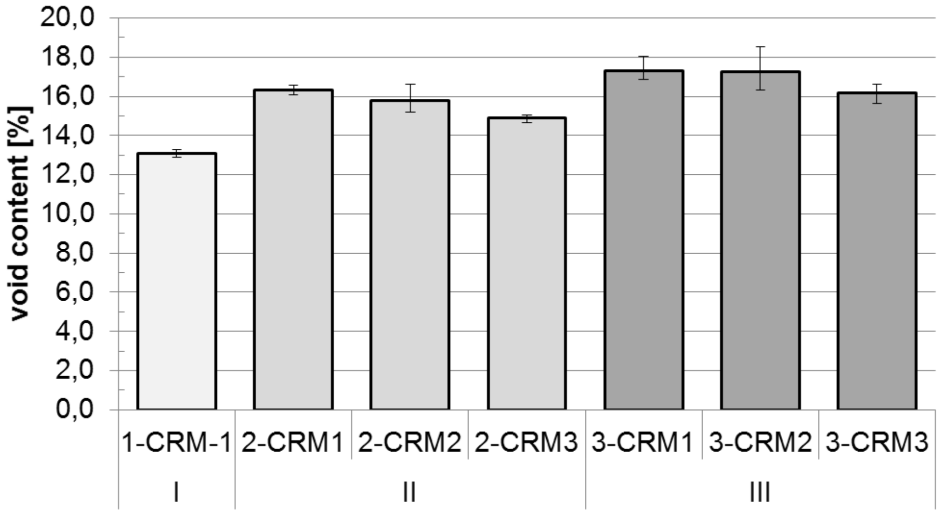

Figure 22: Voids content of specimens from RCRM1 for 3 recycling stages

Figure 23 presents the results of indirect tensile strength for specimens prepared with bituminous emulsion after 3 days of dry conditioning during mix design procedure in the 3 recycling stages.

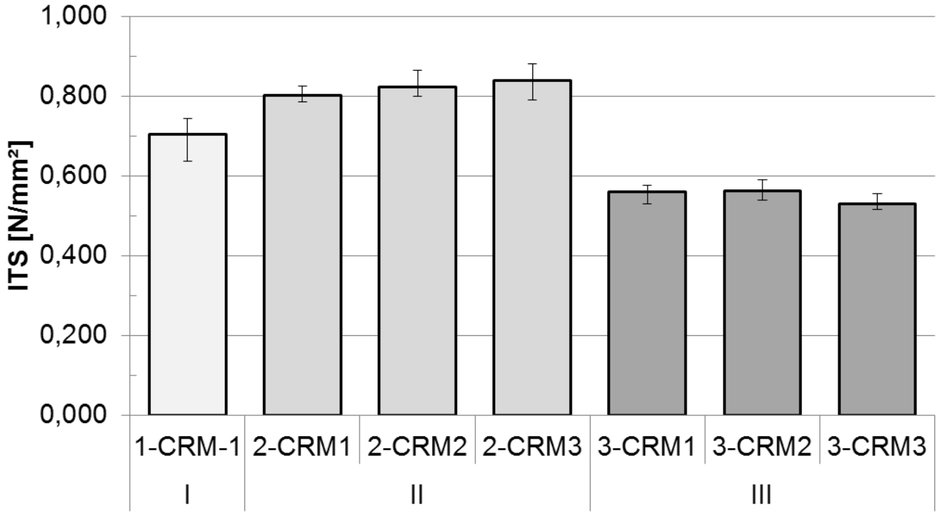

Figure 23: ITS for the 3 recycling stages for RCRM1

The results for mix variations with bituminous emulsion for indirect tensile strength are obviously affected by recycling stages.

For the mixtures with a bituminous emulsion content of 2 % the indirect tensile strength increases from recycling stage 1 to stage 2 (1-CRM1: 0.7 MPa, 2-CRM2: 0.8 MPa) but decreases again to recycling stage 3 (3-CRM2: 0.56 MPa) significantly. This effect cannot be explained by varied voids content. But when considering the increasing total bitumen content in the resulting cold recycled mixture from recycling stage to recycling stage, the results are consistent. In recycling stage 2, the increased bituminous emulsion content results in an increase of indirect tensile strength. This cannot be observed in the third stage. Here an increase in bituminous emulsion has no effect on the indirect tensile strength. A reason is the high total bitumen content in the resulting mix, which reaches values of up to 9.40 %. The viscous material properties will reduce the stiffness and therefore also the strength in the material.

4.1.2 Results obtained on cold recycled mixtures with cement addition (BCSM)

The test results obtained on the cold recycled mixtures prepared with cement addition are summarised in Table 10.

Table 10: Test results obtained on samples based on reclaimed cold recycled mixture RCRM 2 with cement addition

Recycling stage	Specimen no.		Max. density [g/cm³]	Bulk density [g/cm³]		Void content [%]		ITS_{14days} [MPa]	
				single value	mean	single value	mean	single value	mean
I	1-CRM-2	1	2.620	2.248	2.260	14.2	13.8	0.718	0.759
		2		2.259		13.8		0.760	
		3		2.271		13.3		0.798	
II	2-CRM4	1	2.609	2.153	2.118	17.5	18.8	0.767	0.751
		2		2.086		20.0		0.747	
		3		2.114		19.0		0.738	
	2-CRM5	1	2.543	2.178	2.184	14.3	14.1	0.803	0.829
		2		2.174		14.5		0.828	
		3		2.198		13.5		0.855	
	2-CRM6	1	2.496	2.179	2.202	12.7	11.8	0.759	0.752
		2		2.216		11.2		0.764	
		3		2.210		11.5		0.732	
III	3-CRM4	1	2.542	2.073	2.080	18.5	18.2	0.820	0.816
		2		2.087		17.9		0.874	
		3		2.080		18.2		0.753	
	3-CRM5	1	2.440	2.113	2.116	13.4	13.3	0.985	0.948
		2		2.098		14.0		0.872	
		3		2.136		12.5		0.986	
	3-CRM6	1	2.419	2.183	2.160	9.8	10.7	1.072	1.043
		2		2.150		11.1		1.017	
		3		2.148		11.2		1.041	

The voids contents obtained after 14 days of curing at room conditions are shown in Figure 24.

For mixtures with the same content of added binders in the three recycling stages (1CRM2, 2-CRM4 and 3-CRM4) it can be observed that the voids content significantly increases from recycling stage 1 to 2 from 13.8 % up to 18.8 %. In the third stage, similarly high voids content is observed.

Within recycling stages 2 and 3, the increase in bitumen emulsion content will result in significantly decreasing voids content.

The indirect tensile strength obtained for the cold recycled mixtures with added cement are plotted in Figure 25. For the same binder contents applied in recycling stages 1, 2 and 3 (samples 1CRM2, 2-CRM4 and 3-CRM4), very similar indirect tensile strength results are obtained which are not affected by the differing voids content.

In recycling stage 3 a significant strength increase can be observed with increasing bitumen emulsion content.

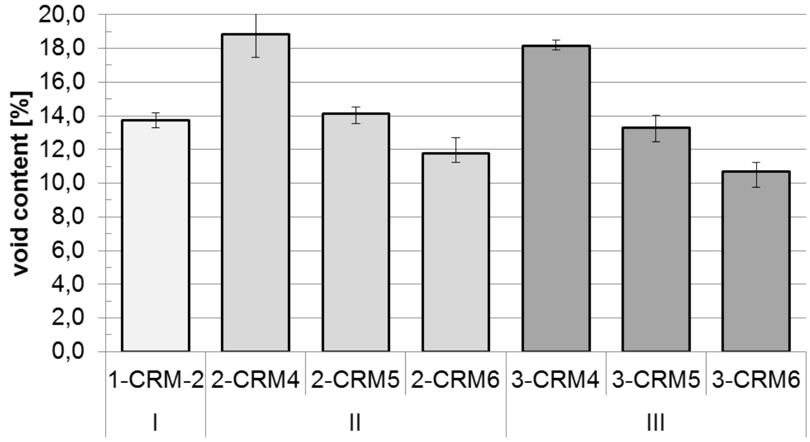

Figure 24: Voids content obtained on samples based on reclaimed cold recycled mixture RCRM 2 with cement addition

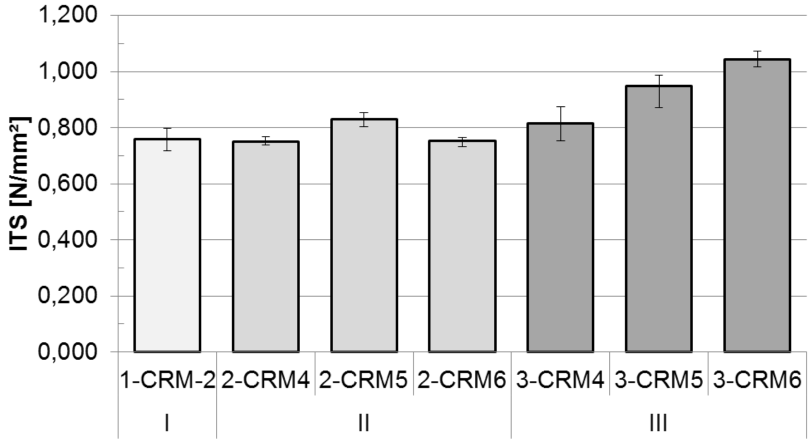

Figure 25: ITS obtained on samples based on reclaimed cold recycled mixture RCRM 2 with cement addition

4.1.3 Results obtained for cold recycled mixtures prepared from crushed specimen of aged mixtures

The test results obtained on the cold recycled mixtures where crushed specimens after laboratory ageing were used as mix granulate are summarised in Table 11.

The voids contents measured after dry conditioning (3 days @ 50 °C) of the compacted samples are plotted in figure 26. The voids content obtained in stage 1 and 3 is similar at values of about 13 %. Only in recycling stage 2 increased voids content can be observed.

Table 11: Test results obtained on samples based on crushed compacted and aged specimen composed of cold recycled mixtures without cement addition

Rec. stage	Sample label	Specimen no.		Max. density	Bulk density [g/cm³]		Voids content [%]		ITS_{3days} [MPa]		ITSR [%]
					single value	mean	single value	Mean	single value	mean	
I	RCRM3	ITSwet	4	2.605	2.284	2.277	12.3	12.6	0.281	0.312	46.5
			5		2.285		12.3		0.350		
			6		2.263		13.1		0.304		
		ITSdry	1	2.617	2.310	2.301	11.7	12.1	0.678	0.670	
			2		2.291		12.5		0.634		
			3		2.302		12.0		0.698		
III	2-CRM7	ITSwet	4	2.556	2.201	2.190	13.9	14.3	0.435	0.429	70.9
			5		2.180		14.7		0.423		
		ITSdry	1	2.591	2.180	2.181	15.9	15.8	0.655	0.605	
			2		2.199		15.1		0.596		
			3		2.164		16.5		0.563		
III	3-CRM7	ITSwet	4	2.563	2.193	2.194	14.4	14.4	0.429	0.441	68.3
			5		2.194		14.4		0.453		
		ITSdry	1	2.539	2.191	2.202	13.7	13.3	0.649	0.646	
			2		2.212		12.9		0.649		
			3		2.204		13.2		0.639		

For evaluating the effect of the application of crushed samples for mix granulate preparation with the usage of aged loose mixture, the results obtained for the same binder contents are added to the figure (compare Table 8). For the recycling stages 1 and 2 similar void contents are obtained independently of the procedure to obtain the laboratory simulated mix granulate. However, for recycling stage 3, the voids content obtained on the mixtures prepared from the crushed specimens is significantly lower compared to the mixtures where loose cold recycled mix was laboratory aged and applied in new mix.

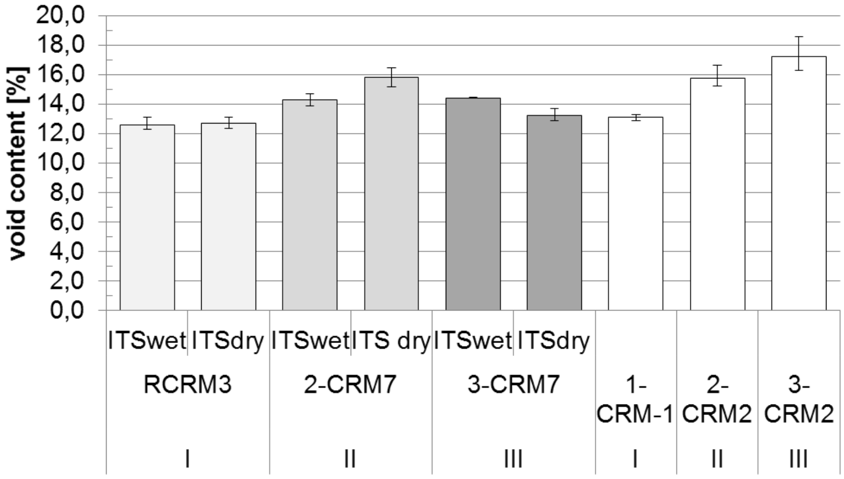

Figure 26: Voids content of specimens obtained from crushed aged BSM specimens for 3 recycling stages and the results obtained on aged loose mix for comparison

The indirect tensile strength results obtained are plotted in Figure 27. For the dry conditioned specimens similar indirect tensile strengths of around 0.60 MPa were obtained.

The wet conditioned specimens indicate a significantly lower strength compared to the dry conditioned specimens. This results in remaining strength (ITSR) values of below 50 % in recycling stage 1 and around 70 % in recycling stages 2 and 3. When comparing the results obtained on cold recycled mixtures prepared from laboratory aged and crushed specimen with the results obtained of cold mixtures where the mix granulate was aged without compaction, significant differences of the indirect tensile strength can be observed.

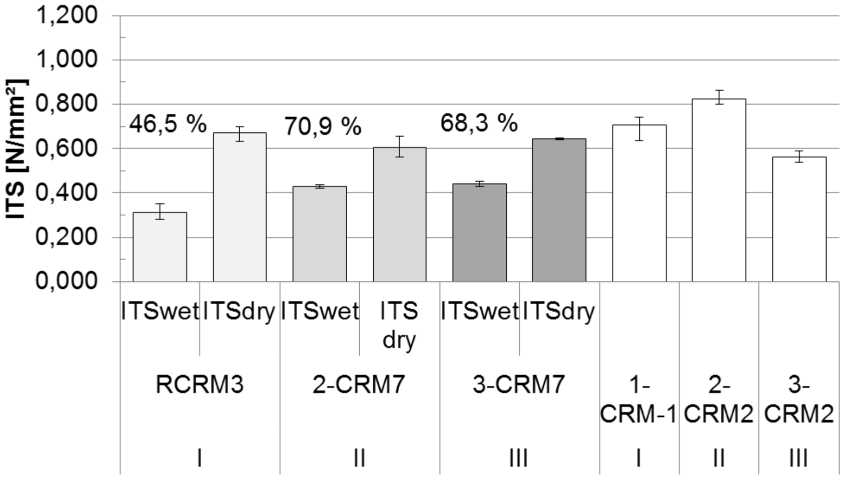

Figure 27: Indirect tensile strength of specimens obtained from crushed aged BSM specimens for 3 recycling stages and the results obtained on aged loose mix for comparison

4.1.4 Discussion about multiple recyclability in cold recycled mixtures

The results obtained for cold recycled mixtures prepared after laboratory ageing of cold recycled materials indicated that generally, a multiple recycling in cold mixtures can be applied. However, the mixtures evaluated have to be discussed separately, because some different tests results could be obtained.

For the cold recycled mixtures without cement, the indirect tensile tests conducted indicate a general applicability of the cold recycling process. All evaluated strength values are between 0.4 MPa and 0.7 MPa which were regarded as reference values (compare **Ошибка! Источник ссылки не найден.**). Therefore, the mixtures in the third recycling stage are suitable for application of cold recycling as well. However the low strength values obtained in the third recycling stage indicate an excess of total bitumen in the mixture. In practice, this issue shall be checked for reclaimed material with high bitumen content by application of suitable tests for evaluation of the material resistance against permanent deformation (e. g. CBR, triaxial tests).

For the cold recycled mixtures with cement addition, also the applicability of three recycling cycles could be proven by indirect tensile stress test results. However especially with repeated cold recycling, the mix demands for a considerable amount of bituminous emulsion in order to reach suitable void contents (≥ 4.2 %). In the third recycling stage, the indirect tensile strength values exceed the upper reference value of 0.7 MPa. Though, the high bitumen content won't result in brittle material behaviour.

The results obtained on cold recycled mixtures based on mix granulate, which was crushed from aged specimens, showed significant differences to material which were prepared from loosely aged cold recycled mixtures. However the above mentioned conclusions also can be drawn for these samples. Only in the first recycling stage, the remaining strength after water saturation is too small indicating reduced water sensitivity of the mix. With increasing binder content in recycling stages 2 and three the remaining strength reaches values allowing the application of these mixtures even without cement addition.

In summary, once cold recycled mixtures reaching the end of their service life they can be recycled again with the same technology.

4.2 Multiple recyclability in cold recycling – Czech case study

The following section discusses the results of the case study presented in chapter 3.4.

The results gained from the measurements of cold-recycled mixtures, with bitumen emulsion/foam including the variant of using the hydraulic binder are described in the following paragraph.

Results gained for assessed cold recycled mixes containing bituminous emulsion/foamed bitumen or variations where also hydraulic binder is used, are described in following sub-sections. Table 12 summarizes basic physical properties of cold recycled mix characterization which was applied for three assessed variations of aged cold recycled mix. Bulk density and maximum density are important parameters, whereas to the bulk density most of the other measured characteristics are related. As is obvious, maximum densities for cold recycled mixes containing bituminous emulsion and cement, as well as mixes containing only emulsion have similar values. Mix C shows slightly increased value. On the other hand maximum density for mix D where only foamed bitumen was used, reaches lower values. Further it is necessary to point out, that for mixes A and C test specimens were gradually prepared in several batches with a time lag of several days.

Table 12: Test results for initial cold recycled asphalt mixes

Variant of cold-recycled mixture	Maximum density [g/cm³]	Bulk density [g/cm³]	Voids content [%]	ITS [MPa]
Mix C - 01	2.441	2.187	10.4	0.935
Mix C - 02	2.407	2.140	11.1	0.963
Mix C - 03	2.400	2.094	12.8	1.068
Mix A - 01	2.399	2.180	9.1	1.219
Mix A - 02	2.388	2.176	8.9	1.189
Mix D - 01	2.323	2.110	9.2	1.203

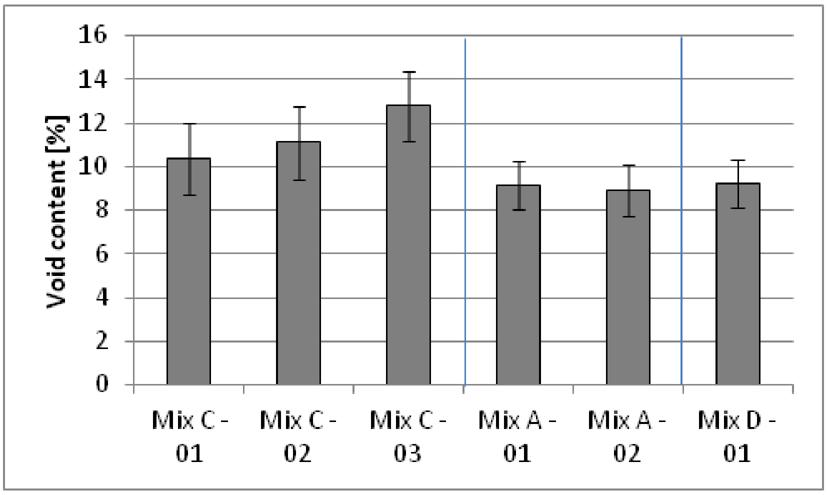

Figure 28: Voids content of experimentally designed cold recycled mixes

Values of cold recycled mix voids content are for better lucidity shown in Figure 28. With respect to this characteristic it is not possible to see any logical trend within these tested mixes. Highest voids content is reached for mix C where bituminous emulsion and no hydraulic binder was used with an average value of 11.4 %-vol. Mixes A and D reach nearly same results, in case of mix A the voids content is 9.0 %-vol. and in case of mix D 9.2 %-vol.

Figure 26 illustrates results of indirect tensile strength test. If it would be assumed to compare ITS results with the requirements given for cold recycled mixes in Czech technical specifications following conclusions can be made. Technical specifications TP 208 prescribe a technical requirement according to used stabilizing agent. For cold recycled mixes where bituminous emulsion or foamed bitumen is used the minimum indirect tensile strength after 7 days is set as R_{it} = 0.3 MPa. In case of mixes where bituminous binder is combined with cement, this required value has to be within the range of 0.3 MPa and 0.7 MPa, whereas the upper limit is selected with respect to avoid the risk on micro-cracking. In both cases the ITS is determined at 15 °C. Results of gained ITS values, which are also shown in Figure 29, were determined on aged test specimens. The quality of the asphalt cold recycled mix is therefore proven by reached required value of particular indirect tensile strength, eventually stiffness modulus. From the results it is obvious, that the highest values of gained ITS after cold recycled mix ageing are reached for mix A and mix D – in average 1.20 MPa. In comparison to that mix C shows only strength values around 0.99 MPa

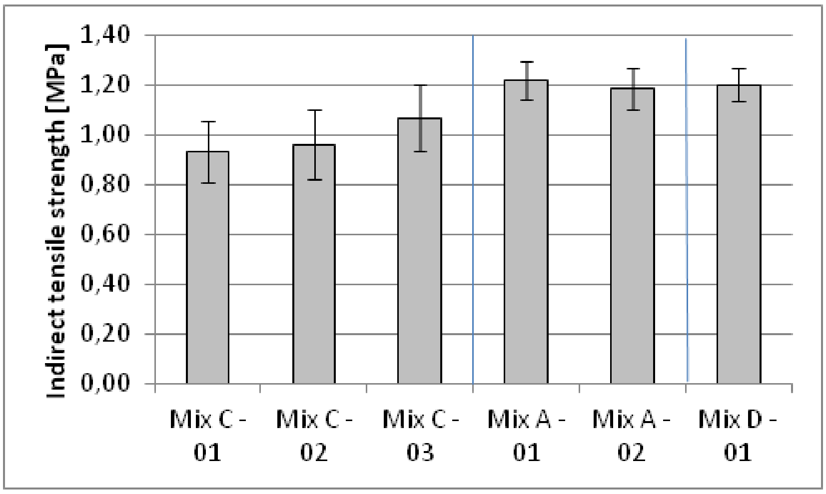

Figure 29: Indirect tensile strength of experimentally designed cold recycled mixes

For all three designed mix types stiffness modulus after first ageing cycle of test specimens was determined as well. The ageing effect depends on the assessed cold recycled mix type. For mixes with use of hydraulic binders the stiffness was determined after 15 days curing, in case of mixes without cement this was determined already after 5 days (accelerated curing). Further the effect of test specimen ageing was reflected simulating material behaviour in the pavement structure which is for a certain time in operation. At the end of ageing the stiffness modulus was determined again and finally the indirect tensile strength was tested. Despite of the fact that Czech technical standards do not require the check on stiffness for this type of material and there is no minimum required threshold value, it is seen as a very important characteristic, which has a good predictive ability for describing cold recycled mix behaviour in a pavement similarly to the destructive testing of indirect tensile strength. At the same time stiffness represents an important parameter from the viewpoint of pavement structural design. Therefore for all mixes with unaged and aged material stiffness was always determined at the temperature of 15 °C by applying the IT-CY test method.

Comparison of stiffness modulus values for cold recycled mixes before and after ageing is illustrated in Figure 30. From the gained results following findings and conclusions can be made. Stiffness modulus of mix A where bituminous emulsion is applied together with cement shows highest average values before ageing (3,943 MPa). On the other hand mixes C and D reach approximately values of 2,100 MPa. It is therefore possible to demonstrate again the influence of hydraulic binder content, which improves stiffness and ITS values. Ageing leads to increase in stiffness of tested mixes and the values correspond again well with results of indirect tensile strengths which were determined after ageing as well. Mix A reaches in average stiffness values of 6,900 MPa. This means an increase of about 75 % of original value before ageing procedure. In case of mix C it can be stated, that stiffness modulus results are in average 4,700 MPa what is an increase by more than 125 %. Highest relative increase after ageing is nevertheless reached for cold recycled mixes with foamed bitumen (mix D). In this case stiffness was raised by more than 140 %. In general this corresponds well with results gained for indirect tensile strength. Only in case of mix D the ITS reaches in average higher increase of measured values.

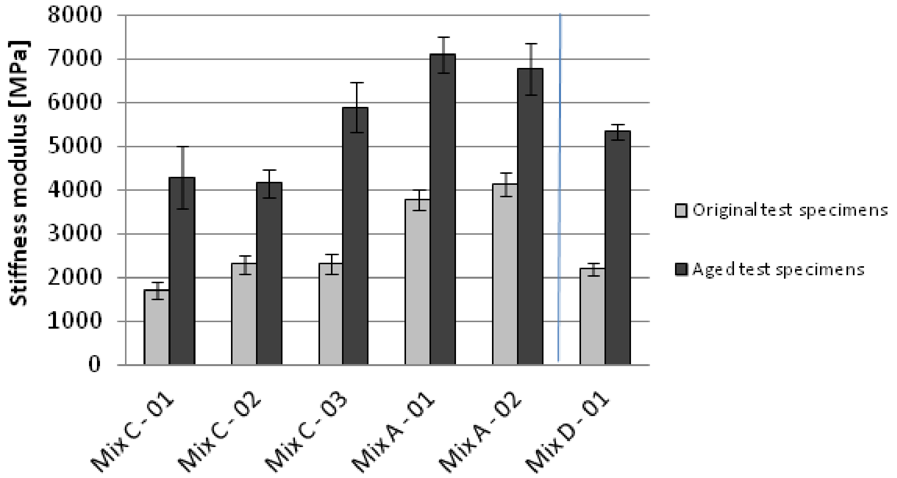

Figure 30: Impact of ageing shown on stiffness modulus values

4.2.1 *Multiple recycled cold mixes*

Aged material from cold recycled mixes described in article 2 was re-crushed by a laboratory jaw crusher and used for new design of cold recycled mixes. The selected mix designs are summarized in following Table 13. For each proposed experimental mix two sets of test specimens were produced and compacted. Test specimens were left for 24 hours in sealed conditions at laboratory temperature and then moved to a climatic chamber and unsealed conditioned at 50 °C for three days. After this time period the test specimens were measured on their dimensions, weighed and divided in two groups. First group of test specimens was left at standard laboratory conditions for three days, second group was water saturated and conditioned for 3 days in a water bath at 40 °C. After 7 days curing stiffness modulus was determined on all test specimens at 15 °C. Lastly indirect tensile strength was set at the same temperature.

Table 13: Design of multiple cold recycled mixes

Mix	RAP	Stabilizing agent content			Water content
		Cement	Bituminous emulsion	Foamed bitumen	
SA	95.5% - RAP A	-	2.0 %	-	2.5%
SC	95.5% - RAP C	-	2.0 %	-	2.5%
SD	94.0% - RAP D	-	-	2.0 %	2.0%

For each reclaimed asphalt material its grading has to be declared, i.e. relative mix composition showing the total mass of particular particle sizes including its expression in form of a grading curve. For the later mix designs and use of aged recycled materials in cold and hot mixes grading curves of all applied re-crushed and aged variations of reclaimed asphalt material were calculated and plotted.

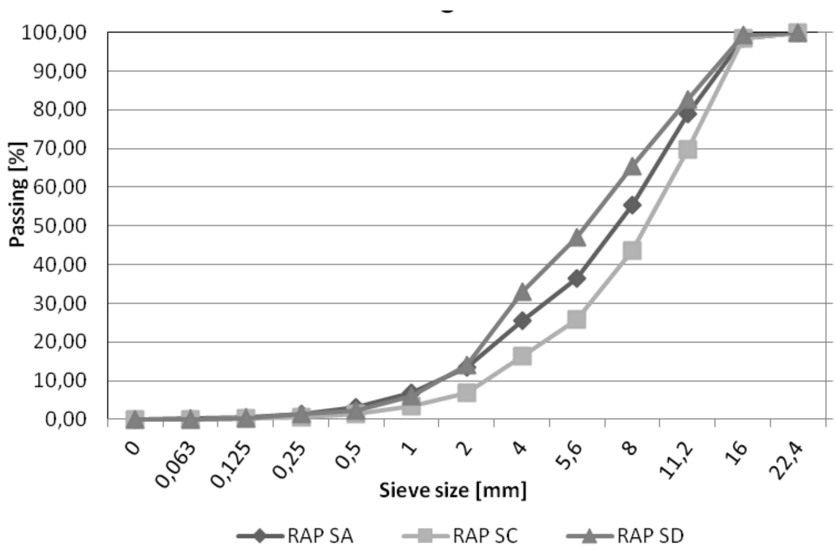

Figure 31: Grading curves of aged and re-crushed material from cold recycled mixes

Basic characteristics determined on test specimens of designed mixes are summarized in Table 14. From the results it is evident that voids content of the assessed mixes have similar trend like for cold recycled mixes produced and compacted before the artificial laboratory ageing. For mixes SA and SC resulting voids content is 13.4 %, experimental mix with foamed bitumen as a binder shows lower value of 9.6 %.

Table 14: The basic empirical and mechanical characteristics

Cold recycled mixture	Maximum density [g/cm³]	Bulk density [g/cm³]	Voids content [%]	ITS_{dry} [MPa]	ITS_{wet} [MPa]	ITSR [%]
SA	2.407	2.059	13.4	0.798	0.546	68.46
SC	2.328	2.017	13.4	0.796	0.666	83.67
SD	2.300	2.078	9.6	0.834	0.526	63.11

If we focus on comparing results of gained ITS values and display them in Figure 33, then it can be concluded, that slightly higher values of 0.83 MPa was reached for the mix SD containing foamed bitumen. Set of test specimens of mixes SA and SC reaches in average similar results around 0.80 MPa.

From the Figure 34 where ratios of indirect tensile strength values are done for dry specimen and water saturated specimen subjected to adverse impact of higher temperature of 40 °C it is obvious that there is a negative impact of water on the test specimens. From the results it is apparent that mix SD containing bituminous emulsion resist better the adverse effects of water if compared with the other two mixes. The mix is less water susceptible. Mixes SA and SD are reaching ITSR value lower than 70 %.

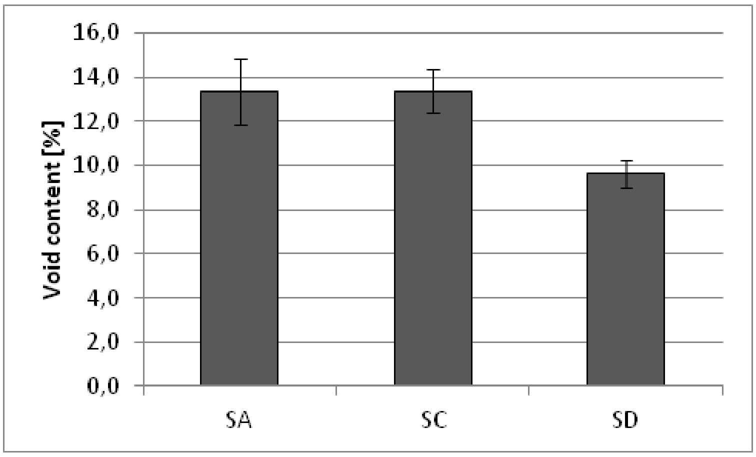

Figure 32: Voids content of cold recycled mixes made with re-crushed and aged RAP

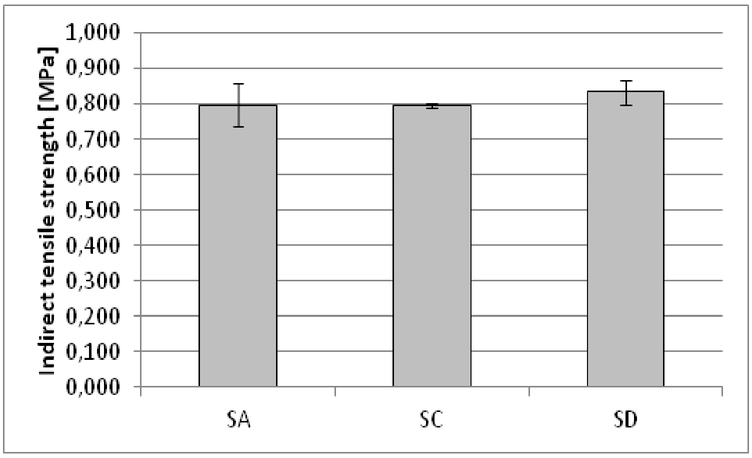

Figure 33: ITS values of cold recycled mixes made with re-crushed and aged RAP

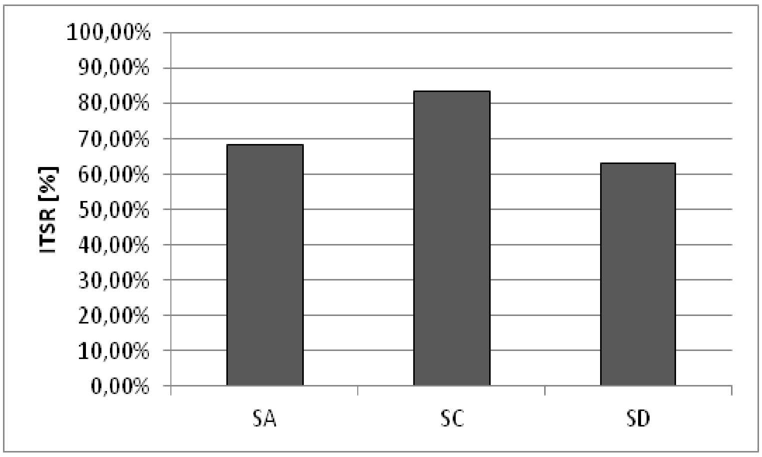

Figure 34: ITSR values of cold recycled mixes made with re-crushed and aged RAP

Last but not least of the attention is paid to comparison of stiffness modules, the results confirm findings made for indirect tensile strength. Cold recycled mix SC resist again better negative impacts of water as against remaining two experimental mixes. Stiffness modulus of used dry test specimens for mix SC (3,161 MPa) and mix SD (3,185 MPa) – both containing bituminous emulsion or foamed bitumen – show in average similar result, whereas mix SA (2,629 MPa) reached a lower value. In this case surprisingly the hydrated cement in the aged and re-crushed cold recycled material A does not have any effect on the properties of newly produced cold recycled mix SA, the binder acts as a regular mineral part of the aggregates.

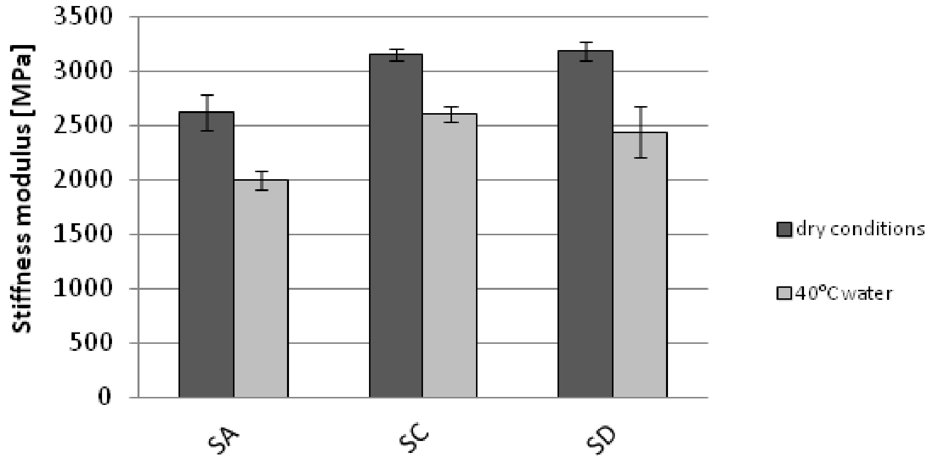

Figure 35: Stiffness of cold recycled mixes with re-crushed and aged RAP, including water susceptibility

4.3 Recyclability in hot mix asphalt – German case study

In this section the results of the laboratory tests are summarised for evaluating recyclability in hot mix asphalt as presented in chapter 3.5. Firstly, the voids content is discussed followed by indirect tensile strength tests (ITS), water susceptibility, moisture damage, wheel tracking, compactibility and bitumen properties. The diagrams indicate the arithmetic mean evaluated for the test results as well as the range of single values measured. All tests were conducted with two or three repetitions.

4.3.1 Voids content

The voids content of impact compacted specimen (2 x 50 blows) is determined from their bulk density and the maximum density of the asphalt mixture. The results are presented in Figure 36.

The reference asphalt mixture (R) has a voids content of 7.0 %. The two samples with reclaimed cold recycled mixture (RCRM), for which all the RCRM-bitumen was considered as active (V1 and V2) reach similar voids contents. The samples, where 50 % or all of the RCRM-bitumen was considered as inactive (V3 and V4) have significantly lower void contents. For these, obviously the high added bitumen content results in differing mix properties compared to the reference mixture.

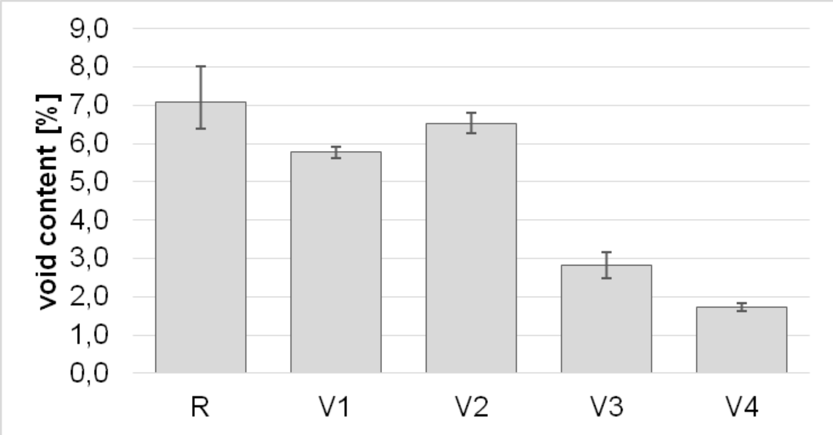

Figure 36: Results for voids content

4.3.2 *Indirect tensile strength on dry, water conditioned and frost/thaw-conditioned specimens*

The measured indirect tensile strengths of the tested hot mix asphalt samples are summarised in Table15 and plotted as mean values and value range in Figure 37.

Table 15: Overview results ITS_{dry}(T = 15 °C)

Sample	No.	Dry			Wet (EN 12697-12)			Ice (AASHTO T283)		
		Bulk density	Indirect tensile strength [MPa]		Bulk density	Indirect tensile strength [MPa]		Bulk density	Indirect tensile strength [MPa]	
			Single value	mean		Single value	mean		Single value	mean
R	1	2.468	2.109	2.107	2.439	2.148	2.142 (102 %)	2.357	1.936	1.956 (93 %)
	2	2.460	2.040		2.430	2.206		2.405	1.976	
	3	2.430	2.171		2.435	2.071		-		
V1	1	2.443	2.124	2.174	2.442	2.333	2.272 (105 %)	2.404	2.413	2.300 (106 %)
	2	2.441	2.224		2.430	2.080		2.382	2.187	
	3	-			2.431	2.402		-		
V2	1	2.464	2.811	2.900	2.431	2.512	2.664 (92 %)	2.391	2.797	2.546 (88 %)
	2	2.442	2.865		2.437	2.771		2.381	2.295	
	3	2.452	3.024		2.463	2.708		-		
V3	1	2.497	3.122	2.843	2.449	2.970	2.962 (104 %)	2.425	2.671	2.624 (92 %)
	2	2.482	2.861		2.496	2.943		2.439	2.576	
	3	2.407	2.545		2.484	2.972		-		
V4	1	2.511	3.112	2.962	2.524	3.247	3.241 (109 %)	2.477	2.854	2.849 (96 %)
	2	2.503	2.938		2.524	3.335		2.476	2.844	
	3	2.507	2.837		2.521	3.140		-		

For the dry conditioned specimen, the indirect tensile strength of samples R and V1 are significantly lower compared to the strength obtained for the samples V2 to V4. The water conditioned as well as the frost/thaw conditioned specimen show an increasing strength from the reference sample “R” with increasing RCRM content (V1 and V2) as well as with increasing bitumen content (V3, V4).

The water conditioning for three days at 40 °C according to EN 12697-12 results in a decrease of indirect tensile strength by 8.2 % (remained strength: 92 %) only in sample V2. For the other asphalt samples, a small increase of the indirect tensile strength could be observed. Therefore, there are no water sensitivity issues in the tested mixtures. Obviously the combination of aggregates (basalt) and bitumen indicates very good adhesion properties.

For the frost/thaw conditioned specimen according to AASHTO T283, a small decrease of the indirect tensile strength could be observed in samples R, V2, V3 and V4. With 88 % the highest strength decrease could be observed in sample V2.

The comparably high effect of water and/or frost conditioning observed for sample V2 can be explained by a comparably high indirect tensile strength of the dry conditioned test specimen. The difference to the other samples therefore is not significant.

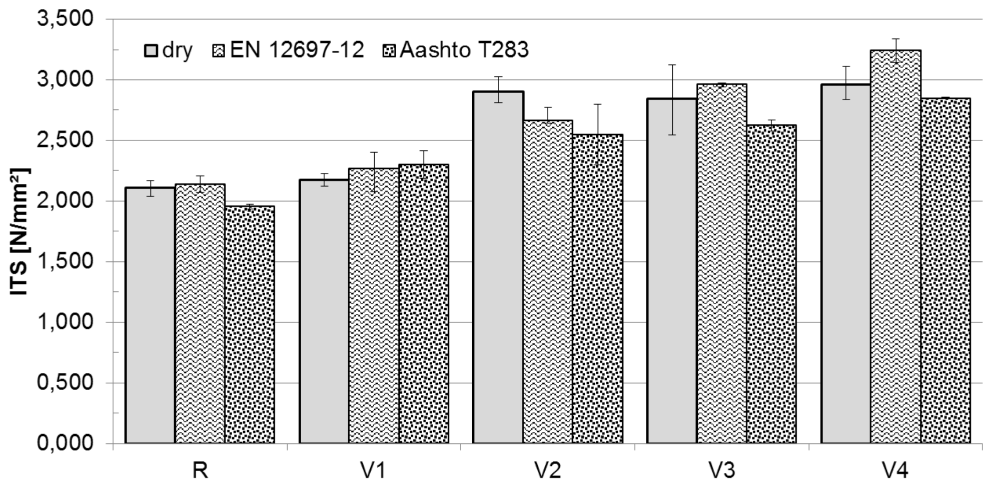

Figure 37: Indirect tensile strength of tested hot mix asphalt samples

4.3.3 Results of wheel tracking tests

Table 16 presents the rut depth obtained in wheel tracking tests according to EN 12697-22 20000 roller passes. In Figure 38 the mean rut depth development during the tests are plotted.

In consideration of mix variations R, V1 and V2 the rutting depth decreases with increasing content of RCRM.

With regard to the mixtures containing 30 % of cold recycled material the increasing content of added bitumen in samples V2 to V4 results in significant increases of the rut depths.

Table 16: results for rutting depth after 10000 cycles

Sample		Bulk density	Rut depth RD_{AIR} [mm]		Wheel tracking slope WTS_{AIR} [µm/cycle]	
			Single value	mean	Single value	mean
R	1	2.532	4.23	4.23	0.11	0.11
	2	2.572	4.16		0.09	
V1	1	2.489	3.03	3.03	0.05	0.05
	2	2.541	3.21		0.06	
V2	1	2.531	2.95	2.95	0.05	0.05
	2	2.518	2.78		0.05	
V3	1	2.597	4.91	4.91	0.07	0.07
	2	2.569	3.61		0.04	
V4	1	2.579	5.60	5.60	0.07	0.07
	2	2.582	5.63		0.06	

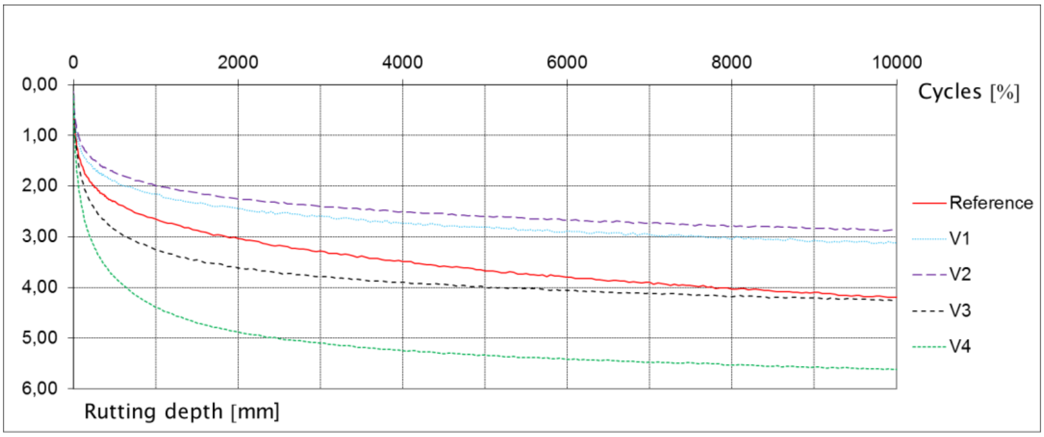

Figure 38: Development of rut depth during wheel tracking tests

4.3.4 Bitumen properties

The properties of the bitumen extracted from the asphalt mixtures prepared with RCRM addition were evaluated by means of the ring and ball softening point temperature. In Table 17 the measured softening points are summarised and compared with the theoretically resulting softening points according to mixing formula (6). The measured and calculated softening points are plotted in Figure 39.

$$T_{R\wedge Bmix} = a * T_{R\wedge B,a} + b * T_{R\wedge B,b} \quad (6)$$

Where *a* and *b* are the contents of the bituminous binders (a + b = 1) and $T_{R\&B}$ are the associated softening points.

Table 17: Properties of bitumen recovered from the asphalt mixtures and the theoretically resulting softening points according to mix formula

Sample	$T_{R\&B}$ [°C]	Fresh bitumen content	RCRM bitumen content	Calculated $T_{R\&B}$
Fresh binder	49.5	-	-	-
RCRM	73.0	0 %	100 %	-
R	52.0	100 %	0 %	49.5
V1	52.5	82.4 %	17.6 %	53.6
V2	58.0	65.2 %	34.8 %	57.7
V3	56.5	70.4 %	29.6 %	56.5
V4	57.0	74.2 %	25.8 %	55.6

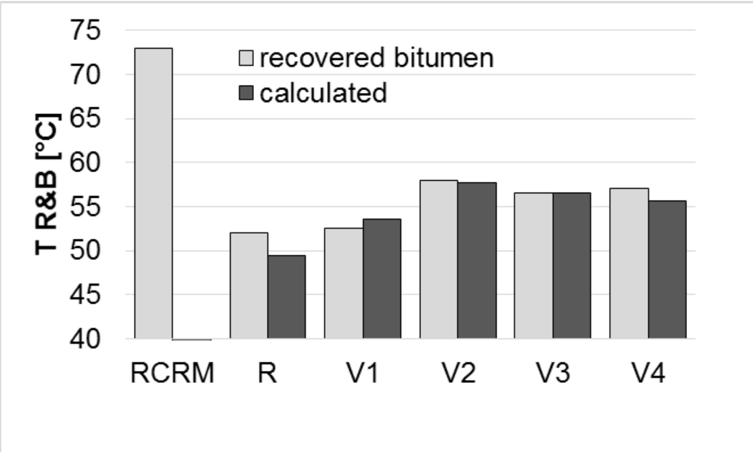

Figure 39: Softening points TR&B measured on bitumen extracted from the asphalt mixtures and compared with calculated values based on contents of fresh and RCRM binder

The calculated softening points conform well to the actually measured softening points evaluated on the recovered bitumen. This indicates that the mixing formula applied to check the resulting bitumen viscosity when adding reclaimed asphalt to new hot-mix asphalt as specified in EN 13108-9 can also be applied for adding reclaimed cold recycled material.

4.3.5 Results of compactibility tests

The resulting regression coefficients obtained from the compactibility tests are summarised in Table 18. The compaction resistance values T are also plotted in Figure 40.

Table 18: Results of the compactibility tests according to EN 12697-11

Sample	Regression coefficient t_∞ [mm]		Regression coefficient t_0 [mm]		Compaction Resistance T [21 Nm]	
	Single value	mean	Single value	mean	Single value	mean
R_1	49.4	48.9	58.7	58.8	75.9	76.1
R_2	49.7		58.8		76.4	
R_3	47.7		58.8		76.1	
V1_1	46.6	46.5	58.7	58.8	75.6	75.4
V1_2	46.5		58.8		75.2	
V2_1	50.6	47.0	58.6	58.7	75.4	75.2
V2_2	43.5		58.7		75.0	
V3_1	37.9	41.4	58.4	58.6	74.0	74.0
V3_2	45.0		58.7		74.0	
V4_1	33.6	35.9	58.5	58.5	74.1	73.7
V4_1	38.2		58.4		73.3	

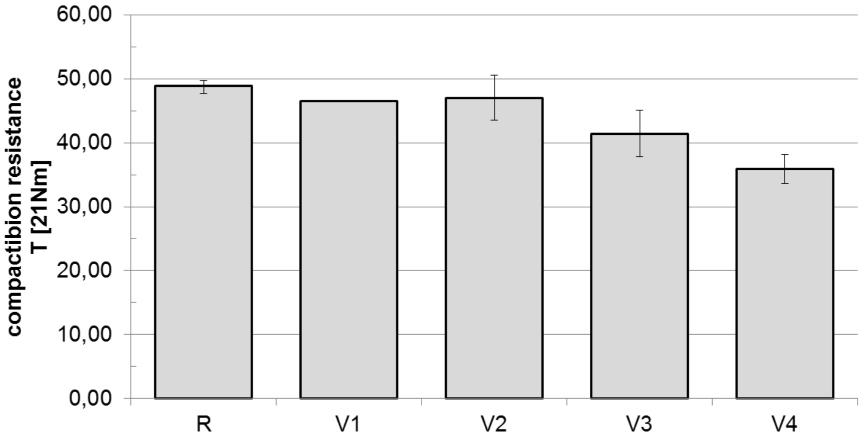

Figure 40: Results for compactibility

For the asphalt mixtures with the same total bitumen content (R, V1 and V2) it can be observed, that an increasing content of RCRM will reduce the compaction resistance. This effect is known for asphalt mixtures containing reclaimed asphalt (De Visscher et al. 2012).

The increase in total bitumen content (samples R, V3 and V4) will significantly reduce the compaction resistance.

4.3.6 Discussion of hot recycling of cold reclaimed and cold recycled mixtures

All mechanical tests applied in the hot recycling study indicate the applicability of reclaimed cold recycled mixtures in hot asphalt mixture at least up to an addition rate of 30 %. When comparing the mix variants V1 and V2 with the reference mix R, higher indirect tensile strengths, higher resistance against rutting and similar water sensitivity and resistance against frost/thaw conditioning can be observed.

On the other hand, the simulation of assumption of inactive bitumen in the reclaimed cold recycled material clearly shows an excess of bitumen in these mixtures (V3 and V4).

This proves that the bitumen in the reclaimed cold recycled mixtures can be considered as active and therefore, the recycling procedures as known and approved for reclaimed asphalt can also be applied for reclaimed cold recycled mixtures.

4.4 Results of the Czech study on hot/warm recyclability.

The following section discusses the results of the case study presented in chapter 3.6.

4.4.1 Empirical and mechanical properties

The basic empirical and mechanical characteristics are given in the Table 19. Voids content of compacted asphalt mix (2x 50 blows) was determined from the bulk and maximum density of the asphalt mix specimens. The technical standard EN 13108-1 prescribes the allowed voids content interval of 2.5 – 4.5 %-vol. for ACO 11+ mixes. The mix variant C does not meet this criterion. Therefore, there additional variants were produced that apparently showed non-homogeneity of re-crushed recycled asphalt material which more or less changes the grading curve of the final asphalt mix. It can be stated that the grading curve mostly influences bulk density and voids content of the assessed mixes with RAP content.

Table 19: Results of empirical mix characteristics

Mix	Used bitumen	Bulk density [g/cm^3]		Maximum density [g/cm^3]	Voids content [%]
Mix A	50/70	2.562	2.569	2.678	4.1
		2.568			
		2.575			
		2.572			
Mix B	70/100 + 0.5% Evotherm	2.605	2.594	2.701	3.8
		2.592			
		2.662			
		2.517			
Mix C	70/100 + 3% FTP	2.520	2.530	2.670	5.3
		2.539			
		2.533			
		2.527			

4.4.2 Indirect tensile strength on dry, saturated and frost/thaw-conditioned specimens

Results of indirect tensile strength test are given in the Table 20. The testing samples were divided into three groups for the indirect tensile strength testing. The first group of test specimens was left at dry conditions in the laboratory by the temperature of 15 °C. The second group of specimens was saturated and then exposed to unfavourable water impact for 3 days in water bath with 40 °C (in accordance with EN 12697-12). The last group of specimens was water saturated and then exposed to the impact of one freezing cycle at temperature of -18 °C for minimum 16 hours. Then the specimens were moved to water bath with temperature of 60 °C for one day (in accordance with AASHTO T283). The American procedure is stipulated on the principles of test specimen compaction defined either in California method (compaction according to AASHTO T312 standard) or in Superpave method using primarily a gyratory compactor (AASHTO T247). Both methods preserve reaching required voids content of 7.0 ± 0.5%. In the Czech Republic this procedure was modified and all test specimens are compacted by Marshall hammer with 2x25 blows.

Table 20: Indirect tensile strength results

Mix	Used bitumen	Bulk density [g/cm^3]		Indirect tensile strength [MPa] ITS$_{dry}$		ITS$_{wet}$ (EN 12697-12)		ITS$_{ice}$ (AASHTO T283)	
Mix A	50/70	2.466	2.482	2.757	2.778	2.801	2.814	2.742	2.699
		2.483		2.740		2.852		2.795	
		2.498		2.835		2.789		2.561	
Mix B	70/100 + 0.5% Evotherm	2.536	2.547	2.387	2.525	3.060	3.049	2.220	2.336
		2.549		2.522		3.029		2.449	
		2.556		2.664		3.057		2.339	
Mix C	70/100 + 3% FTP	2.386	2.378	2.149	2.032	2.279	2.062	1.696	1.738
		2.320		1.970		1.819		1.783	
		2.429		1.979		2.089		1.737	

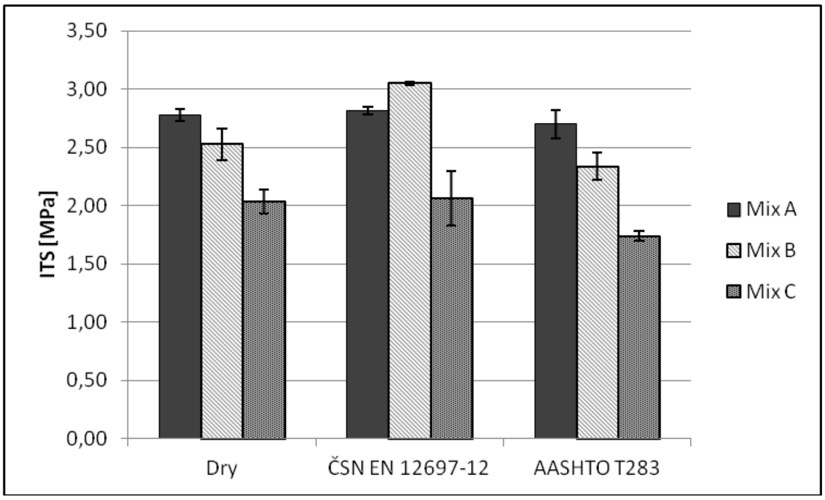

Figure 41: Results of water susceptibility (durability shown by ITS values and their ratios)

Comparing the first two groups of test specimens it can be stated that there is not any decrease but small increase of indirect tensile strength values after the saturation of all three compared mixes. The increase is insignificant for the mix A and C. The ITS for mix B grew by 0.5 MPa, which is about 121 % (see Figure 41). Similar comparison was conducted for the specimens exposed to the impact of a frost cycle. The A mix results show very small decrease of indirect tensile strength compared to dry specimens. The mixes B and C evince lower values of indirect tensile strength, in average about 0.3 MPa. This means ITSR of 95.5 % for mix B and 85.5 % for mix C. Considering the conducted measurements, the tested mix variants are not susceptible to water impact in terms of decreasing the durability properties given by indirect tensile strength. Very small influence was detected for the conditioning with one frost cycle.

According to the results achieved, all of the observed mixes meets the ITSR criterion set for ACO 11+ mixes of 70 % which is required by the EN 13108-1 standard. It is valid for procedures both according to EN 12697-12 and the AASHTO T283 approach (Figure 4ě).

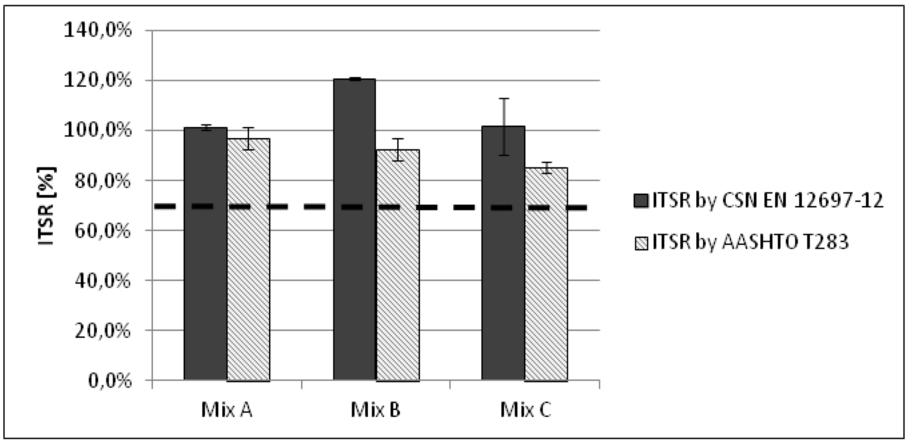

Figure 42: Results of water susceptibility (limiting requirement for ITSR)

4.4.3 Flexural strength test

Bending tensile strength (flexural strength) was tested in compliance with the test method defined in Czech technical specifications TP 151 of the Czech Ministry of Transport. The procedure test was carried out at -5°C with a choice of two loading speed - 50 mm/min and 1.25 mm/min. Test results gained for the lower loading speed are determine the final results according to the Technical Conditions. The A mix gave the best results in the bending tensile strength.

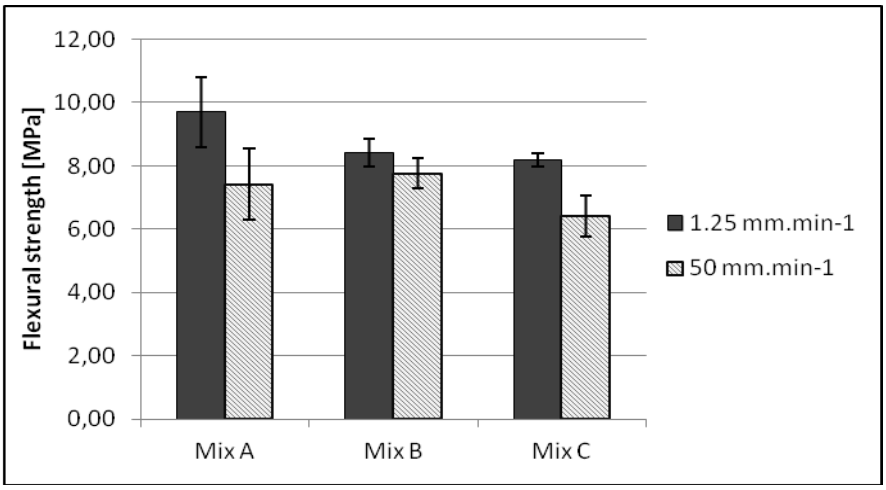

Figure 43: Results of flexural strength test

4.4.4 Stiffness modulus

Stiffness modulus was determined in compliance with IT-CY test method (repeated indirect tensile stress by means of non-destructive testing) defined in EN 12697-26. The used test procedure considered three different testing temperatures: 5 °C, 15 °C and 27 °C. For the test five loading pulses for two loading directions are conducted for defined target deformation. The stiffness modulus is calculated based on knowledge of cylindrical specimen dimensions, Poisson's ratio and measured transversal deformation. Several repeated testing for assessed temperatures were made for this study (see Figure 44).

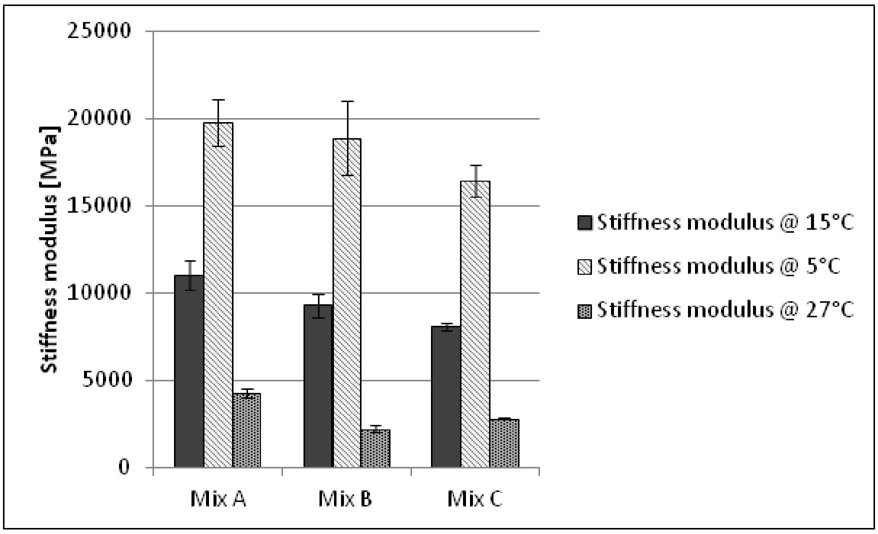

Figure 44: Stiffness modulus for assessed temperatures

Based on the results it can be stated that the stiffness modulus is affected by the bitumen contained in RAP. This binder is aged and has different characteristics than newly added binder and thus is stiffer. As can be seen from the results, experimental mix with FTP (with the highest voids content) has the lowest values of stiffness modulus (except for the temperature of 27 °C). The best results in terms of highest stiffness are given for mix A where only bitumen 50/70 was added. The mix A reaches in average stiffness modulus of approx. 11,000 MPa for the temperature of 15 °C, mix B has an average stiffness modulus of 9,250 MPa and mix C 8,100 MPa at same temperature. This temperature is crucial for pavement design methodology and results shown for mix A and B fulfill criteria for HMAC mixes. Reached results correlate very well with measured values for the flexural strength test.

4.5 Recyclability in hot-mix asphalt –case study from Portugal

This part summarizes the results of laboratory assessments performed at LNEC, in order to evaluate the recyclability of cold recycled mixtures through in plant hot recycling as presented in section 3.7. Taking this in view, a comparison study was conducted in which performance related properties of a reference Hot Mix Asphalt (AC14 using new aggregates) were compared to the ones obtained for the same type of mixture, but incorporating 30 % of "aged" cold recycled asphalt material (cold recycled mix produced using bituminous emulsion. In order to evaluate the influence of "reclaimed cold asphalt" (produced in the lab in order to simulate reclaimed asphalt pavement from site) the same bitumen binder was used, as previously described in section 3.6.

4.5.1 Marshall test

Cylindrical test specimens were prepared for each type of HMA (AC14 and HRM30%RCRm) by impact compaction, applying 75 blows on each side of the specimen, according to EN 12697-30. Afterwards, Marshall test were performed in accordance to EN 12697-34. The results obtained are shown in Table 20.

Table 21: Summary of Marshall test results

Marshall test		Hot Mix Asphalt	
		AC14	**$HRM_{30\%RCRm}$**
Bulk density (EN 12697-6, Procedure B)	**ρ_{bSSD} (Mg/m^3)**	2.620	2.594
Volume of voids (EN 12697-8)	**V_m (%)**	2,2	1.3
Marshall Stability	**S (kN)**	18.5	29.0
Marshall Flow	**F (mm)**	6.3	12.8
Tangential flow	**Ft (kN)**	2.3	3.4
Marshall quotient	**S/F (kN/mm)**	2.9	2.3

Both mixtures show relatively high Marshall stabilities and flows, with emphasis for the Hot recycled one (HRM30%RCRm). The fact that its void content is relatively low could be related with the results obtained. The results obtained with Marshall tests are somewhat inconclusive, and in order to evaluate the mixtures permanent deformation, wheel tracking tests were performed, as it is presented in following paragraph.

4.5.2 Resistance to permanent deformation (wheel tracking tests)

In order to evaluate the mixes resistance to permanent deformation, wheel tracking tests were performed according to EN 12697-22, small size devices, procedure B, in air. Slab test specimens (30.5 x 30.5 x 5 cm^3) were prepared using the roller compacter (EN 12697-33, method using a steel roller sector). Table 22 and Figure 45 show the results of wheel tracking tests, which were performed at a temperature of 60 °C.

Table 22: Summary of Wheel Tracking test results

Wheel tracking test t=60 ºC		**Hot Mix Asphalt**	
		AC14	**$HRM_{30\%RCRm}$**
Bulk density (EN 12697-6, Procedure B)	ρ_{bSSD} (Mg/m^3)	2.629	2.534
Volume of voids (EN 12697-8)	V_m (%)	1.4	3.6
Rut depth, after 1 000 load cycles	*RD* (mm)	3.7	4.3
Wheel-tracking slope, in air	WTS_{AIR} (mm/10^{3}cycles)	0.09	0.12
Proportional rut depth, in air	PRD_{AIR} (%)	7.4	8.8

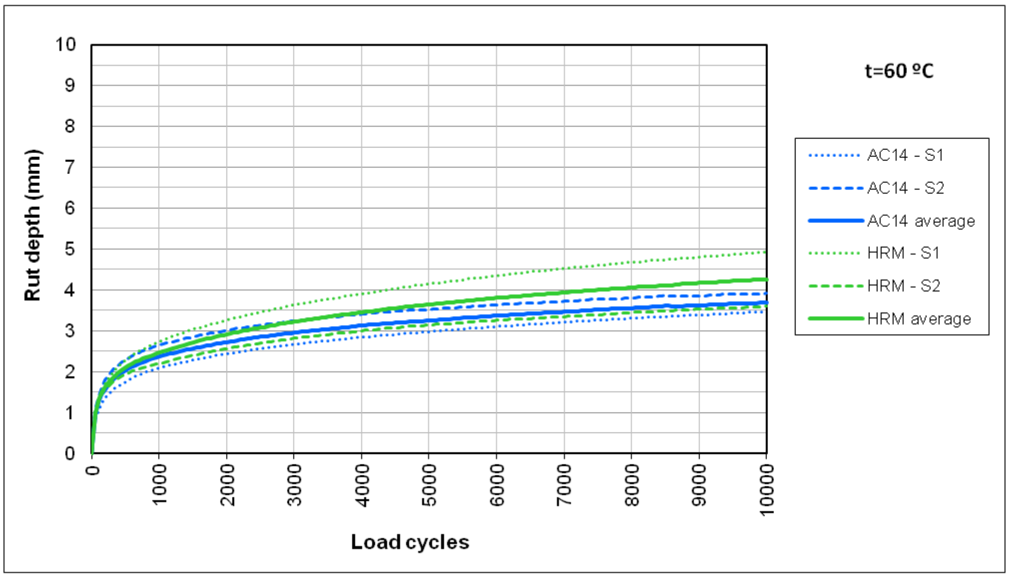

Figure 45: Rut depth evolution with load cycle

From the results presented in Table 22 and Figure 45, it can be concluded that both conventional hot mixture (AC14) and hot recycled mixture (HRM) present quite similar and satisfactory resistances to permanent deformation. However, it should be noted that HRM showed a slightly higher variability, which is probably related to the variability of the reclaimed cold recycled mixture that was used in its production (in a percentage of 30 %).

4.5.3 Moisture susceptibility tests

In order to evaluate the moisture susceptibility, cylindrical test specimens were prepared by impact compaction according to EN 12697-30.

Afterwards, the moisture susceptibility was determined, in accordance with EN 12697-12 (method A: ITT), at a temperature of 15 °C (Table 23 and Figure 46). The results presented allow to conclude that both hot mixtures have a very good resistance to water.

Table 23: Summary of moisture susceptibility test results

Water sensitivity test ITT, t=15 ºC		Hot Mix Asphalt	
		AC14	**HRM$_{30\%RCRm}$**
Bulk density (EN 12697-6, Procedure B)	**ρ_{bSSD} (Mg/m^3)**	2.623	2.550
Volume of voids (EN 12697-8)	**V_m (%)**	1.6	3.0
Indirect tensile strength of “dry” specimens	**ITSd (kPa)**	2100	2740
Indirect tensile strength of “wet” specimens	**ITSw (kPa)**	2100	2790
Indirect tensile strength ratio	**ITSR (%)**	**100**	**100** (102)

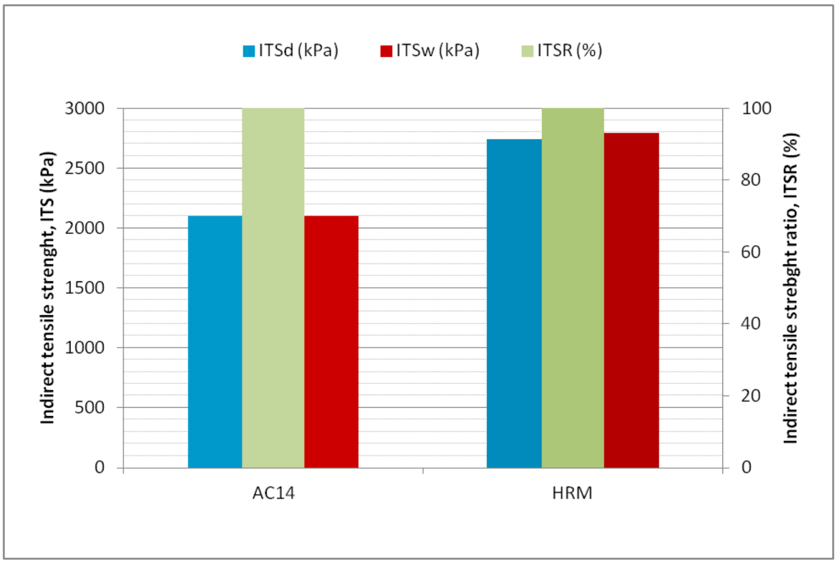

Figure 46: water sensitivity tests

5 Conclusions

Following conclusions can be drawn from the results of the recyclability studies summarized in this deliverable report:

- Pavement layers consisting of cold recycled materials can be recycled both by cold recycling as well as hot/warm recycling at the end of their service life.
- When cold recycling is applied, the resistance against permanent deformation shall be evaluated in order to avoid mixtures with excess of total bitumen content.
- For the assessment of recyclability, it is recommended to obtain the mix granulate by crushing of prior compacted and laboratory aged specimens in order to simulate milling process on site.
- For hot recycling, reclaimed cold recycling mixtures can be handled in the same way as reclaimed hot mix asphalt. Cement included in the cold recycling mixture doesn't interfere with the recyclability of the bitumen.
- For warm recycling the applied study shows the applicability of reclaimed cold recycled material. However, as the reactivation of the binder in the reclaimed material depends on manufacturing temperature and mixing time, additional experiments are required.
- Providing suitable aging properties, the bitumen “stored” in cold recycled mixtures can be recovered and reactivated again during hot recycling process.

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