End-of-life strategies for cold recycled mixtures and the multiple recycling approach

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ABSTRACT

Cold recycling is a road rehabilitation procedure, where the reclaimed road material from demolished pavements is recycled completely in the new structure with only small contents of new road materials. Cold recycling is applied worldwide since several centuries but little is known about end-of-life strategies for this kind of pavement materials. However, European construction regulation demands for taking the recycling strategies into consideration already during the mixture and pavement design phase.

Therefore the multiple recyclability of cold recycled materials was analyzed during European CoRePaSol project. Therefore, artificially aged cold recycled material was prepared in laboratory in order to simulate end-of-life characteristics of these road materials. On these material options for multiple cold recycling as well as the application of hot and warm recycling in new asphalt mixtures was analyzed designing suitable mixes with reduced binder content and RAP content of up to 30 %.

The results indicate that cold recycled pavement layers can be rehabilitated again by applying cold recycling at least once. However, each applied cold recycling cycle will raise the bituminous binder content which may lead to lower stiffness and reduced resistance against permanent deformation. It is necessary to focus more intensively on combining these approaches with rejuvenation and better reactivation of the used bitumen. Nevertheless the cold recycled material also can be recycled in new warm and hot-mix asphalt where the bitumen originating from the initial asphalt pavement as well as from the applied cold recycling cycles can be reactivated in future. Here common recycling strategies can be applied without the need for modifications.

As a result, the recyclability of cold recycled materials is similar to the recyclability of road layers composed of hot-mix asphalt and don't indicate a constraint against the application of this methodology in pavement rehabilitation.

Keywords: In-situ Recycling, Performance testing, Reclaimed asphalt pavement (RAP) Recycling, Warm Asphalt Mixture

1. INTRODUCTION

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. The procedures for recycling in these materials are widely well researched and described in several guidelines [1, 2] and further prescribed for the European harmonization process in CoRePaSol project [3].

Though, what is not yet researched is the end-of-life characteristics of cold recycled materials. For hot recycling process, it could be shown that the commonly approved hot recycling process can be repeated several times considering moderate contents (50 %) of reclaimed asphalt in new hot mixtures [4]. The properties of the aged binder in the reclaimed asphalt can be leveled 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 not been done jet. The material performance of cold recycled mixtures depend besides the content and type of bituminous and mineral binders applied also of the composition of the mix granulated originating from the milled road [5]. Here a significant effect of the content of reclaimed asphalt in the mix granulate on the mechanical properties could be analyzed.

When cold recycling mixtures reach their end of service life, they need to be recycled in new road 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. Therefore, a multiple cold recycling experiment was conducted which is discussed in section (2).

On the other hand, still cold recycling road layers cannot be compared with hot-mix asphalt layers. Later reach lower void contents and higher stiffness and strength and would allow reduced pavement thicknesses. Therefore, the recycling of reclaimed cold-recycled layers in new hot-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 recovering bitumen from former cold-recycling mixtures by hot recycling. For evaluating the recyclability in hot-mix asphalt, an experimental campaign was conducted and is discussed in section (3).

For further improving the energy efficiency of asphalt pavements, warm-mix asphalt approaches gain increasingly importance. In order to evaluate the applicability of reclaimed road material originating from cold-recycled layers in warm-mix asphalt a third experiment was conducted as discussed in section (4).

2. MULTIPLE COLD RECYCLABILITY EXPERIMENT

In order to evaluate the recyclability of cold recycled road construction layers themselves, an experimental program was designed based on two main experiments. Firstly, the recycling of these layers again by cold recycling technology was evaluated. Secondly, it was assessed if reclaimed material gained from cold recycled base layers can also be recycled even in hot asphalt mixtures.

2.1 Material properties of initial BSMs

For the assessment of the multiple recyclability of cold recycled pavement layers, two cold recycling mixtures were designed. As road material granulate, a crushed reclaimed asphalt sampled from a stockpile in an hot-mix asphalt mixing plant was used. This reclaimed asphalt had a binder content of 5.4 %, with recovered binder properties (Pen = 23 1/10 mm, $T_{R\&B}$ = 63.5 °C). The grading of the reclaimed asphalt particles and of the aggregates bound in the asphalt mix is plotted in Figure 1.

Two cold recycled mixtures were designed representing internationally applied cold mixtures based on bitumen emulsion. In order to raise the grading curve for small aggregate sizes, 5 % of inactive limestone filler was added to the mix granulate. By proctor tests, the optimum fluid content was evaluated to 7.8 %. For all mixtures a cationic emulsion C60B1 according to EN 13808 was applied (bitumen content: 60 %; slow breaking; bitumen properties of recovered binder: Pen = 78 1/10 mm; $T_{R\&K}$ = 46 °C). Whereas the first cold recycled mix represents a classical bitumen stabilized material (BSM), the second mix was prepared with adding 3 % of cement of type CEM I 42.5 N acc. to EN 197, representing a cement-bitumen stabilized material (CBSM).

Based on these mix compositions, the mixes were prepared in a Wirtgen compulsory pugmill mixer WLM 30. Afterwards, cylindrical specimens (diameter 150 mm, height 90 mm) were compacted by applying a static load with a double-plunger system of 50 kN for 5 minutes. The compacted specimens were stored in their moulds at room conditions (~20 °C, 80 % relative moisture) for 1 day. After demoulding, the BSM specimens were cured by storage for 3 days at 50 °C. The CBSM specimens were cured for 14 days at room conditions.

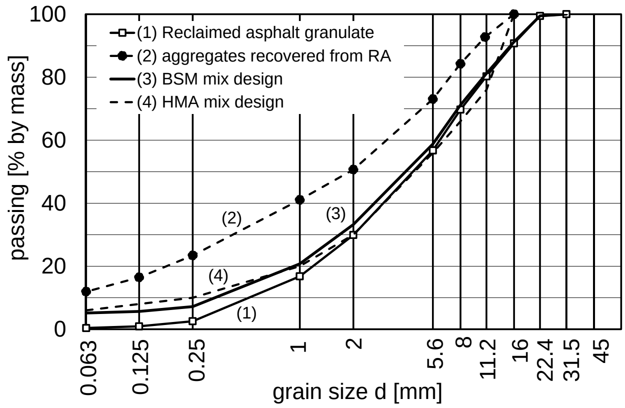


Figure 1. Grading of reclaimed asphalt granulate (1), aggregates (2) as recovered from RA well as of mix designs of BSM (3) and hot recycled mix (4).

2.2 Simulation of long-term ageing

In order to simulate long-term ageing on BSM, two procedures were applied, one method for ageing conditioning of loose mix (based on [6, 7, 8]) and a similar method for ageing compacted specimen. For the preparation of laboratory-aged BSM to be used for additional recycling stages, the freshly prepared mixture was spread on a tray and conditioned in the same way as the compacted specimen. After the curing phase, the ageing conditioning was applied by storing the tray with non-compacted BSM for nine days at a temperature of 85 °C in a ventilated heating cabinet.
For evaluating the ageing process onto the mechanical BSM properties, the same ageing conditioning was applied on compacted specimens after curing. Afterwards the specimens were temperature conditioned and the mechanical tests were conducted.
In order to evaluate if the ageing procedure on loose BSM or compacted specimen will affect the results of the recyclability study, one of the mixtures analyzed was laboratory aged in both – non-compacted as well as compacted to specimens. After the ageing conditioning, the specimens were taken from the heating cabinet, cooled to room temperature and crushed manually for the next mixing processes.

2.3 Experiment design of multiple cold recycling experiment

The first recycling stage is represented by the initial mix design study. From this the BSM samples result, which are aged in laboratory in order to prepare the simulated mix granulates for the second recycling stage BSMs.
For analyzing the multiple recyclability of cold recycled road materials three sample materials were prepared and laboratory aged:

- Reclaimed bitumen stabilized material (RBSM1):
  2 % bitumen emulsion, 0 % cement, aged as loose mix
- Reclaimed cement-bitumen stabilized material (RCBSM1): 2 % bitumen emulsion, 3 % cement, aged as loose mix
- Reclaimed bitumen stabilized specimens (RBSMS1):
  same as RCRM 1 but aged as compacted specimens and crushed afterwards.

For the evaluation of the second recycling stage, three cold recycled mixtures were prepared for each of the reclaimed cold recycled materials 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 cured by storing BSM mix or the specimens for 3 days at 50 °C and the CBSM mix for 14 days at room conditions.
Using the aged reclaimed materials (RBSM1) for preparing the second stage BSM, the added bitumen emulsion content was varied with 1 %, 2 % and 3 %.
Based on the RCBSM1, three new CBSM mixtures were prepared by applying 2 %, 4.2 % and 6.7 % of bituminous emulsion as well as 3 % of cement.
In order to evaluate if different test results will be obtained from aged loose BSM or of crushed aged compacted BSM, the crushed laboratory aged specimens (RBSMS1) were used for preparing on new BSM with an added bitumen emulsion content of 2 %.
For evaluating the third recycling stage, the cold recycling mixtures prepared during second stage with 2 % of added bitumen emulsion content were again laboratory aged. This aged material then again was used for preparing new cold recycled materials based on the same mix designs as in second recycling stage.
The sample labeling as well as the sample composition and the calculated residual bitumen contents are summarized in Table 1. The unique ID of each sample is identified by the recycling stage number (1 to 3), the type of cold recycled mix (BSM / CBSM) followed by a number representing the mix sample.

Table 1: Composition of samples evaluated during multiple cold recycling study

Recycl. stage	Sample ID	Mix composition			Calculated total bitumen content	Sample ID after ageing
		Mix granulate	Added bitumen emulsion content	Added cement content		
1	1BSM-1	RA	2 %	0 %	6,3	RBSM / RBSMS
	1CBSM-1	RA	2 %	3 %	6,1	RSBSM
2	2BSM-1	RBSM	1 %	0 %	6,5	-
	2BSM-2		2 %	0 %	7,1	RBSM2
	2BSM-3		3 %	0 %	7,6	-
	2CBSM-1	RCBSM	2 %	3 %	6,8	RCBSM2
	2CBSM-2		4,2 %	3 %	8,0	-
	2CBSM-3		6,7 %	3 %	9,4	-
	2BSM-4	RBSMS	2 %	0 %	7,1	RBSMS2
3	3BSM-1	RBSM2	1 %	0 %	7,3	-
	3BSM-2		2 %	0 %	7,9	
	3BSM-3		3 %	0 %	8,4	
	3CBSM-1	RCBSM2	2 %	3 %	7,4	
	3CBSM-2		4,2 %	3 %	8,6	
	3CBSM-3		6,7 %	3 %	10,0	
	3BSM-4	RBSMS2	2 %	0 %	7,3	

2.4 Test procedures applied in multiple cold recycling experiment

For evaluating the recyclability of the prepared cold recycled mix samples, cylindrical specimens (diameter 150 mm, height 90 mm) were prepared and their void contents were calculated. The obtained void content is a parameter for evaluating the materials compactibility, because of same compaction energy applied to all sample mixtures. Note, that all sample mixtures were compacted with the same water content. For increased bitumen emulsion contents, less water was added to the mixes.

The specimens indirect tensile strengths (ITS) were evaluated according to EN 12697-23 at a temperature of 15 °C by applying a vertical loading rate of 50 mm/min. Afterwards the bitumen was recovered from the specimens and the softening point ring and ball were measured.

2.5 Results of multiple cold recycling experiment

The results obtained in the multiple cold recyclability experiment are summarized in Table 2. The mean voids contents and indirect tensile strengths obtained at 15 °C for 3 specimens are given.

Table 2: Results of multiple cold recyclability Experiment

Recycl. stage	Sample ID	Voids content V (%)	ITS (15°C) (MPa)	Softening Point of rec. bitumen $T_{R\&B}$ [°C]
1	1BSM-1	13.4	0.705	70.5
	1CBSM-1	14.6	0.759	64.5
2	2BSM-1	16.5	0.803	68.5
	2BSM-2	16.0	0.823	68.5
	2BSM-3	15.3	0.840	69.0
	2CBSM-1	19.6	0.751	70.5
	2CBSM-2	15.1	0.829	71.0
	2CBSM-3	12.6	0.852	68.0
	2BSM-4	16.6	0.605	74.0
3	3BSM-1	17.5	0.561	73.5
	3BSM-2	17.4	0.563	71.5
	3BSM-3	16.5	0.531	71.5
	3CBSM-1	18.3	0.816	78.5
	3CBSM-2	13.5	0.948	78.5
	3CBSM-3	11.0	1.043	75.0
	3BSM-4	14.1	0.646	78.5

The void contents of the specimens after static compaction with a vertical force of 50 kN for 5 minutes is plotted in Figure 2. The resulting void contents range between 11 % and 20 %. For the two mix types BSM and especially for CBSM it can be observed that increase bitumen emulsion content will decrease the compaction resistance and less void contents will be obtained. When comparing the three recycling stages the BSM mixtures indicate increasing voids contents from recycling stage 1 to 3. However, the CBSM mixtures show decreasing voids contents and therefore better compactibility from recycling stage 1 to 3. When comparing the samples BSM-2 and BSM-4 with the same material composition but the varied ageing and mix granulate preparation procedure (BSM-1 was aged loosely spread, whereas BSM-4 was aged in compacted specimens), the specimen ageing and crushing procedure resulted in significantly lower voids contents in the 3rd recycling stage.
The mean ITS results are plotted in Figure 3. The resulting ITS reached values between 0.53 MPa and 1.05 MPa.
For the CBSM samples, the increasing bitumen emulsion content will significantly increase the indirect tensile strength values obtained. This can be explained by the decreasing voids contents. The increasing total bitumen content in the mix will reduce the voids and therefore will strengthen the material.
For the BSM samples, the applied bitumen content doesn't significantly affect the ITS. Whereas in the second recycling stage a slight increase of ITS with increasing bitumen content is observed, it shows small decreasing tendency in stage 3. This unexpected effect can be explained by the increasing void content which countervails the usually increasing cohesion caused by added binder content.
Whereas the CBSM samples indicate increasing ITS values between the recycling stages, the strength decreases for the BSM. A reason for this observation can be seen within the ageing procedure applied for the samples BSM-1, -2 and -3. When the aged material is thoroughly crushed before the new mix preparation, similar strength values are obtained within the recycling stages, as indicated by sample BSM-4.

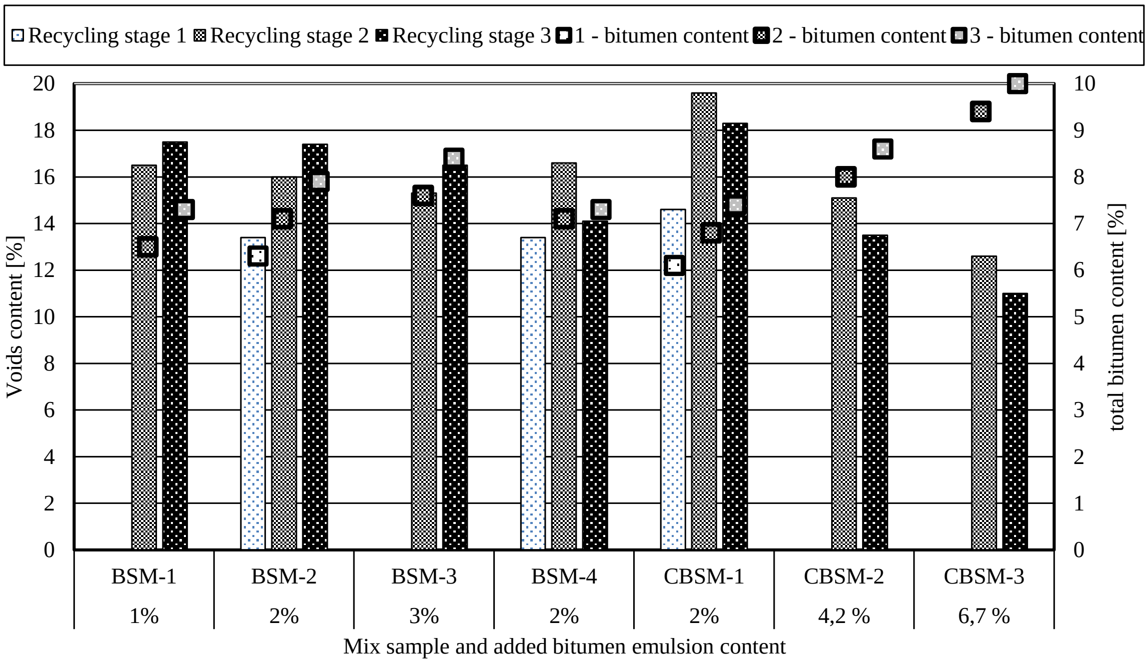


Figure 2. Void contents of BSM and CBSM samples with varied bitumen emulsion contents

2.6 Discussion of multiple cold recycling study results

The results of the multiple cold recyclability campaign generally indicate feasible resulting void contents and indirect tensile strengths obtained even after repeated recycling stages. However, the results clearly show, that the compactibility as well as the strength of the material changes from recycling stage to recycling stage. This emphasizes the importance of individually conducted mix design experiments.
However, especially for the CBSM mixtures with high bitumen emulsion contents the repeated recycling will increase the total bitumen content as indicated in Table 1. Even with low added bitumen emulsion contents after two recycling stages total bitumen contents of at least 7.3 % were reached.
This raises the question, if these large quantities of bitumen may be recovered in future times considering the expected shortage of bitumen supply or the increasing price of bitumen. One way for indirectly recovering bitumen from old asphalt road is the application of hot recycling techniques. This topic was evaluated in a second study as presented in following section.

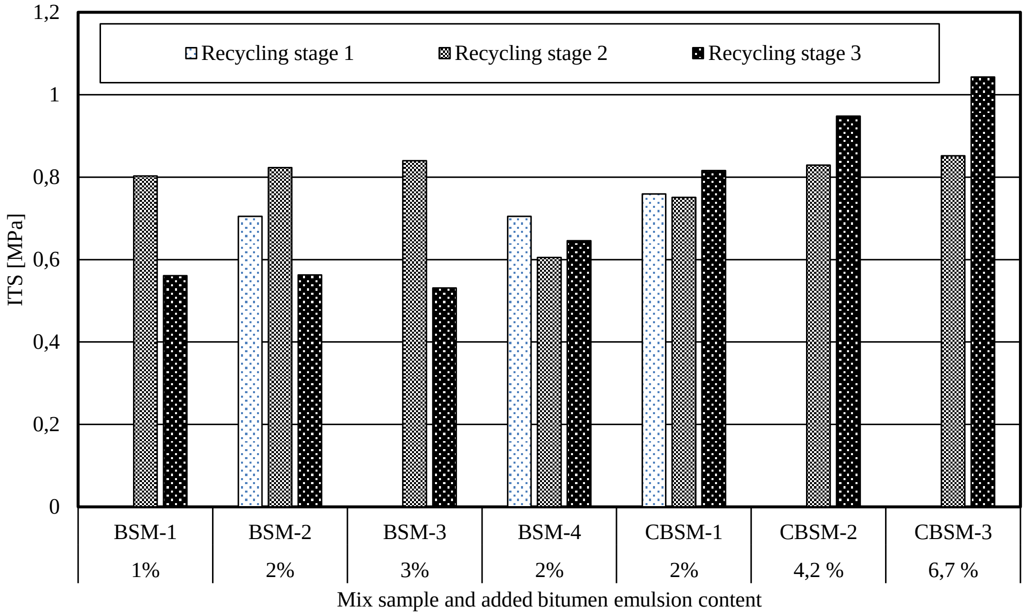


Figure 3. ITS of BSM and CBSM samples with varied bitumen emulsion contents

3. HOT RECYCLING EXPERIMENT

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 for RA contents below 50 % – be reactivated during the mixing process and therefore, the consumption of new binder can be reduced. During mix design, it is assumed, that the properties of the added binder and the binder in the RA are thoroughly mixed. For the choice of a suitable added bitumen, the resulting binder properties can be calculated according to (1) from the softening points of the added binder $T_{R\&B,added}$ and of the binder recovered from the reclaimed asphalt $T_{R\&B, Rec}$ as well as the content of each binder ($B_{added} + B_{Rec} = 1$).

$$T_{R\&B,result} = B_{added} \cdot T_{R\&B,added} + B_{Rec} \cdot T_{R\&B,\mathrm{Rec}} \quad (1)$$

3.1 Experimental design of hot recycling experiment

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 3 presents the mix variants containing an asphalt concrete mix AC 16 as applied for asphalt binder courses. Besides the reference mix (V0), AC 16 variations containing 15 % or 30 % of reclaimed cement-bitumen stabilized material (RCBSM) 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).

Table 3: Mix variations in hot recycling study

Sample Mix	RCBSM content	Content of added bitumen [%]	Content of RCBSM bitumen [%]	Total bitumen content [%]
V0	0%	4.6	0	4.6
V1	15%	3.8	0.8	4.6
V2	30%	3.0	1.6	4.6
V3	30%	3.8	1.6	5.4
V4	30%	4.6	1.6	6.2

For the hot recycling study, the reclaimed cold recycling mixture RSBSM (compare Table 1) was applied. The cold recycled material was prepared with 2 % bituminous emulsion and 3 % cement. Specimens were compacted according to EN 12697-30 (Marshall impact compaction) from the cold recycled mixture, cured for 14 days under room conditions and afterwards aged in laboratory for 10 days at 85 °C.
Afterwards the compacted specimens were crushed for simulating the milling process.

3.2 Source materials and mix design applied in hot recycling experiment

For mixing AC 16 washed and sieved basalt aggregates and limestone filler was used. The aggregate composition was varied between the 5 asphalt concrete samples in order to obtain the same unique grading curve. In Figure 4 the grading curve of the designed asphalt concrete is plotted into the grading requirements for an asphalt concrete for asphalt binder courses according to German hot-mix design standard [9]. The grading of the aggregates recovered from the RCBSM is added to the diagram. The recovered bitumen content was evaluated to 5.4 % and the recovered binder had a softening point of $T_{R\&B}$ = 73 °C.
A bitumen content of 4.6 % in the reference mixture was chosen based on a mix design study. As a binder, a straight bitumen 50/70 was applied. The added bitumen had a softening point $T_{R\&B}$ of 49.5 °C.

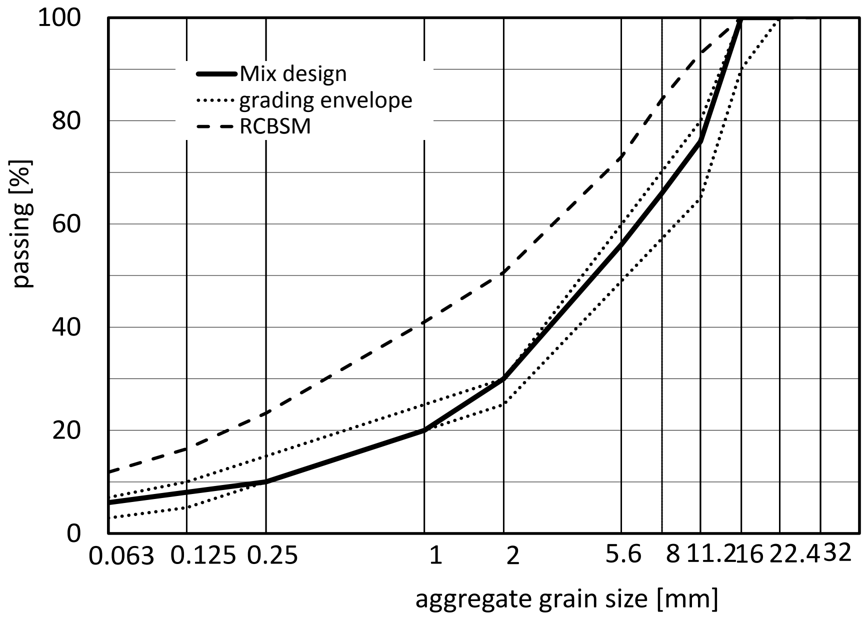


Figure 4. Grading of RCBSM aggregates and the designed AC 16 mixture.

3.3 Test procedures applied in hot recycling experiment

The asphalt mixtures were prepared at a mixing temperature of 135 °C. After mixing subsamples were separated allowing the compaction of the required specimens.
Directly after mix preparation, the binder content was evaluated by extraction and recovery as well as the softening point $T_{R\&B}$ was measured for the recovered binder.
For checking the void contents V of a normative specimen, maximum density as well as bulk density of impact compacted specimens according to EN 12697-30 (Marshall compaction) with 2 x 50 blows was evaluated.
The compactibility of the mixtures was evaluated by Marshall impact compaction procedure with 100 blows on each specimen side according to EN 126978-10. In this procedure each compaction blow has compaction energy of 21 Nm. During the compaction, the specimen height t(E) was measured after each compaction blow. E represents therefore the cumulated compaction energy (in 21 Nm) and equals the number of applied compaction blows. The recorded thickness reduction during the compaction process can be mathematically interpreted by an exponential function (2) where three regression coefficients are evaluated. The parameter t_0 represents the initial specimen thickness prior to compaction. t_∞ is the theoretically possible minimum specimen thickness after an infinite number of compaction blows and T represents the compaction resistance.

(2)

For evaluating the resistance of the asphalt mixtures 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. During 20.000 wheel passes applied at a temperate of 60 °C, the rut depth was measured. As a result, the rut depth (RD) after 20.000 wheel passes is evaluated.
For measuring the indirect tensile strength, specimens were compacted by Marshall impact compaction with2 x 50 blows. The indirect tension test according to EN 12697-23 was applied 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.
Further indirect tensile stress tests were conducted on specimens compacted with 2 x 25 impact blows in order to evaluate the materials resistance against environmental impacts. Therefore, the specimens were sorted into three sets. One set of specimens were stored in room conditions. The second set was conditioned according to AASHTO T283 for evaluation of its resistance against frost-thaw. After water saturation, the specimens were frozen for -18 °C for 16 h and afterwards water conditioned at 60 °C for 24 h. For evaluation of water susceptibility according to EN 12697-12, a third set of specimens was water saturated and stored in a water bath at 40 °C for 72 h. After the conditioning procedures, the specimens were temperature conditioned to 15 °C and their indirect tensile strength was measured.

3.4 Test results of hot recycling experiment

The test results are summarized in Table 4 as means from three test repetitions for each property.

Table 4: Test results of the hot recycling study

Property	V0	V1	V2	V3	V4
Softening point $T_{R\&B}$ [°C]	52.0	52.5	58.0	56.5	57.0
Voids content V [%]	7.1	5.8	6.5	2.8	1.7
Compaction resistance , T [21 Nm]	48.9	46.5	47.0	41.5	35.9
Rut depth RD [mm]	4.2	3.0	3.0	4.9	5.6
ITS_{dry} [MPa]	2.11	2.17	2.90	2.84	2.96
$ITS_{frost-thaw}$ [MPa]	2.14	2.27	2.66	2.96	3.24
ITS_{wet} [MPa]	1.96	2.3	2.55	2.62	2.85
$ITSR_{frost-thaw}$ [%]	102	105	92	104	109
$ITSR_{wet}$ [%]	93	106	88	92	96

In Figure 5 the softening points measured for the bitumen samples which were recovered from the mix samples are compared with the values calculated according to (1) from the binder properties of the added binder and the RCBSM bitumen. For the reference sample, the recovered bitumen has a significantly higher softening point compared to the calculated one. The differences can be explained by thermal loads during mix preparation. For the other mixtures containing significant proportions of bitumen originating from the reclaimed cement-bitumen stabilized material (RCBSM) a good agreement is obtained. This result indicates that the equation (1) can also be applied for hot recycling of reclaimed emulsion and cement bound road materials.

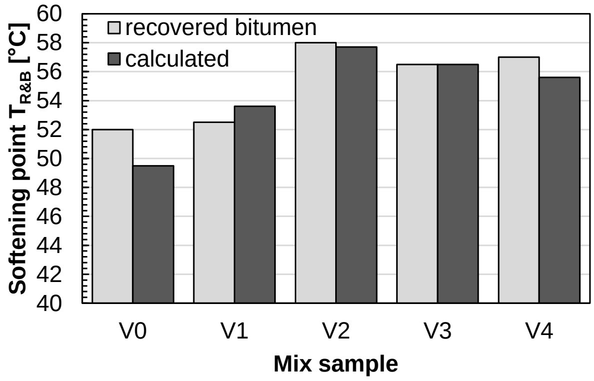


Figure 5. Softening points TR&B of recovered binders compared to values calculated according to (1) from the source material properties

The voids contents obtained for the sample mixtures are plotted in Figure 6. Whereas similar void contents are obtained for the mixtures V0, V1 and V2 of approximately 6.5 %, the void contents of mixtures V3 and V4 are significantly lower. This also affects the additionally plotted values of VFB. Obviously the high total binder contents in mixes V3 and V4 result in binder excess.

The results of compactibility tests are plotted in Figure 7. For the asphalt mixtures with the same total bitumen content (V0, V1 and V2) it can be observed, that an increasing content of RCBSM will reduce the compaction resistance. This effect is known for asphalt mixtures containing reclaimed asphalt [4]. The increase in total bitumen content (samples V0, V3 and V4) will significantly reduce the compaction resistance.

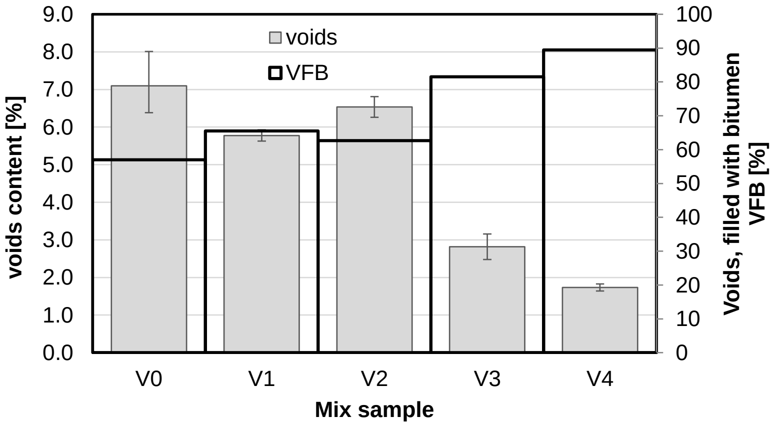


Figure 6. Voids contents V and voids filed with bitumen VFB of impact-compacted specimens

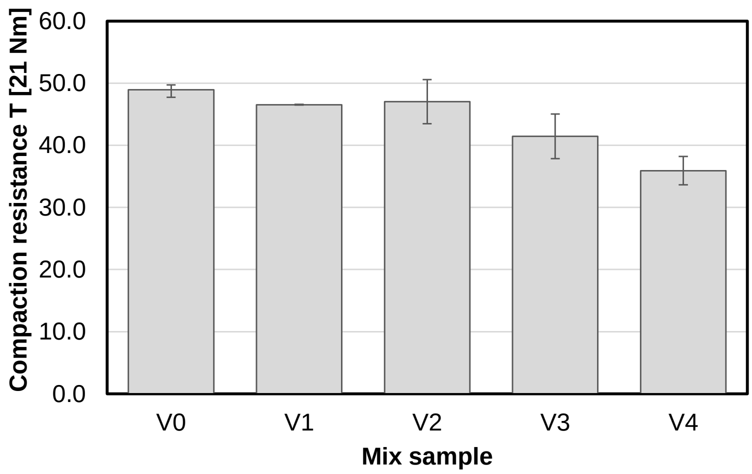


Figure 7. Results of compactibility tests: Compaction resistance T

In Figure 8the mean rut depth development during the tests are plotted. In consideration of mix variations V0, V1 and V2 the rutting depth decreases with increasing content of RCBSM. This can be caused by decreasing voids content as well as because of the increasing bitumen viscosity due to mixing of the added and the reclaimed CBSM bitumen. 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.

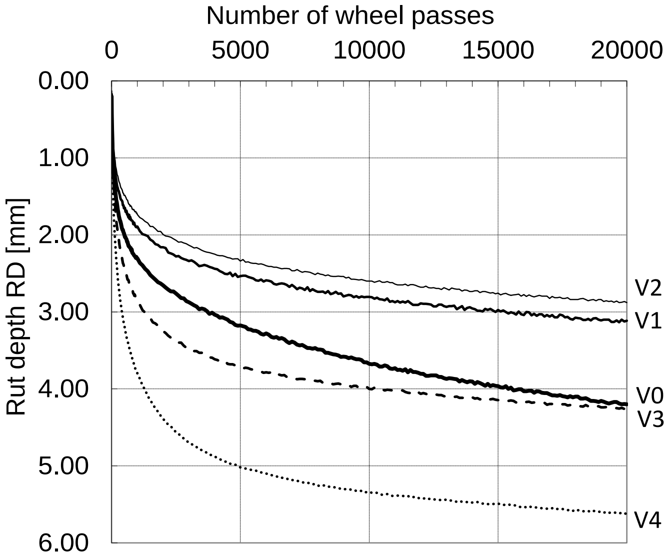


Figure 8. Rut development in wheel tracking tests (60 °C)

The indirect tensile strength results obtained on the specimens after varied conditioning procedures are plotted in Figure 9. For the dry conditioned specimen, the indirect tensile strength of samples V0 and V1 are significantly lower compared to the strength obtained for the samples V2 to 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.

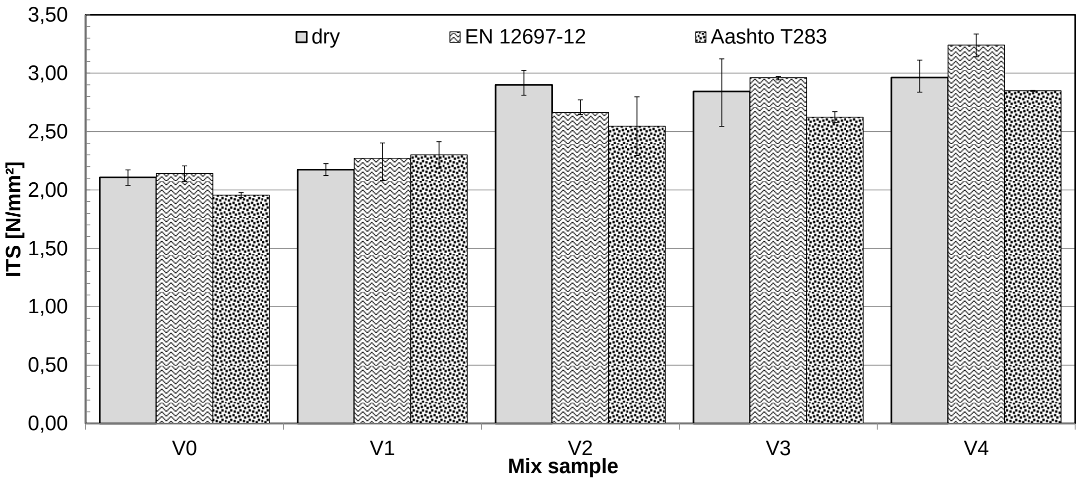


Figure 9. Indirect tensile strengths obtained on specimens after dry conditioning, water saturation (60 °C, 3 days) and frost-thaw conditioning

3.5 Discussion of hot recycling study results

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 V0, 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) as indicated by low void contents and high VFB results as well as low resistance against rutting.

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.

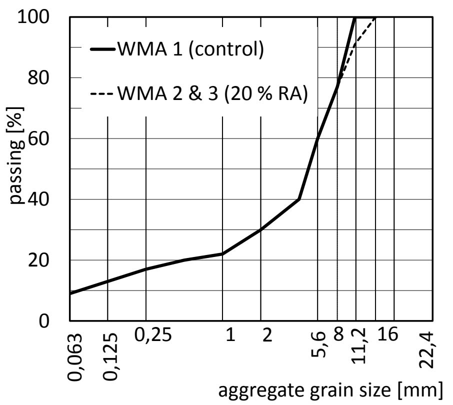
4. WARM RECYCLING EXPERIMENT

4.1 Experimental design of warm recycling study

For determining if warm asphalt mixtures based on additives can still be applied with asphalt mixtures where reclaimed asphalt is added which originates from cold recycled road layers, three asphalt mixtures for surface courses were designed. As laboratory-prepared reclaimed asphalt material, an artificially aged (compare section 2.2) emulsion mix without addition of cement was used. In total three asphalt concrete surface mixtures according to Czech specification were assessed. The mix variant compositions are summarised in Table 5. Two WMA additives were applied. Besides a chemical additive (Evotherm®) which reduces the surface friction within the mix, a Fisher-Tropsch wax additive (Sasobit®) was added to the mix which reduces the binder viscosity above 110 °C. As can be seen by the grading, similar values were achieved between the mixtures containing RA as well as the control mixture.

For evaluating the applicability of the WMA approach on mixtures containing 20 % of RA specimen were compacted according to EN 12697-30 by applying 2 x 50 blows for assessment of the void content as well as 2 x 25 blows for assessment of indirect tensile strength and moisture conditioning. The indirect tensile strength tests were applied according to EN 12697-23 at a temperature of 15 °C on dry conditioned specimens as well as on specimens stored for 3 days at 40 °C in water bath and frost-thaw conditioned specimens (compare section 3.3). For assessing low-temperature properties 3-poiunt bending strength tests were applied at a temperature of -5 °C and two loading rates (1.12 mm/min and 50 mm/min). Stiffness properties were assessed by indirect tensile tests according to EN 12697-26.

Table 5: Mix samples in warm recycling experiment

Asphalt sample	Added Binder	Binder content [%]			WMA additive	Grading
		Added binder	binder from RA	total		
HMA (control)	50/70	5.2	-	5.2	-	
WMA 1 (20 % RA)	70/100	3.6	1.6		0.5 % Evotherm	
WMA 2 (20 % RA)	70/100		1.6		3 % F.T.-wax	

4.2 Results of warm recycling experiment

The test results obtained on the three mixtures for assessing the applicability of warm recycling approaches are summarised in Table 6.

As can be observed on the test results, considerable difference in the void contents occur. The technical standard EN 13108-1 prescribes the allowed voids content interval of 2.5 – 4.5 %-vol. for AC 11 mixes. The mix variant WMA 2 does not meet this criterion. For this mixture, considerable variation of the grading curve could be observed on aggregates recovered from the mix. The heterogeneity of RA had a significant effect on the compaction results.

These differences in compactibility also resulted in different void contents in the specimens used for indirect tensile strength tests. Here considerable differences in the resulting voids contents could be observed. Nevertheless, also the very high void content of the specimens used for testing the mixture WMA 2 resulted in feasible ITSR values after frost-thaw conditioning. The requirement of ITSR (70 %) is reached by all mixtures despite the high voids content.

Regarding the low-temperature flexural strengths obtained very little differences can be observed for the loading speed of 50 mm/min between the mixtures. At the slower loading speed the control mix reaches higher flexural strength compared to the WMA mixtures. This can be explained by the harder bitumen used in the mixture. The binder viscosity of the WMA mixtures resulting from the mixture of aged RA bitumen and the added 70/100 is obviously smaller compared to the viscosity of the 50/70 applied in the control mix.

The effect of reduced bitumen viscosity in the warm mix asphalt samples can also be observed when comparing the stiffness test results. Despite lower void content of the Marshall-compacted specimen, the sample WMA 1 reaches lower stiffness values compared to the control mix. The stiffness values obtained in WMA 2 are even lower - however this can be a result of increased voids content. For the highest test temperature of 27 °C already the stiffening effect of the wax additive can result in the higher stiffness modulus of WMA 2.

Table 6:Results of warm recycling experiments

Property / Test result		HMA (control)	WMA 1 (20 % RA, surfactant)	WMA 2 (20 % RA, F.-T. wax)
Void content (2 x 50 blows)		4.1 %	3.8 %	5.3 %
Void content (2 x 25 blows)		7.3 %	5.7 %	10.9 %
Indirect tensile strength (15 °C) [MPa] (ITSR)	dry	2.778	2.525	2.032
	3 d @ 40 °C in water	2.814 (101 %)	3.049 (120 %)	2.062 (101 %)
	Frost-Thaw	2.699 (97 %)	2.336 (93 %)	1.738 (85 %)
Flexural strength (-5 °C) [MPa]	1.25 mm/min	9.6	8.4	8.2
	50 mm/min	7.5	7.7	6.4
Stiffness modulus (IT-CY)	5 °C	19500	18200	16500
	15 °C	11000	9200	8000
	27 °C	4200	2000	3000

5. CONCLUSIONS

Following conclusions can be drawn from the results of the two recyclability studies presented in this paper:

- Pavement layers consisting of cold recycled materials can be recycled by cold recycling, hot recycling as well as 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, the mix granulate shall be obtained 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.
- 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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