Tolerances for inhomogeneity of pavement structure for in-situ cold recycling

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Digital Object Identifier (DOI): dx.doi.org/10.14311/EE.2016.151

ABSTRACT

Cold recycling technique is a road construction method for producing a new base layer from existing road material. For in-situ cold recycling, a recycler mills the existing road structure in a depth up to 30 cm by mixing these materials with bituminous emulsion or foamed bitumen and/or hydraulic binder (e.g. cement). The composition of the mix granulates results from the structure of the recovered pavement and may contain different proportions of reclaimed asphalt, reclaimed cement concrete and reclaimed unbound material. The mix design of the new cold-recycling material is optimised for the site-specific mix granulate composition. Though, pavement structures may show inhomogeneities due to partly conducted road maintenance, road widening or former excavation works.

In this study it is evaluated, in what extend inhomogeneities in pavement structure will influence the mechanical properties of cold recycling materials. Therefore, cold recycling mixtures are produced with constant binder content by varying the mix granulate composition (reclaimed asphalt, reclaimed cement concrete and reclaimed unbound material) to evaluate the sensitivity of the material performance on differing pavement structures. As a bias, it is evaluated if the binder of the reclaimed asphalt materials affects the properties of the new cold recycled material. In total eight different cold recycling mixes were produced in laboratory by varying the composition of the mix granulate material. All mixtures were produced with the same grading, a constant residual virgin bitumen content of 4% and cement content of 2%. After static compaction, indirect tensile strength after 7 and 28 days of conditioning, water susceptibility and CBR properties were tested.

Limits of pavement inhomogeneity could be evaluated which may be tolerated during cold recycling mix application. Further the test results indicate a significant effect of old RA bitumen on the performance of the cold recycled material.

Keywords: Cold Asphalt, Emulsions, Foam, In-situ Recycling, Quality assurance

1. INTRODUCTION

Reduced availability of natural resources increases the importance of recycling of road materials in traffic infrastructure. Especially cold recycling is a possibility to produce a recycled layer in situ. For this method, countries in the world use bitumen emulsion or foamed bitumen – often combined with a hydraulic binder – that is mixed in situ into the milled material and a cold recycling layer is produced. During this procedure a cold recycler mills the existing road construction up to a depth of about 30 cm. Especially full depth reclamation (FDR) is a technology for cold recycling where the recycler mills the whole pavement structure independently of bituminous layer, unbound and cement-treated courses [1,2].
Cold recycling mixes can be produced by using bitumen emulsion or foamed bitumen as a binder in the new material [3]. For both types of bituminous binders similar mix design procedures are applied.
During mix design of cold recycled materials the composition of the cold recycling mixture (contents of additional aggregates, water, bitumen and cement) is optimised for a representative sample milled from the original pavement [3,4]. During laboratory mix design, the significant properties of the road mix are evaluated.
However, in reality, pavement structures often show non-homogeneous structural conditions. Due to road partial maintenance works or former excavation works the thickness as well as the structural layout of a pavement can vary in transversal as well as in longitudinal direction. Also former road widening will result in differing layers and thicknesses in the cut-section of the pavement. These non-homogeneities will result in varying composition of the milled granulate material produced during in-situ recycling.
The aim of this study is to evaluate on the composition of milled granulate materials influencing the mechanical properties of cold recycling layers. By these results it can be estimated, in what extend non-homogeneities in road structures can be tolerated for in-situ cold recycling works. As a bias, the activity of the bitumen from the reclaimed asphalt can be assessed [5].

2. EXPERIMENTAL WORK AND LABORATORY TESTS

2.1 Source materials and mix design

Cold recycled materials summon a large variety of different road materials, which have in common, that they are produced of milled road materials. However, the applied content of binders may vary from very low bitumen content resulting in bitumen-stabilised mixtures (BSM) to which sometimes cement is added in order to bind excessive water and to gain early-life-strength (cement-bitumen stabilised materials CBSM). In specific climatic conditions, the binder contents can be increased in order to achieve higher moisture resistance (by higher bitumen contents) as well as higher bearing capacity (by increasing the cement content). Furthermore, the cold recycling technology has proven to successfully allow the recycling of road materials with hazardous substances, which prohibit the hot recycling process (e. g. tar) and by sealing the dangerous substances in the pavement. Latter mixtures demand for the highest bitumen contents applied in cold mixtures.
For this study, the cold recycling mix was designed according to German Mix Design standard [6] for a cold recycling mix with maximum content of reclaimed asphalt (RA) aiming at sealing tar-containing road materials. The mix design is based on requirements on the granulate grading as well as on properties of the cold recycling mixture prepared in laboratory conditions.
The mix design study was conducted for a cold recycled mixture, which is composed of reclaimed asphalt (RA). The RA was obtained from a stockpile located in an asphalt mixing plant and represents material milled from various asphalt layers types. The binder content of the RA was evaluated to 5.4 %. The recovered bitumen from the RA had an softening point ring and ball of $T_{R\&B}$ = 63.5 °C and a penetration of 23 1/10 mm. The grading of the RA particles is plotted in figure 1.
The reclaimed cement concrete was obtained from a jobsite section of a German motorway BAB A7, Bockenem. The grading of reclaimed cement concrete particles is added in figure 1.
For simulating reclaimed aggregates from unbound base layers, crushed basalt aggregates were obtained from a quarry located in Fritzlar. It is believed, that aggregates reclaimed from unbound base layers have very similar properties compared to new natural aggregates. Therefore, new, unused aggregates were used for this study.
The overall mix design is based on the specific grading of the reclaimed asphalt granulates. However, in order to meet the specification regarding a minimum content of fines (< 0,063 mm) of 5 % as demanded by German mix design standard [6], 3.6 % of inactive limestone filler was added to the granulated RA. Figure 1 indicates the resulting grading for the mix granulate applied. The portland cement (CEM I 42,5 N) content was fixed to 2 % [2, 7]. The mix design study conducted resulted in an optimum residual added bitumen content of 4.0 %.
For the cold recycling mixtures with bitumen emulsion, 6.4 % of cationic slow-breaking bitumen emulsion of the type C60B1 according to EN 13808 was added to the mixtures. The emulsion binder was a straight 50/70.
For the foamed bitumen mixtures, the bitumen of penetration grade 50/70, which was provided by Shell especially for foaming applications, was foamed at 180 °C with a water content of 4.5 % by bitumen mass and a pressure of 5.5 bar using a Wirtgen foaming generator WLB 10 S.

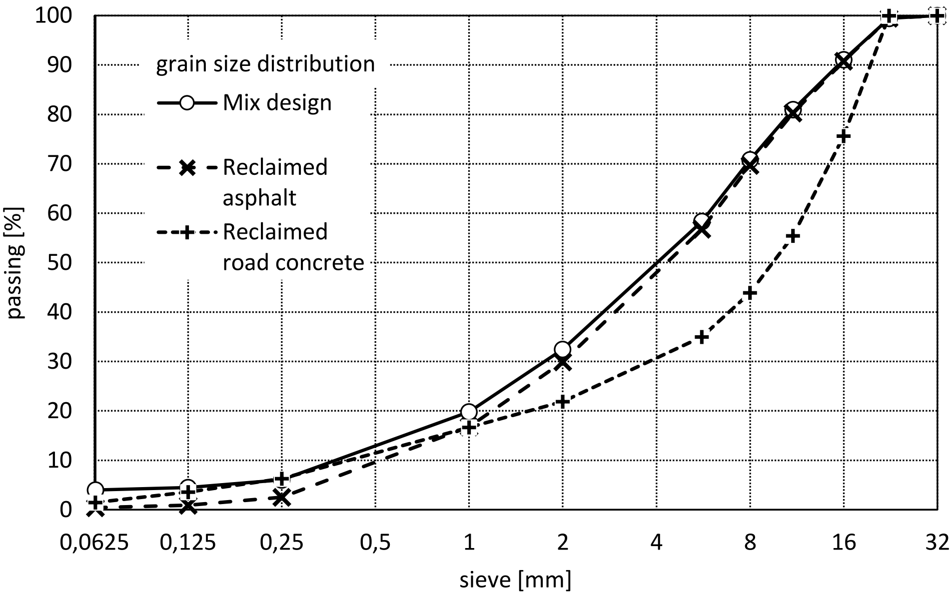

Figure 1. Mix design and particle size distributions of source reclaimed asphalt and reclaimed road concrete.

By conducting Proctor compaction tests according to EN 18127 the optimum water content was estimated to 7,8 %. The added binder content was calculated from the optimum fluid content as well as the added binders:

$$W_{water\ add\ em} = w_{OFC} - w_{air\text{-}dry} - w_{em} - 0,5 * PRB$$

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

According to German national standard (FGSV2005) w_{em} and PRB can be set with 0 when using foamed bitumen. This recommendation was followed in this study.
The mixtures were prepared by using a double-shaft mixer. The aggregates as well as added water and bitumen emulsion was added to the mixer ad ambient room temperature (~ 22°C).

2.2 Mix variations

In order to evaluate the effect of inhomogeneous pavement structure, the composition of the mix granulate was varied. As the milling depth usually is held constant during in-situ cold-recycling, a varying thickness of the asphalt layers will result in the presence of granulated material from below the asphalt layer. The base-layer below the asphalt usually consists of unbound bases but also hydraulically bound road bases (e. g. lean concrete) may occur. During the milling process these granulates will be mixed homogeneously with the milled asphalt layers. Especially if the cold recycler is equipped with a twin-shaft pugmill mixer, even transversal non-homogeneities will result in evenly distributed road material with changed composition over the width of the road.
For assessing the effect of these varying cold mix granulates, in total 16 cold recycled mixtures were prepared, based on the mix design discussed in section 2.1. Both, for bitumen emulsion bound mixtures as well as for foamed bitumen mixtures, eight mix granulate variations were used for the preparation of the cold recycling mixtures in laboratory. The eight variations were prepared by varied contents of reclaimed asphalt (RA), reclaimed road concrete obtained from a recycling site for crushed concrete pavement and natural basalt aggregates for simulating reclaimed unbound base layers. The grading of the RA and the crushed concrete are identified in figure 1. The natural aggregates were added to the mix according to the required mix design from washed and sieved samples. The contents of each type of granulate material in the eight mix granulates are summarised in table 1.
These mixes simulate different pavement structures which may occur during cold recycling on non-homogeneous pavements as well as control mixtures with pure reclaimed road concrete or pure-natural aggregate materials.
The mixture labelled “A” is the base mix for which the mix design was optimised, in which the mix granulate consists of 96.4 % of RA and 3.6 % of inactive limestone filler needed for raising the fines content. Samples mixture F and G represent mix granulates milled from rigid pavements with unbound base layer and different concrete layer thicknesses. Here the mix granulate is composed of 50 % reclaimed road concrete and 50 % basaltic aggregates. The basaltic aggregates were added in the exact composition in order to reach the common grading. Mix H is another control mix consisting of basaltic aggregates only.

Sample B consists for 75 % of reclaimed asphalt with basaltic aggregates forming the rest of the mixture. Samples C and D consist to one half of reclaimed asphalt. The other half is composed evenly of crushed concrete and basalt aggregates (Sample C) or pure basalt aggregates (Sample D). The sample E contains all three granulates types with lower proportions of the crushed concrete pavement.
For all sample mixtures the mix design grading as indicated in Figure 1 was applied. This procedure resulted in identical grading for all the mix granulate variations. Further all mixtures were prepared with the same added water and binder contents simulating the situating in field, where the mix composition can't usually be changed during the construction process.

Table 1: Varied cold recycling mixtures - Composition of mix granulate

Mix variations		Reclaimed asphalt (RA)	Reclaimed road concrete (RRC)	(Reclaimed) Unbound material (unb.)
A	100/0/0	100%	-	-
B	75/0/25	75%	-	25%
C	50/25/25	50%	25%	25%
D	50/0/50	50%	-	50%
E	40/20/40	40%	20%	40%
F	0/50/50	-	50%	50 %
G	0/25/75	-	25%	75%
H	0/0/100	-	-	100%

2.3 Sample preparation and curing procedure

The cold recycling mixtures were produced using a Wirtgen compulsory mixer WLM 30. Each freshly produced mixture was compacted to 9 cylindrical specimens (diameter 149.6 mm. height 80 mm) by applying a static force of 45,9 kN, resulting in a vertical pressure of 2.61 MPa for 30 seconds. After compaction, the moulded specimens were stored in a climate control chamber at 20 °C and 80% relative humidity for 1 day. After demoulding, the specimens were cured for additional 2 days in humid conditions (20 °C, 80 % humidity). The additional curing was varied according to the mechanical tests to be conducted.

2.4 Laboratory tests

According to German mix design specification, requirements on void content after dry conditioning, indirect tensile strength evaluated at a temperature of 5 °C and water sensitivity tests defined. However, by these properties, the resistance of the mix against permanent deformation are not considered. Therefore, CBR tests were added to this study. This rather simplified test was chosen due to limited experimental facilities which didn't allow the application of triaxial tests as well as for applying a widely spread test procedure.
Following test parameters were applied:

- Indirect tensile strength (ITS) tests acc. to EN 13286-42 were conducted at 5 °C for evaluating the indirect tensile strength. Two specimens were tested after 7 days of curing (ITS_7), whereas three specimens were cured for at room conditions for 25 days for evaluating ITS_{28}.
- California Bearing Ratio CBR was evaluated according to EN 13286-47 on two specimens from each mixture at 20 °C. The specimen were cured at room conditions for 25 days.
- For evaluation of water susceptibility, ITS was evaluated on two immersed specimens ($ITS_{28,wet}$) which were cured in room conditions for 11 days and immersed in water (20°C) for additional 14 days. The water susceptibility is evaluated by comparing the strength values obtained on the immersed specimens compared to the dry conditioned specimens (strength loss = $(ITS_{28} - ITS_{28,wet})/ITS_{28}$ [%]).
  The water conditioning was applied according to the German mix design guide for cold recycled materials.
- For the dry-conditioned specimens, the bulk density $\rho_{b,dim}$ was evaluated according to EN 12697-6. From these values and the calculated maximum densities, the void content was calculated.

3. TEST RESULTS

3.1 Water and void content

The content of water and the void contents of the room-conditioned specimens are indicated in Figure 2 and 3.
As can be observed, the water content in the specimen changes during room conditioning. For the bitumen emulsion samples, the water content of the specimens with an age of 14 days before transferring to the water immersion conditioning indicate significantly lower water contents compared to the specimens, which were stored for 7 or 28 days at room conditions. However, for the foamed bitumen mixtures, these specific specimens show the highest moisture contents. This indicates effects from the changing humidity and temperature changes in the laboratory room, where the specimens

were stored. Nevertheless, when comparing the samples A to H which were conditioned for a specific time, similar moisture contents can be observed.

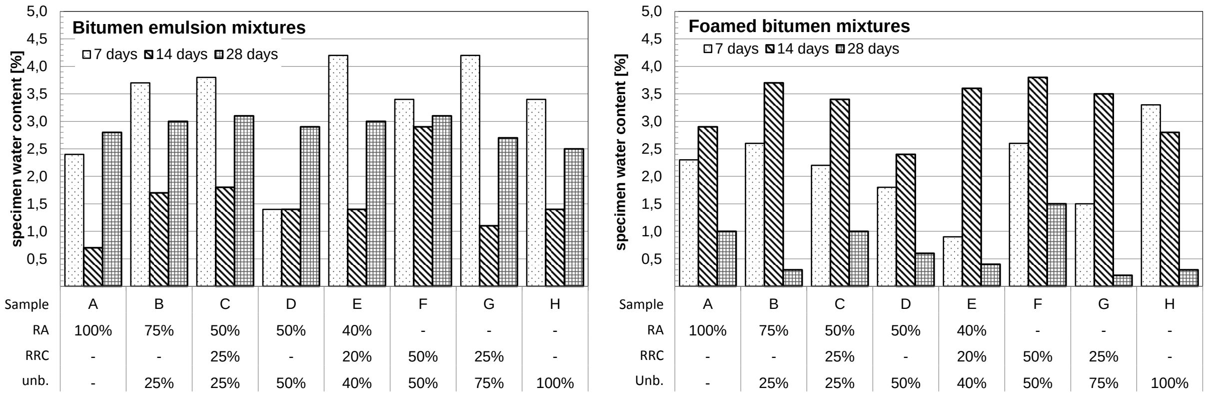

Figure 2. Content of moisture (top) for emulsion mixtures (left) and foamed bitumen mixtures (right).

The reference mix variation A (100/0/0) for which the mix granulate is composed of 100 % reclaimed asphalt reaches the specification limit for maximum void content of 15 %. The other mix samples for which the mix granulate composition was varied, show higher void contents and would not comply with the German mix design specification. These results indicate the importance for specific mix design to be conducted for each pavement to be recycled.
An increase in RA content in the mix granulate will improve the compactibility of the cold recycled mix and therefore will result in significant lower void contents.

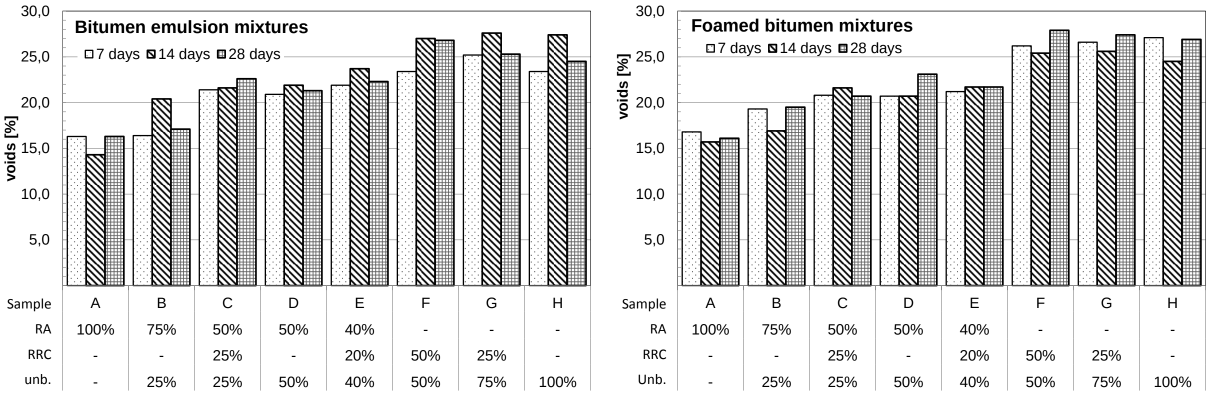

Figure 3. Void content for emulsion mixtures (left) and foamed bitumen mixtures (right).

3.2 Indirect tensile strength

The results from the indirect tensile strength tests applied at 5 °C are given in figure 4 for the bituminous emulsion mixtures and figure 5 for the foamed bitumen mixtures. The indirect tensile strength values vary significantly regarding the mix granulate composition.
All samples indicate a strong strength increase between 7 days of curing and 28 days of curing. The applied cement content of 2 % obviously demands for time needed for complete hydratisation.
Similarly to the void content, the indirect tensile strength after 28 days of curing depends on the RA content in the mix granulate. A decreasing RA content in the mix granulate results in decreasing indirect tensile strength values of the cold recycling mixtures. This behaviour is more obvious for the indirect tensile strength after 28 days of curing compared to tests conducted after 7 days.
On the other hand, the composition of the non-bituminous granulate material doesn't affect the indirect tensile strength values as indicated by similar strengths obtained for the mix samples F, G and H (0 % RA) as well as for the samples with 50 % RA content (C and D).
For the foamed bitumen mixtures plotted in Figure 4, a similar effect of RA content in the mix granulate can be observed as for the emulsion mixtures. However for the foamed bitumen mixtures also an effect of non-bituminous bound mix granulate can be observed. For these mixtures the presence of reclaimed concrete in the mix granulate will improve the strength in the mixtures as obvious when comparing sample C and D but also F and H.
When comparing the indirect tensile strength values obtained for the two binder types applied, it can be observed that the bitumen emulsion mixtures reach considerable higher indirect tensile strength values compared to the foamed bitumen mixtures.

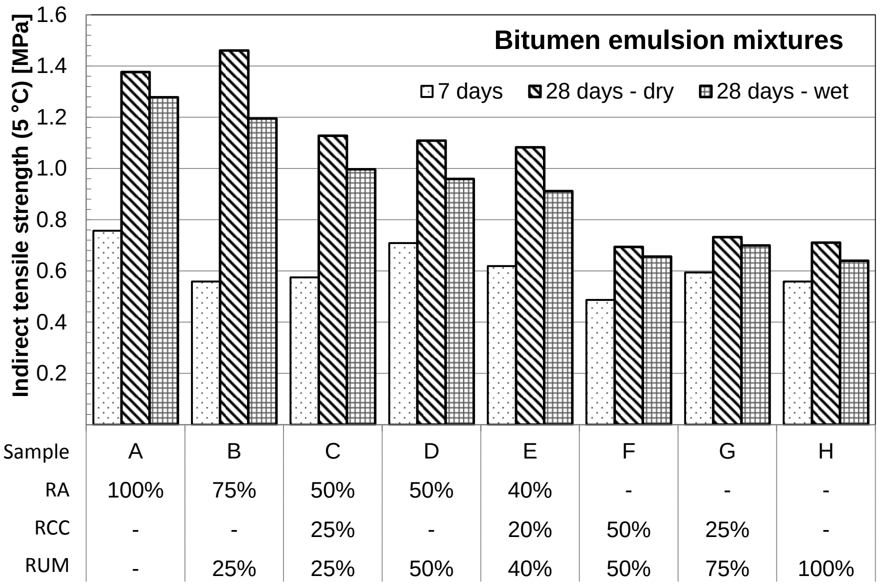

Figure 4. ITS after 7 days and 28 days for the bituminous emulsion mixtures

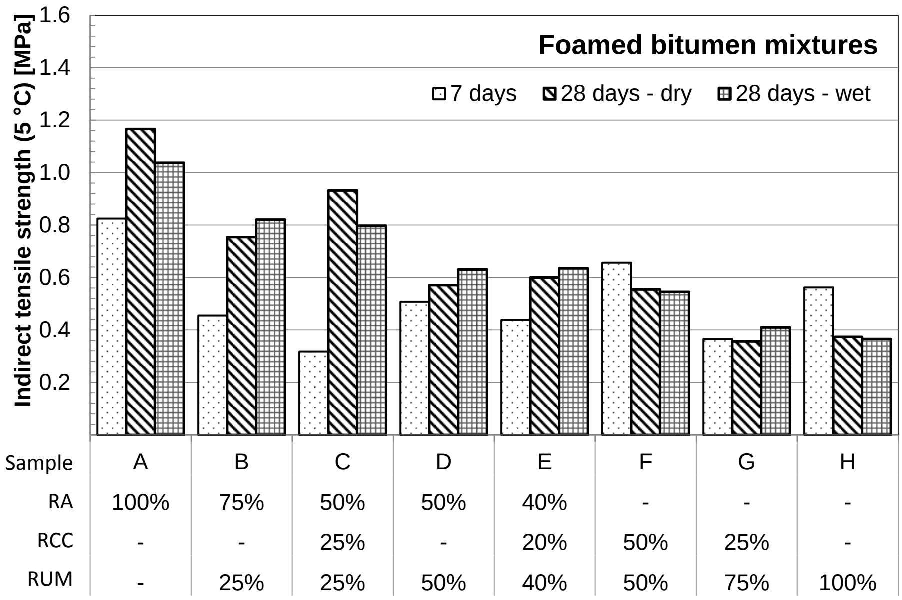

Figure 5. ITS after 7 days and 28 days for the foamed bitumen mixtures sorted according to the RA content.

3.3 Water susceptibility

Figures 4 and 5 also contains the ITS values obtained on specimen which were water immersed after 14 days until testing at the 28th day. The remaining strength after water conditioning at 40 °C is plotted in figure 6 in percent relative to the indirect tensile strengths obtained for the dry conditioned specimens.

All mixtures with bitumen emulsion show a decrease in ITS after water conditioning. The mixtures without RA (F, G, H) indicate only a slight strength loss of below 10 %, whereas for the mixtures containing both, RA and non-bituminous mix granulate, the strength loss is higher than 10 %, except for sample A for which the mix design was optimised.

For the foamed bitumen mixtures, the water immersed curing results in an increase of ITS for four mix samples (B, D, E and G). The strength increase can be explained by further hydraulic activity of the added cement in the cold recycling mixture for the case that the original water content was not high enough for allowing a complete hydration of the active cement content.

All samples tested comply with the mix design specification of a maximum strength loss of ≤ 30 % [3] as applied in Germany for cold recycling mixtures.

Despite of mix granulate samples A and C, all foamed bitumen samples indicate a better water susceptibility compared to the bitumen emulsion mixtures with same mix granulate composition.

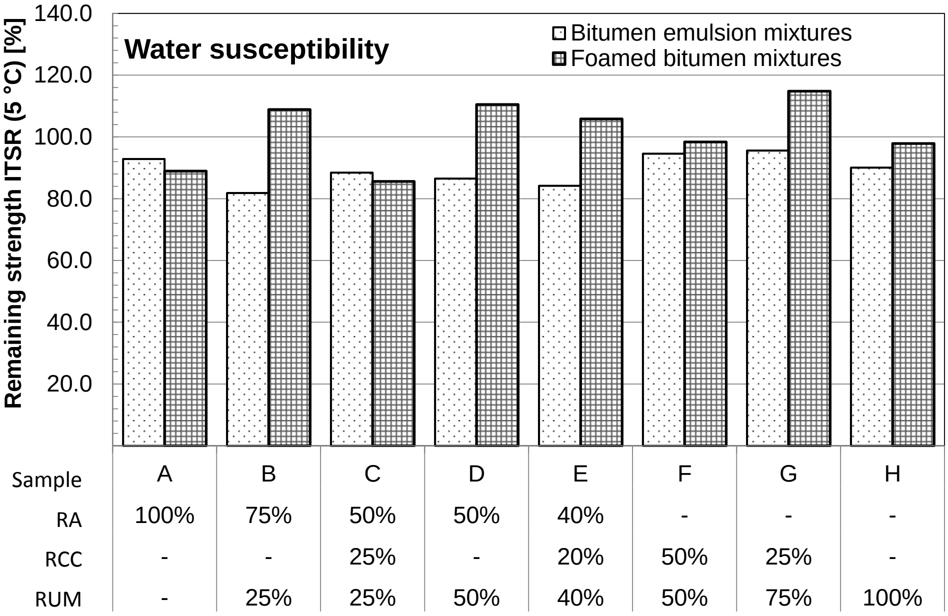

Figure 6. Results of water susceptibility tests: Remaining strength after water conditioning.

3.4 California bearing ratio (CBR)

The results of CBR tests are summarised in figure 7. The highest CBR values are obtained for the mixtures without any RA components in the mix granulate (F, G and H). Generally foamed bitumen mixtures indicate for the same mix granulate composition higher bearing ratio values compared to the bitumen emulsion mixtures.

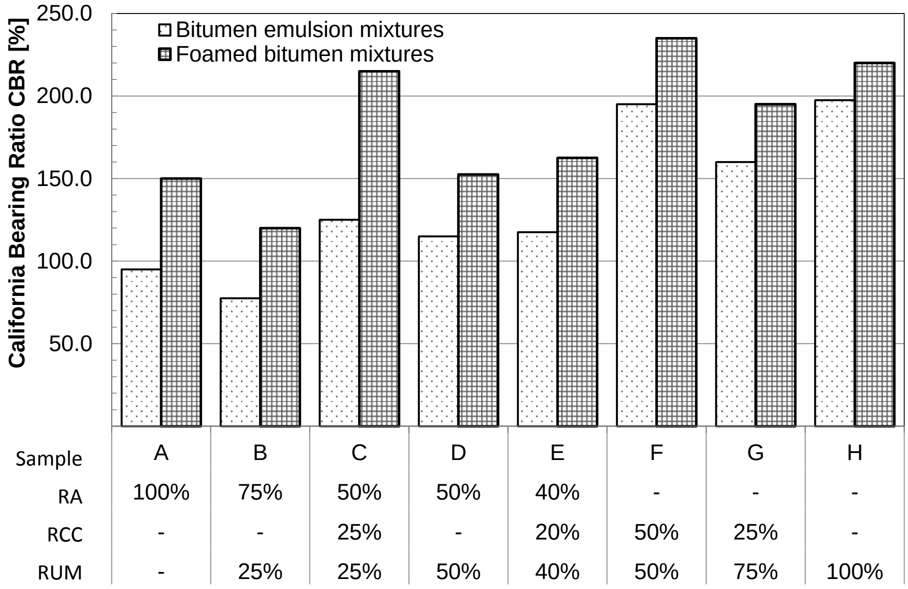

Figure 7. CBR for bituminous emulsion mixtures (left) and foamed bitumen mixtures (right).

4. DISCUSSION

The 16 tested cold recycling mixtures with same binder content but varied binder type (bitumen emulsion or foamed bitumen) and varied mix granulate composition of the same grading indicate considerable different mechanical properties. At similar void contents for bitumen emulsion and foamed bitumen specimens, higher indirect tensile strength values could be obtained for the bitumen emulsion bound mixtures. The continuously bitumen film around the mix granulates will result in better cohesion in the cold mix specimen compared to the non-continuously bound foamed mix. On the other hand, the foamed bitumen mixtures indicate better water susceptibility as well as higher bearing capacity as indicated by CBR tests compared to emulsion mixtures with same composition. For the CBR tests, the non-continuously bonding in the foamed bitumen mix results in a higher internal friction and therefore in less permanent deformation compared to the bitumen emulsion mixture.

Regarding the question of allowable tolerances when cold recycling is applied on inhomogeneous road structures, the results clearly show, that a variation of mix granulate composition will affect the mechanical properties of the prepared cold recycling layer. In order to evaluate limits for tolerated pavement inhomogeneity, the requirements for cold recycled mixtures as applied in Germany [6] are applied. The mix design standard contains threshold values for indirect tensile strength, measured at 5 °C as well as the void content. Requirements are demanded during mix design (a) as well as after pavement construction in compliance tests (b).
Figure 8 shows these threshold values on ITS and void content compared to the test results obtained within this study. The test results are plotted versus the RA content in the mix granulate applied. As observed earlier, the RA content affects both properties – the void content as well as the indirect tensile strength. An increasing content of RA in the mix granulate will result in a decrease of void content (left) and an increase of ITS. Both properties indicate a nearly linear relationship regarding the RA content.
From these results it can be concluded, that for bitumen emulsion and foamed bitumen mixtures non-homogeneous pavement structures may be tolerated if the resulting RA content in the mix granulate is higher than 75 %. In both cases the void content requirement is the limiting property. When only considering the ITS requirements, lower contents of RA can be tolerated. These differences won't lead to incompliance for water susceptibility as all samples evaluated fulfilled the mix design requirement. Furthermore, the bearing capacity of the mix samples with reduced RA content will be higher compared to the mix design material and therefore, the overall pavement structure won't be under-designed.
Further the results showed, that the composition of the non-RA granulate (reclaimed cement concrete material or unbound material) doesn't affect the pavement performance when bitumen emulsion is applied. For the foamed bitumen mixture and constant content of RA an increased content of reclaimed cement concrete will result both in higher indirect tensile strength as well as higher CBR values.
The predominating effect of RA content on the mechanical properties of cold recycled materials indicate that the bituminous binder of the RA still influences the material properties. Therefore, it inhibits a remaining binder activity important for specific material properties as indirect tensile strength.

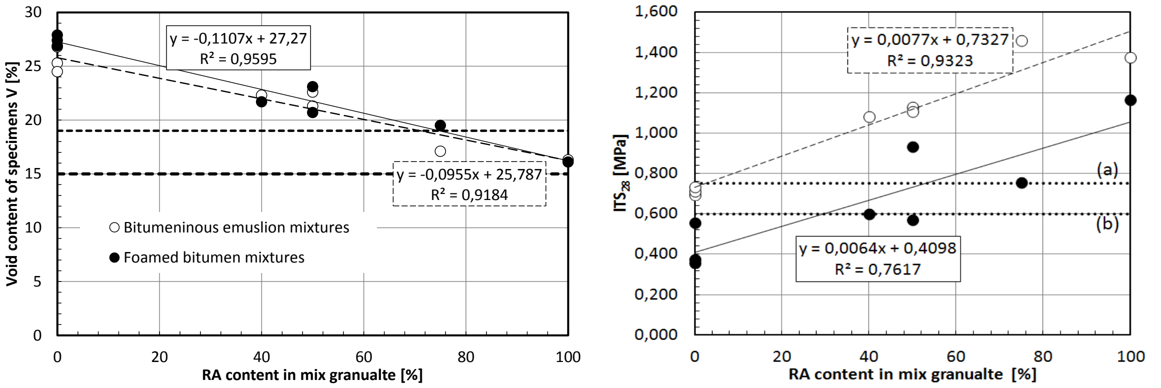

Figure 8. Void content (left) and ITS after 28 days of dry conditioning (right) versus the RA content in the mix granulate for bituminous emulsion and foamed bitumen mixtures. German specification requirements are plotted in dotted lines.

5. CONCLUSIONS

Regarding the question about inhomogeneous pavement structure and its effect on the material performance following recommendations can be drawn from the results of this study:

- Both material properties evaluated in this study, the indirect tensile strength as well as the bearing capacity are affected by composition of mix granulate and therefore may be sensitive to inhomogeneous pavement conditions.
- An increased content of reclaimed asphalt in the mix granulate will increase the indirect tensile strength and decrease the CBR value and therefore the bearing capacity of the cold-recycled layer. Therefore, the effect of granulate composition is contrary compared to the indirect tensile strength.
- Pavements with inhomogeneous structural properties in terms of variations in layer thickness and composition are feasible for cold in place recycling if the resulting mix granulate doesn't show too large deviations from the mix design. For the example in this study of a pure RA mix design, non-RA granulates up to a proportion of 75 % for both bitumen emulsion and foamed bitumen mixtures can be tolerated. However this limit is given by the void content, which is considerable high in this study.
- The significant effect of RA content on the mechanical properties of cold recycling mixtures (compactibility, tensile strength, bearing capacity) can be interpreted as bitumen activity of the bitumen which is part of reclaimed asphalt.

6. ACKNOWLEDGEMENT

The work reported here was part of the project “CoRePaSol” funded by the CEDR Transnational Road Research Programme Call 2012: Recycling: Road construction in a post-fossil fuel society that is being funded by Denmark, Finland, Germany, Ireland, Netherlands and Norway and managed by Nation Road authority, Ireland. The project started in January 2013 and is due to be completed by March 2015.

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