Re-Road *End of life strategies of asphalt pavements*

# Mix design and performance of asphalt mixes with RA

Joëlle De Visscher et al.

SEVENTH FRAMEWORK PROGRAMME

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007–2013) under grant agreement n° 218747.

# Re-Road – End of life strategies of asphalt pavements

## D2.4
## Mix design and performance of asphalt mixes with RA


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**EUROPEAN COMMISSION**
**DG RESEARCH**

A FP7 Collaborative Project
Work programme:
Sustainable Surface Transport
SST.2007.1.2.2 End of life strategies
for vehicles/vessels and infrastructures

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# Executive summary

This deliverable report investigates the impact of using reclaimed asphalt (RA) on mix design procedures and performance testing of asphalt. The work is focused on the recycling of RA with polymer modified binders (PmB) in new surface courses, as these are the gaps in the knowledge we already have on hot mix recycling. It is necessary to fill these gaps, since the highest amounts of RA nowadays originate from surface courses that very often contain PmB and the highest need of new mixtures is for surface courses. Recycling of old surface courses in new surface courses is however still very limited because the impact on the performance of these asphalt layers is not well understood.

A correct mix design, combined with laboratory performance testing, is necessary to guarantee the quality and durability of a surface course with RA. The initial type testing study is made by contractors to demonstrate that the required specifications for a mix are satisfied. Therefore, it shall be based on performance testing. However, as we notice that in Europe most of the initial type testing is made with laboratory prepared mixes, one of the first questions to be answered is whether laboratory mixes are representative for the plant mix (which means they have the same performance characteristics) and whether the parameters of the laboratory mixing procedure have an impact. If they would have a large impact, type testing studies made by different laboratories could lead to different results.

Therefore, a laboratory mixing study was carried out. Five laboratories participated in this mixing study, using different mixers and different mixing times. To investigate the impact of the mixing times, each laboratory also doubled their usual mixing times. The study was done with stone mastic asphalt (SMA) with 15 % of RA containing PmB as produced by a German asphalt plant. In this way, the test results obtained on the laboratory mixes could be systematically compared to the plant mix.

The laboratory mixing study showed no significant differences between the mixes prepared by the different laboratories and with different mixing times. Mix control tests, X-ray CT scans and Optical Image Analysis of the specimens produced from the mixes confirmed this. The differences in performance test results were limited and could also partly be explained by the specimen compaction method, since every laboratory that produced mixes also compacted the test specimens. On average, the results of the performance tests made on the laboratory prepared mixes were the same as on the plant mix. From this study, it is concluded that it is possible to do an initial type testing study with laboratory prepared mixtures and that there is no significant impact from the laboratory mixing procedure, as long as the European standard for laboratory mixing EN 12697-35 is correctly followed.

As surface courses need to be replaced more frequently than base layers, we will in the near future encounter more and more RA that already contained RA when it was newly placed. Hence, the same material will have to be recycled multiple times. The impact of multiple recycling on the performance is also a topic that still raises many

questions. The performance will depend on the selection of the new binder which is added to the mix. A softer binder will be needed in order to obtain the right consistency after blending with the hard aged binder. The new and old binder also have to be compatible (this is investigated in task 2.1 of WP2).

To gain more understanding of these questions, the effect of multiple recycling cycles on the performance of an asphalt mix was evaluated in a multiple recycling study. A laboratory produced asphalt mix was subjected to laboratory long-term ageing in order to simulate a mix with similar properties as RA. After simulated long-term ageing, the aged material was added as RA into new stone mastic asphalt (SMA) variants. This recycling cycle was repeated twice in combination with three different types of new PmB (all chemically or physically linked SBS modified binders). In this study, twelve SMA variants were produced.

The multiple recycling study showed no negative impact of multiple recycling on the performance characteristics of the mixtures. Also, there were no signs of incompatibility between the SBS modified binders. It has to be noted however that the simulation of RA by laboratory ageing only simulates the ageing effect. The effects of milling, crushing and sieving of RA, which could have an impact on the aggregate quality, was not evaluated by this study.

Throughout the experimental work done in this task 2.2 of WP2, the various mixtures with RA were designed in such a way that the grading was the same, and the performance tests made on the various mixes showed the success of this approach. Indeed, knowing and controlling the grading of the RA, it is possible to determine correctly the grading of the new mixture and consequently also the volumetric composition of the mix. This is very important because of the impact of the volumetric composition on the performance characteristics.

Besides the grading, the content and the characteristics of the recovered binder also need to be determined to make a correct selection of the new binder and binder content. For daily practice in asphalt plants, this requires the development of procedures to store the RA on separate homogeneous stockpiles of which the characteristics are determined correctly. The initial type testing study shall be done with material from the same stockpile.

When using the same kind of PmB, the application of mixing laws for predicting the final binder properties of the mix of old and new binder is feasible. No problems of incompatibility were encountered in the multiple recycling study that combined SBS modified PmB. When using binders of a different nature, binder compatibility shall be investigated more thoroughly (see D2.6).

Predicting the performance of the asphalt mix using simple mixing laws is less reliable, as shown in the multiple recycling study. It may be acceptable to make a first estimation, but performance testing on the final mix remains necessary.

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# 1 Introduction

## 1.1 Overview Re-Road WP2, task 2.2

The vast majority (90%) of European roads are paved with asphalt material. At the end of the service lifetime of a road, when the damaged pavement cannot further fulfil its purpose as a comfortable carrier of traffic, the road pavement must be renewed. Sustainable construction processes that conserve natural resources are well recognized within the asphalt industry, although practices for asphalt recycling vary to a great extent across Europe. Today a large amount of demolished asphalt pavement ends up as unbound granular layers where neither the bituminous binders nor special aggregates from old surface layers are reused at their full potential. Replacing new materials with recycled asphalt in the production of new asphalt mixtures reduces $CO_2$ emissions significantly.

The Re-Road project aims to develop knowledge and innovative technologies for enhanced end of life strategies for asphalt road infrastructure. Such strategies have an important positive impact on the energy efficiency and the environmental footprint of the European transport system and fit within the life-cycle thinking which is being introduced in waste policy at European level.

The objectives of work package 2 “WP 2: Impact of RA quality and characteristics on mix design and performance of asphalt containing RA” is to analyse the potential use of RA in new asphalt surface layer mixes in consideration of the use of modified binders. Therefore, the chemical compatibility of new binders with old (polymer modified) bitumen in RA and the physical and mechanical performance of the resulting binder and asphalt mixes are examined to develop mix-design guidelines to ensure a long service life of asphalt mixes with reclaimed asphalt.

The mix design of asphalt mixes is addressed in task 2.2 “Impact of RA on asphalt mix design and laboratory performance” because hot mix asphalt (HMA) containing RA needs different approaches compared to standard asphalt mix design due to the specific properties of the RA material. To reach the overall goal to elaborate a mix design procedure for asphalt containing RA, following research topics will be addressed:

- Mix design and initial type testing of a mix are usually done with laboratory produced mixes. Therefore, laboratory mixing procedures are investigated with regards to the specific influence of mixing conditions and mixing times which influence the mix quality especially when RA is added (e.g. distribution in the mix and double coating of RA particles).
- The laboratory mixing procedures are validated by comparison of the laboratory produced mixes to industrially produced mixes. It has to be noted that the specific conditions at various kinds of mixing plants and different industrial procedures may also have an impact on the RA quality (e.g. thermal shocks during heating).
- The influence of RA quality on the performance in mechanical laboratory tests is analysed to identify suitable test methods for application in mix design procedures.

## 1.2 Partners/Authors

This deliverable summarises the research work conducted for the Re-Road project, work package (WP) 2, task 2.2, lead by Joëlle De Visscher (BRRC). Following authors and partners from 5 research laboratories contributed to the experimental studies and discussions of the results presented:

- Authors:
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  - Jørn Raaberg (DRI)
  - Rawid Khan (UNott)

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    - Erik Nielsen
  - University of Nottingham (UNott)
    - Davide Lo Presti
  - TU Braunschweig (ISBS)
  - IFSTTAR
    - Thomas Gabet
  - CETE Méditerranée
    - Virginie Mouillet

Additionally, the technical staff conducting the experiments at the participating laboratories is acknowledged.

## 1.3 Scope of the report

In order to elaborate knowledge to reach the overall WP2 objective, which is the improvement of mix design methodology in order to increase the reuse of reclaimed asphalt (RA) originating from surface asphalt courses in new surface asphalt mixtures, several sub-tasks were defined for task 2.2:

### *1.3.1* Effect of laboratory mixing on asphalt performance

Before starting the full-scale production of an asphalt mixture in an asphalt plant, contractors will perform a series of initial tests to show that the mixture satisfies the performance requirements. This is the so-called initial type testing study. Initial type testing is part of the European requirements for CE-marking of asphalt mixtures.

Initial type testing is done with a mixture with the same components and composition, usually mixed on a small scale in a laboratory environment. It is therefore essential to ensure that the laboratory mixing process gives a mixture with similar performance characteristics as the mixture prepared in an asphalt plant with the industrial mixing process.

This point is particularly critical for mixtures with high percentages of RA and PmB:

- RA is very sensitive to additional ageing during the process of heating and mixing with new materials. Depending on the type of asphalt plant, there are different ways of introducing RA into the mix. This may have an influence on the RA properties and therefore also on the properties of the resulting mix. During the mixing, the old binder will be mixed with the new binder. This requires a lot of energy, because the old binder is very hard and sticks strongly to the old aggregate. The degree of mixing will depend on the temperature to which the RA is heated, the mixing speed, the time of mixing, the type of mixer, …. When the RA is not sufficiently heated and mixed with the new materials, it will remain as a separate phase in the mix (“black rock”) and the performance of the resulting mix will be different from the behaviour anticipated for a perfect mix. The same questions arise when preparing a laboratory mix with RA: how shall the RA be heated to prevent too much additional ageing, while achieving a sufficient reduction of the viscosity of the old binder to be able to mix it with the new binder?
- In case of PmB the question is even more complicated, because of the interaction between the two binders. The questions are then whether the two binders are chemically compatible and whether the effect of the polymer is still the same in the mixed binder. These questions of RA compatibility with new binders are studied in Task 2.1 of WP2 of the Re-Road project.

In this report, it is investigated which parameters of the laboratory mixing process have a significant effect on the performance of the asphalt. This is based on the results of an experimental lab mixing study that was carried out in the framework of task 2.2. The goal was to investigate if the lab mixing leads to mixes with the same performance characteristics as measured on the mix prepared in the asphalt plant. This will give information about the impact of the mixing process, without going into details about the degree of mixing or binder compatibility. The most important objective is to demonstrate that the adopted mixing process in the lab leads to a mix with similar performance as the plant mix, which is essential for the validity of the initial type testing study. This part of task 2.2 will be referred to as the "lab mixing study".

### *1.3.2* Performance of asphalt with RA and PmB

When RA is recycled into a new asphalt mixture, the RA is usually considered as an additional component, consisting of aged binder and aggregates, which mixes with the new binder and aggregates.

The real situation is much more complex due to the following:

- Reheating and remixing of the RA will cause effects like additional binder ageing and micro-cracking, crushing or polishing of the aggregates due to thermal and mechanical shocks. This will change the characteristics of the RA during the production and may have an impact on the performance of the resulting mix, depending on the RA handling and the production process.
- Mixing of the old binder with the newly added binder is never perfect, because the old binder is very hard and viscous and strongly sticks to the RA aggregate. The degree of mixing again depends on the production process.
- In case of PmB, the effect of the polymer may be different or disappear when mixed with another binder. This is studied in task 2.1 of the project (Mollenhauer et al. 2012).

The practice of recycling asphalt that already contains recycled asphalt will take place more and more in the near future. This is especially true for surface courses, which need to be renewed more frequently. The effect of multiple recycling on the asphalt properties is therefore also an important question to be investigated.

The performance of asphalt, particularly with high amounts of RA and with PmB, may therefore differ from what is theoretically expected on the basis of the characteristics of the individual components. This was investigated in this task 2.2 for some practical test cases involving high percentages of RA, PmB and multiple recycling. This part of task 2.2 will be referred to as the "multiple recycling study".

### *1.3.3* Test methods applied

In the lab mixing study, the mixtures prepared in the laboratory were compared to the mixtures prepared in an asphalt plant on the basis of their performance characteristics and some advanced visual techniques.

The most important performance tests carried out in the framework of initial type testing are: compactability by gyratory compaction (for void content), water sensitivity, stiffness (for bearing capacity) and resistance to permanent deformation.

The mixtures were also compared in a visual way: advanced techniques such as CT X-ray scanning and Optical Image Analysis have been applied to verify the homogeneous distribution of all the components, the void content and the distribution of the voids, coating quality,…

In the multiple recycling study, the mixtures were also compared on the basis of performance. The tests applied were: compactability by impact compaction, stiffness, resistance to permanent deformation and resistance to low temperature cracking.

In both studies, the mixtures were also compared on the basis of their composition (mix control): aggregate grading, binder content, maximum density and some empirical properties of the recovered binder (PEN and R&B softening point).

The different test methods are described in paragraph 3 of this report. The performance tests were all carried out according to the European test methods (EN 12697 series).

#### *1.3.4* Proposal of design methodology

The effect of RA and multiple recycling on performance will be different depending on the type of mixture, the RA characteristics, the type of asphalt mixing plant and the mixing procedure, … Therefore, it will not be possible to generalize observations or conclusions drawn from a limited number of case studies.

A proposal for a design methodology is therefore necessary. This design methodology shall describe the different steps to be followed for the characterization of the components, the theoretical mix design, the optimization of the mixing procedure and the initial type testing, in order to maximize the amount of recycling and to ensure the long term performance of the mixture.

# 2 State of the art

## *2.1 Lab mixing*

In WP 4 of the Re-Road project (“RA Processing and RA management at the mixing plant”), a questionnaire was issued addressing the common practices of laboratory mixing during the mix design process. The results were summarized in deliverable report D4.1 “Laboratory mixing - state of the art - Overview of returned responses on a questionnaire on laboratory mixing practice – especially linked to the introduction of reclaimed asphalt” (Nielsen 2009). The report is based on questionnaire answers by companies and specification bodies in Belgium, Denmark, Germany, Slovenia, Sweden and the UK.

The mixing devices used vary considerably. 10 laboratories are equipped with vertical planetary mixers, 5 use vertical mixers with counter-rotating mixing bowl and 6 labs are equipped with horizontal twin axle mixers. Nearly all mixers are equipped with an electrical heating device to satisfy the requirements for the mixing temperatures. The mixing capacity ranges from 2 kg to 80 kg.

The mixing procedure is usually according to the European standard EN 12697-35. Nevertheless, the standard allows varying mixing times and feeding sequences. Therefore the questionnaire asked for the individual mixing times and sequences applied both for laboratory mixing and for plant mixing (in case of batch plants).

Several producers gave mixing times for the dry mixing (after addition of RA to the aggregates and for wet mixing (after addition of the binder). Whereas the mean plant batch mixing cycle duration is about 60 s (varying from 25 s to 90 s), the mean laboratory mixing time varies from 45 s to 180 s with a mean of 100 s. Especially the wet mixing time required to reach a homogeneous asphalt mix in laboratory mixers is with a mean duration of 80 s considerably longer than the wet mixing time in a batch mixing plant.

The answers for the feeding sequence are summarized in Table 2-1. While in batch plants the mixer is running permanently and the constituents are added one after the other, in laboratory the mixer is often stopped before another constituent is added to the mix.

For the laboratory mixing procedure, the predominant technique is the dry mixing of all aggregates including the RA before the binder is added to the mix. Only 3 labs indicate an additional mixing step for the RA before the binder is added.

In the asphalt plant there are more differences in the mixing sequence. For the predominant mixing sequence all aggregates are added to the mixer first, followed by the RA and by the binder. Two asphalt producers add the RA before the filler is added to the mixer. In Sweden most asphalt producers add first the aggregates, then the RA, followed by the binder and at last the filler.

**Table 2-1: Summary on questionnaire answers on mixing sequences (data source: Nielsen 2009)**

| Feeding sequence | Number of answers | |
|---|---|---|
| | For lab mixing | For plant mixing |
| (Coarse – Fine – Filler – RA) **–** Binder | 17 | 9 |
| (Coarse – Fine – Filler) **–** RA **–** Binder | 3 | |
| Coarse – Fine – RA – Filler – Binder | - | 2 |
| Coarse – Fine – RA – Binder – Filler | - | 5 |
| No Answer | 3 | 7 |

## 2.2 Performance of asphalt with RA and PmB

Polymer modified binders (PmB) are applied regularly in surface courses subjected to high traffic loads. As the lifetime of these layers is approximately between 15 and 25 years (depending on mixture type, asphalt quality, traffic loading, weather conditions ...), high amounts of RA containing PmB are currently recovered from roads during maintenance services. Instead of downgrading this RA with high quality components by recycling in unbound layers or base layers, the beneficial properties of the modified binders and the high quality aggregates could be used more efficiently and enhance the performance of new asphalt mixes for surface courses containing RA with PmB.

However, recycling of high quality RA containing PmB is still limited because of several restrictions. Very often, the recovered PmB doesn't meet the requirements on the characteristics of the recovered binder (i. e. pen ≥ 15 1/10 mm and/or $T_{R\&B}$ ≤ 70 °C) as applied in several EU countries (Mollenhauer et al., 2010b). Furthermore, as the effect of PmB in RA is not sufficiently evaluated yet, the application of RA containing PmB in new asphalt mixes for surface courses is restricted to 10 % and for binder courses to 20 % according to relevant parts of EN 13108.

On the other hand, some recent research activities indicate that these restrictions are too conservative and that high quality asphalt mixes can be obtained when special requirements are fulfilled, i. e. separated milling of surface layers, storing of RA originating from similar sources, homogenisation and characterization of the RA stockpiles, correct type testing of the mix with RA and optimised RA addition technology in the mixing plant.

The European project PARAMIX (Road PAvement Rehabilitation techniques using enhanced Asphalt MIXtures, 2001-2003) considered recycling in base layers (AC) and surface layers (SMA). Using only RA of the same type as the new mix, SMA (containing PmB) for SMA and AC for AC, high percentages of recycling could be achieved, since the grading of the RA was always similar to the target grading of the final mix (Perez et al, 2004). Up to 30 % RA was used in SMA and up to 50 % in AC. For the selection of the new binder, viscosity and rheological tests were performed on combinations of new binders and recovered binders (De Visscher et al, 2004). For the SMA mix, PmB were also considered as new binders. Based on viscosity tests, the new binder selected was always a very soft binder. PmB could be used, but combined with recovered binder, the viscosity and stiffness was less than expected in the low frequency range. Wheel tracking tests were done to verify the resistance to permanent deformation of the mixtures. The test results were good, despite of the use of very soft new binders. So, based on performance tests, it appeared that the new and the old aged binders mixed well. Rejuvenators were also used, but a positive neither a negative effect could be demonstrated. From the experimental work done in the PARAMIX project, one can conclude that using higher percentages of RA than what is usually allowed, with or without PmB, can lead to mixtures with a good performance, comparable to the performance of a similar control mix without RA. The European project DIRECT-MAT (2009-2011) showed case studies in which RA containing PmB was successfully applied in new hot mix asphalt surface course (20 % RA in new AC 14) and in base course asphalt (40 % RA in new AC14) without indicating disadvantages compared to control sections (Direct-Mat, 2012).

By laboratory performance testing, Renken & Lobach (2008) showed that asphalt concrete for binder layers containing 15 % or 30 % of RA containing PmB, results in comparable mix performance than the control mix without RA addition if adequate mixing times are applied. Grönniger et al. (2009) showed that the recycling of 15 and 30 % of RA from PA courses containing highly aged PmB ($T_{R\&B}$ up to 107 °C) in new SMA surface course mixes or AC binder course mixes results in comparable material performance as the control mix without RA when virgin binders of lower viscosity are added except for fatigue resistance, where a higher percentage of RA as well as RA with higher binder viscosity resulted in a lower number of load cycles until failure.

## *2.3 Mix design procedures*

The deliverable report D4.1 “Laboratory mixing - state of the art - Overview of returned responses on a questionnaire on laboratory mixing practice – especially linked to the introduction of reclaimed asphalt” (Nielsen, 2009) also contains information about the mix design procedures in use by the countries who have responded to the questionnaire (Belgium, Denmark, Slovenia, Sweden and UK).

Belgium and the UK use a volumetric approach to design the mixtures. France and the Netherlands were not involved in the questionnaire, but they also follow a volumetric approach. The other countries represented by the questionnaire answered that they use the Marshall mix design method.

Concerning the applied mixing technique for mix design, from the total of 23 answered questionnaires, six out of 23 use lab mixing only for the mix design, whereas eight answers stated the application of plant mixing only for the mix design. Nine answers indicate that new mixes are first mixed in laboratory and then in plant for mix design.

The questionnaire also contained the question if crushing, which happens during the mixing process, is taken into account for the mix design. The large majority simply answered “no”. Some answered they don’t, because they observe no considerable degradation of the aggregates in laboratory mixing. One answered it is not relevant to consider aggregate crushing in the mix design, because there is much less crushing in a laboratory than in a plant mix and, to account for the production of additional fines in the plant, the mix design formula needs to be translated into a plant mix formula anyway. Probably the degradation of aggregates during mixing is very small, if not negligible, due to the high quality aggregates used in Europe, especially for surface courses as addressed in the Re-Road project.

On the question “What is the mean percentage of RA added in base or surface layers (AC and SMA)?” only very approximate answers were given. The only trends that can be observed are:

- The percentages are much smaller in surface courses, in most countries RA is not used in surface courses. Only answers from Belgium and Sweden indicate the use of RA in AC surface layers.
- In general, the given percentages are very low (5 to 20 %). Only in Denmark and Belgium, up to 50 % is used in case of AC base layers according to the questionnaire answers.

None of the answers mentions that this percentage depends on the characteristics of the RA, while the authors of this report are aware that this is already the case in many countries. In Belgium for example, the maximum percentage of RA added is restricted by limits which depend on the homogeneity of the RA stockpile. The optimum percentage then follows from the volumetric mix design, which takes into account the characteristics of the RA from the stock pile.

The German approach to evaluate the maximum possible RA content in order to reach the requirements on the mix tolerances of the hot mix asphalt is to evaluate the range of relevant RA characteristics for a given stockpile or other source of RA. The higher the scattering of the relevant RA properties ($T_{R\&B}$, binder content and grading), the lower is the possible percentage of RA in the resulting mix. The nomograph shown in Figure 2-1 is applied to evaluate the maximum RA content possible. For the German procedure, the ranges of relevant RA characteristics are evaluated for a number of RA samples taken from the RA source (at least 5 samples per stockpile). For each relevant RA characteristic, the total range of values measured are calculated (Max – Min). By plotting a horizontal line from the highest range in means of vertical location in the left part of the nomograph to the right part, the black line can be used to evaluate the maximum allowed RA content.

As a result of Direct-Mat project additional approaches are added to the German nomograph. The dotted line indicates the resulting RA content as applied in France using a similar approach as explained.

The coloured points in the left part of the nomograph indicate general specifications on the homogeneity of RA properties used as threshold values in order to characterize RA quality. As the result of RA quality, the RA addition rate limits for surface course asphalt mixes as applied in other countries are plotted. For example, to enable a RA content higher of up to 25 % in Belgium, the range of RA characteristics shall not exceed the values given in the left part of the diagram.

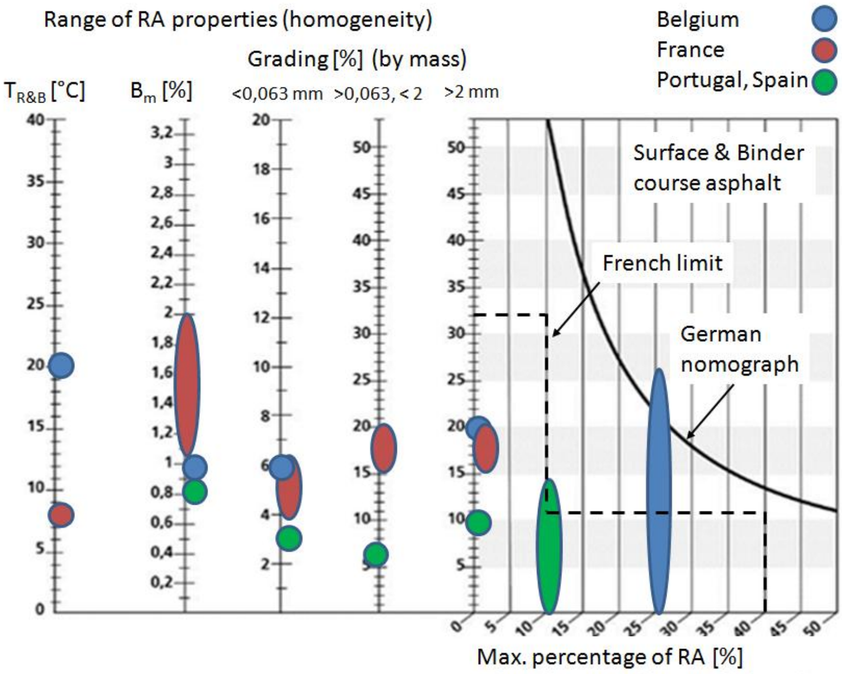



**Figure 2-1: Specifications on RA homogeneity and maximum allowed RA content for Belgium, France, Portugal and Spain summarized in German nomograph approach (Mollenhauer et al. 2011).**

Further limitations for RA content result from asphalt mix plant design and RA feeding technique applied.

The conclusion is that mix design procedures are still very different from country to country and depend a lot on local experience and habits, especially for mixes with RA.

# 3 Experimental work

## 3.1 Materials analysed

### *3.1.1* Lab mixing study

The experiments were conducted on a mix used in a road construction work of a federal rural road in Northern Germany (B 209 Honedingen – Bad Falligbostel). The material is stone mastic asphalt with a nominal grain size of 8 mm (SMA 8) according EN 13108-5, containing 15 % of reclaimed asphalt (RA) from porous asphalt layers. In plant, the RA was added without additional heating directly into the mixer (cold feed) of the batch plant.

Further, a second SMA 8 was sampled, which was used as reference mix without RA on the same road construction works as control section.

On 10$^{th}$ and 11$^{th}$ June 2009 the asphalt mixes were sampled at the DEUTAG mixing plant in Hambostel. From each mix 40 samples of 15 kg each were filled into buckets and closed with metal lids. The samples were labelled as followed:

- SMA 8 without RA
- SMA 8 with RA

During the sampling of the SMA 8 with RA a binder sample of approximately 2 kg was taken from the used bitumen tank.

The constituent materials were sampled at their producing sites:

Twenty buckets of 10 kg binder were taken from the PmB-plant “H + W Mischwerke GmbH” at Hamburg. The buckets were closed with metal lids and labelled with “Caribit”, which is a SBS modified binder of the class “25/55-55 A” according EN 14023.

From the mixing plant in Hambostel the steel slag aggregates were sampled. The stockpile from which the RA was sampled contained granulated RA material from porous asphalt (PA 8) from motorway surface layers in Lower Saxony. By homogenization, the properties of this RA vary only slightly according to results (softening temperature $T_{R\&B}$ and elastic recovery according EN 13398 of the recovered binder) provided by the plant operating company (see Figure 3-1).

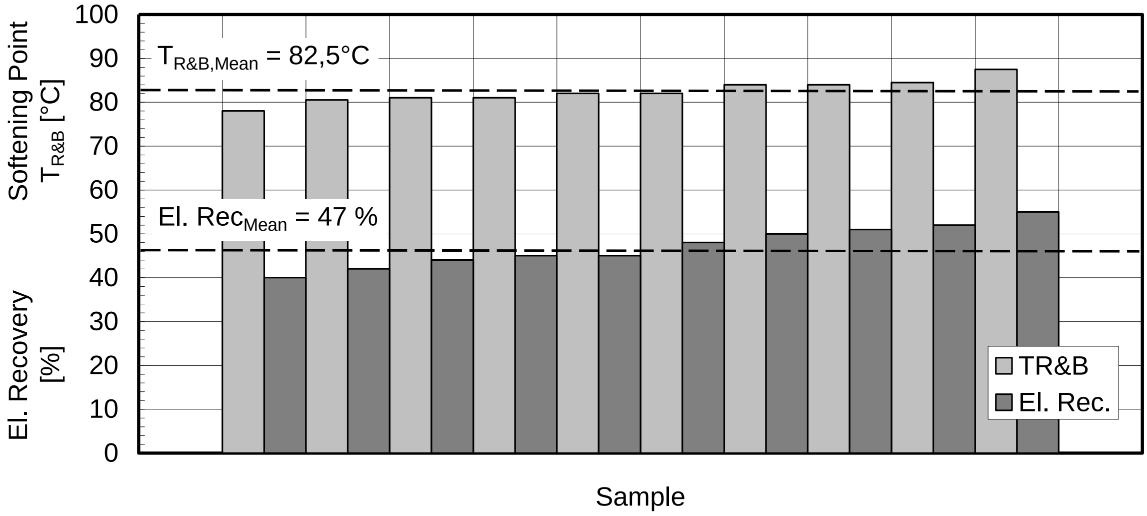



**Figure 3-1: Homogeneity of binder properties (TR&B and El. Recovery) from the RA stockpile (Deutag 2009)**

The gabbroid aggregates were sampled at the quarry HARZBURGER-GABBRO-STEINBRUCHS-GESELLSCHAFT MBH in Bad Harzburg. The aggregates and the RA were stored in open plastic buckets of 65 l each.

The grading of the sampled constituent aggregates, of the aggregates in the RA and the grading of the reference SMA asphalt mixture are plotted in Figure 3-2.

For ensuring that the same binder product would be used in the lab mixes (sample “Caribit”) as which was used in the reference mix, force-ductility tests (FD) were conducted according EN 13589. PmB products of the same kind but from different producers (different polymers and/or modification technique) usually show clear differences in the FD-curves.

Therefore, three specimens were cast from each binder sampled at the mixing plant and at the PmB plant. The resulting force-ductility curves are summarized in Figure 3-3.

The very similar FD-curves for both tested fresh binder samples indicate that the binder sampled at the mixing plant was indeed the same product as the binder sampled at the PmB plant.

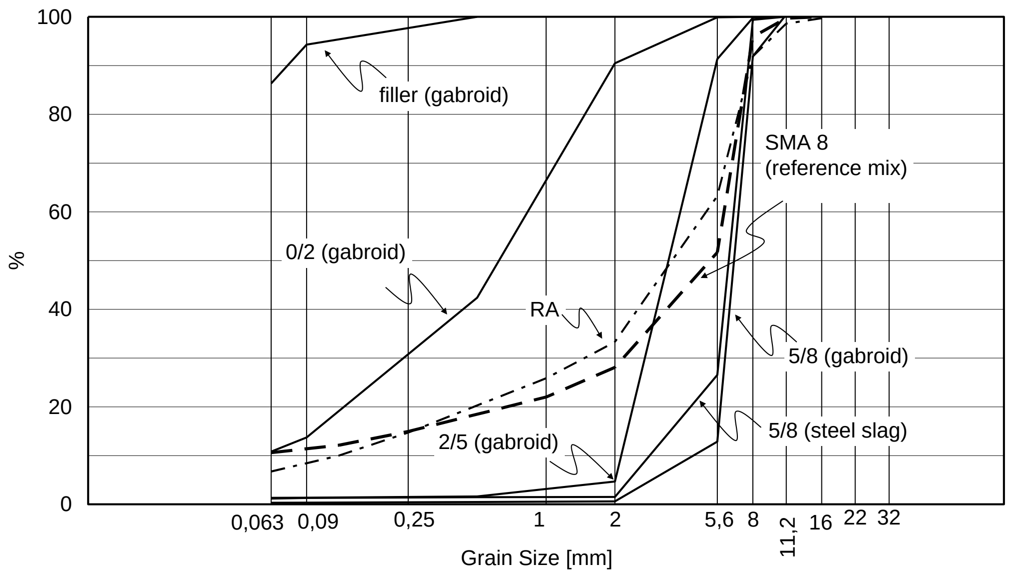



**Figure 3-2: Grading of constituent aggregates, aggregates of reclaimed asphalt and asphalt mixture**

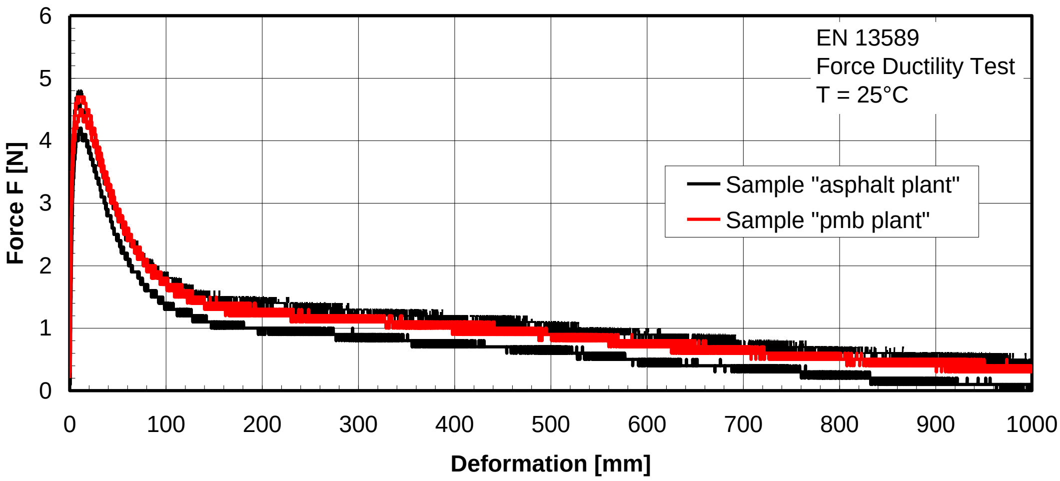



**Figure 3-3: Results of force-ductility tests according EN 13589 to compare binder samples**

The original mix design as provided by the asphalt producer DEUTAG is summarized in Table 3-1: (column 1). The asphalt mixtures produced in laboratory shall result in the same composition as the reference plant mix. Therefore, the real composition of the SMA reference mix sample was analysed by control methods. After recovery of the binder using TCE as solvent, the grading of the aggregates was evaluated (see Figure 3-2). The results are added in the second column of Table 3-1: A slightly higher percentage of fines and a lower percentage of large aggregates was found.

The characteristics of the binder (PEN and R&B softening point) were both measured on the recovered binder as calculated from the characteristics of the fresh binder and the old aged binder of the RA. For the PEN-value, the logarithmic mixing law was used and for the Ring & Ball temperature, the linear mixing law was used. It is observed that the R&B softening temperature of the recovered binder is higher than the theoretically calculated value. For the PEN-value, the measured value is lower than the theoretically calculated value. This is easily explained by the fact that the calculations were done with the characteristics of the new fresh binder, while the new binder is not fresh anymore after mixing and recovery.

To obtain the same grading with the laboratory mixes, the single percentages of aggregates were optimized resulting in a new mix design (column 3 of Table 3-1).

**Table 3-1: Material composition of SMA 8**

| | 1<br>Original mix design<br>(asphalt producer) | 2<br>Results of mix control<br>(plant mix) | 3<br>Composition<br>for lab mixing |
|---|---|---|---|
| **Aggregate composition:** | percentage (100 % = aggregates + RA) [%] | | |
| Filler (gabbroid) | 6,9 | - | 6,9 |
| 0/2 (gabbroid) | 16,5 | | 16,4 |
| 2/5 (gabbroid) | 16,9 | | 11,6 |
| 5/8 (gabbroid) | 34,5 | | 39,8 |
| 5/8 (steel slag) | 10,0 | | 10,0 |
| RA | 15,0 | | 15,0 |
| Fibres (Viatop) | 0,3 | | 0,3 |
| **Grading of resulting mix:** | percentage (100 % = aggregate mass) [%] | | |
| d < 0,063 | 9,0 | 10,6 | 9,0 |
| 0,063 ≤ d < 0,125 | 2,7 | 1,5 | 2,7 |
| 0,125 ≤ d < 0,25 | 2,7 | 2,8 | 2,7 |
| 0,25 ≤ d < 1,0 | 6,4 | 7,1 | 6,4 |
| 1,0 ≤ d < 2,0 | 6,2 | 6,1 | 5,9 |
| 2,0 ≤ d < 5,6 | 23,5 | 23,6 | 23,0 |
| 5,6 ≤ d < 8,0 | 45,0 | 44,2 | 44,7 |
| 8,0 ≤ d < 11,0 | 4,5 | 3,8 | 5,6 |
| d > 8,0 | | | |
| **Asphalt mix composition:** | percentage (100 % = total asphalt mix) [%] | | |
| fresh binder | 6,0 | - | 5,9 |
| total binder content | 7,0 | 7,1 | 7,0 |
| Binder properties (type of fresh binder: 25/55-55 A; Caribit, Shell) | | | |
| $T_{R\&B}$ (fresh binder)[°C] | 60,0 | 61,2 | |
| $T_{R\&B}$ (RA) [°C] | 82,6 | 72,2 (after recovery) | |
| $T_{R\&B}$ (mix) [°C] | 63,2<br>(calculated) | 68,0 (after recovery): | 63,0<br>(calculated) |
| pen (fresh binder) | - | 34 1/10 mm | |
| pen (RA) | - | 14 1/10 mm | |
| pen (mix) | - | 21 1/10 mm<br>(after recovery) | 30 1/10 mm<br>(calculated) |

### *3.1.2* Multiple recycling study

For evaluating the multiple recyclability of asphalt containing PmB as well as for checking the applicability of mixing formula for binder and asphalt mix properties and for analysing the binder compatibility, SMA 8 mixes were prepared in the ISBS laboratory. The mix composition of the SMA 8 mixes with 25 % or 50 % RA was determined in order to obtain the same nominal grading as the SMA 8 mixture without RA (see Table 3-2).

**Table 3-2: Material composition of sample SMA 8**

| RA-content: | 0 % RA | 25 % RA | 50 % RA |
|---|---|---|---|
| Aggregate composition: | percentage (100 % = aggregates + RA) [%] | | |
| Filler (limestone) | 8,4 | 6,3 | 4,2 |
| 0/2 (gabbroid) | 18,3 | 13,7 | 9,2 |
| 2/5 (gabbroid) | 23,1 | 17,3 | 11,6 |
| 5/8 (gabbroid) | 47,0 | 35,2 | 26,5 |
| 8/11 (gabbroid) | 2,9 | 2,2 | 1,4 |
| Fibres (Viatop) | 0,3 | 0,23 | 0,15 |
| RA | 0 | 25 | 50,0 |
| Grading of resulting mix: | percentage (100 % = aggregate mass) [%] | | |
| d < 0,063 | 9,0 | | |
| 0,063 ≤ d < 0,125 | 2,8 | | |
| 0,125 ≤ d < 0,25 | 2,7 | | |
| 0,25 ≤ d < 1,0 | 6,2 | | |
| 1,0 ≤ d < 2,0 | 6,3 | | |
| 2,0 ≤ d < 5,6 | 23,2 | | |
| 5,6 ≤ d < 8,0 | 47,1 | | |
| 8,0 ≤ d < 11,0 | 2,7 | | |
| d > 11,0 | 0,0 | | |
| Asphalt mix composition: | percentage (100 % = total asphalt mix) [%] | | |
| total binder content | 7,0 | 7,1 | 7,2 |
| virgin binder content | 7,0 | 5,5 | 3,8 |
| RA binder content | 0,0 | 1,6 | 3,4 |

In order to verify the applicability of mixing laws on asphalt mix properties, the equations known for calculating penetration by a logarithmic mixing law (eq. 1) or R&B softening point by a linear mixing law (eq. 2) are applied to the results of mechanical tests on specimens compacted from the asphalt mixes.

The applied mixing laws are given as follows:

**logarithmic mixing law:**

$$\log A_{m,log} = \frac{b_0}{100}\cdot \log A_0 + \frac{b_{RA}}{100}\cdot \mathbf{A}_{\mathbf{RA}} \qquad \textbf{Eq. 1}$$

**linear mixing law:**

$$\mathbf{A}_{\mathbf{m,lin}} = \frac{b_0}{100}\cdot \mathbf{A}_{\mathbf{RA}} + \frac{b_{RA}}{100}\cdot \mathbf{A}_{\mathbf{RA}} \qquad \textbf{Eq. 2}$$

in which $b_o$ and $b_{RA}$ are the percentages of respectively virgin and RA material in the total mix, $A_0$ and $A_{RA}$ are the properties of respectively virgin and RA material and $A_m$ are the properties of the mixture.

Note that: $b_o + b_{RA} = 100$.

## *3.2 Laboratory mixing methods*

### *3.2.1* General

Five laboratories collaborated in the development of the laboratory mixing method: ISBS, BRRC, IFSTTAR, DRI and UNott. All laboratories essentially follow the European standard EN 12697-35.

The European standard is precise in describing the heating temperatures and times. It is important to respect these specifications, since excessive heating may alter the binder properties and even the aggregate grading. Insufficient heating on the other hand will lead to poor coating.

However, the European standard does not exactly specify all mixing conditions, like mixing times and mixing speed, since these conditions depend on the laboratory mixing device. The standard only gives a table with maximum mixing times (table 2 of the EN). These mixing times are longer when one of the following factors applies:

- When the mix is an SMA
- When the binder is a PmB
- When RA is used

(note that all three factors apply to the mix described in 3.1)

The mixing sequence is also not specified in detail. It is said that first, the dry aggregates shall be mixed. Then, the binder is added and mixing shall be continued long enough to have a good coating (but not longer than the maximum times given in the standard). The filler may be added in the beginning together with the other dry aggregates, or after the binder. The sequence for adding RA is also not specified.

In the following paragraphs, the lab mixing devices of the five laboratories are briefly described, as well as the mixing times and mixing sequence that are usually followed. This depends largely on their own experience with their specific mixer.

### *3.2.2* Lab mixing procedure at ISBS

The laboratory mixing device used at ISBS laboratory consists of a rotating heatable drum with a capacity of 30 litres for about 40 kg asphalt mix (see Figure 3-4). While the drum is rotating in one direction, the axial stationary paddle counter-rotates.

The mixing procedure applied is specified in the German test protocol (FGSV 2007b) mirroring the EN 12697-35. The order of adding the constituent materials is specified to:

1. Add aggregates, mix for 15 s
2. Add RA, mix for 15 s
3. Add binder, mix for 30 s.

**Figure 3-4: Counter-rotating drum mixer at ISBS laboratory**

### *3.2.3* Lab mixing procedure at BRRC

The laboratory mixing device used at BRRC laboratory consists of a stationary heated bowl with one planetary rotating vertical helicoidal axle and one scraper (BBMAX25 from MLPC, see Figure 3-5). The capacity is about 25 kg of asphalt mix.

The mixing procedure follows EN 12697-35. The order of adding the constituent materials is usually:

1. Add aggregates and RA and mix for ± 90 s
2. Add binder, mix for 10 s
3. Add filler, mix for ± 60 to 90 s.

The filler is added at the end, because it is expected that by adding the pure binder before adding the filler, a better coating of the aggregates can be achieved. This does not complicate the mix preparation, because the filler is a separate fraction anyway. The reason is that Belgium uses washed aggregates for preparing bituminous mixtures, so it is necessary to add also a separate filler fraction to the mixture.


**Figure 3-5: Laboratory mixing device used by BRRC and IFSTTAR**

### *3.2.4* Lab mixing procedure at IFSTTAR

The laboratory mixing device used at IFSTTAR laboratory is also a stationary heated bowl with one planetary rotating vertical helicoidal axle and one scraper (BBMAX25 from MLPC, see Figure 3-5). The capacity is about 25 kg of asphalt mix.

The mixing procedure follows EN 12697-35. The order of adding the constituent materials is usually:

1. Add aggregates and filler and mix for 30 s
2. Add binder, mix for 120 s

When the binder is a PmB or when a SMA is mixed, the procedure is the same.

When RA is used, the order of adding the constituent material is:

1. Add aggregates and filler and mix for 30 s
2. Add RA and mix for 90 s
3. Add binder and mix 1for 80 s

### *3.2.5* Lab mixing procedure at DRI

The Danish Road Institute asphalt mixer is produced by Strabag Bau A.G. The capacity of the mixer is 20 kg and the optimum mass of mix produced in the mixer is between 12 and 15 kg.

Heating is controlled by a thermostatically controlled heating jacket and covers the temperature range from 50 to 300 ° C. The stirrer is fitted with 4 wings to ensure adequate mixing of the material and can be set continuously adjustable from 40 to 80 rpm. The stirrer is driven by a 3 kW motor.

The normal procedure for mixing asphalt containing RA at DRI is:

1. Add aggregates, filler and fibres and mix for 30 s
2. Add RA and mix for 30 s
3. Add binder and mix for 90 s

**Figure 3-6: Laboratory mixing device used by DRI**

### *3.2.6* Lab mixing procedure at UNott

The laboratory mixer at UNott / NTEC (Nottingham transportation Engineering Centre) consists of a vertical axial spindle rotating clockwise and a drum rotating anticlockwise while mixing (Figure 3-7). It has a capacity of 30 litres and can mix up to 60 kg in a single load. There is a self heating system to maintain the mixing temperature.

The procedure for mixing is:

1. Place aggregate, filler and RA in the preheated drum and mix for 60 seconds
2. Add binder and mix for 110 seconds

**Figure 3-7: Laboratory mixing device at UNott**

## *3.3 CT scan and Optical Image Analysis methods*

### *3.3.1* CT scan method

This non-destructive test method was used for this project at UNott. A Venlo H-350/225 X-Ray CT system with IMPS operating software was used for scanning the samples. The 350 kV X-Ray source was used to obtain 2D images (slices). The scanning parameters (primary filters, back filters, voltage, current and exposure time) were selected after several trials. These parameters are dependent on the density of the material and the size of the sample. After several trials it was found that a good quality image was obtained using the following parameters:

| | |
|---|---|
| Voltage: | 342 kV |
| Current: | 2.0 mA |
| Exposure: | 7.5 minutes |
| Primary filter: | Copper, 2 mm in thickness |
| Back filter: | Aluminium, 25 mm in thickness |

The sample was fixed vertically on the X-Ray CT turn-table such that the circular faces were at the bottom and top. The position of the 2D images was mapped onto a paint brush image of the sample which was obtained before scanning (see Figure

3-8). The 2D cross-sectional images (slices) were taken at 1 mm intervals along the height of the sample (see Figure 3-9). In total 68 2D slices were taken for each of the samples. Each slice took approximately 7.5 minutes, which results in about 9 hours for a complete scan of one sample.

Samples of virgin aggregate, steel slag and recycled material were also scanned separately so that a grey value could be identified for each component separately (Figure 3-10 to 3-12).

Using image analysis techniques, the 2D images were stacked to regenerate a 3D representation of the specimen (Figure 3-13).

The images were analysed to determine the distribution of the steel slag and air voids. A threshold grey value for void content was selected so that the distribution of air voids in the specimens could be visualized. A typical distribution of steel slag can be seen in Figure 3-14, while the air voids in a 3D specimen are seen in Figure 3-15. The different components of the SMA mix can be seen in Figure 3-16.

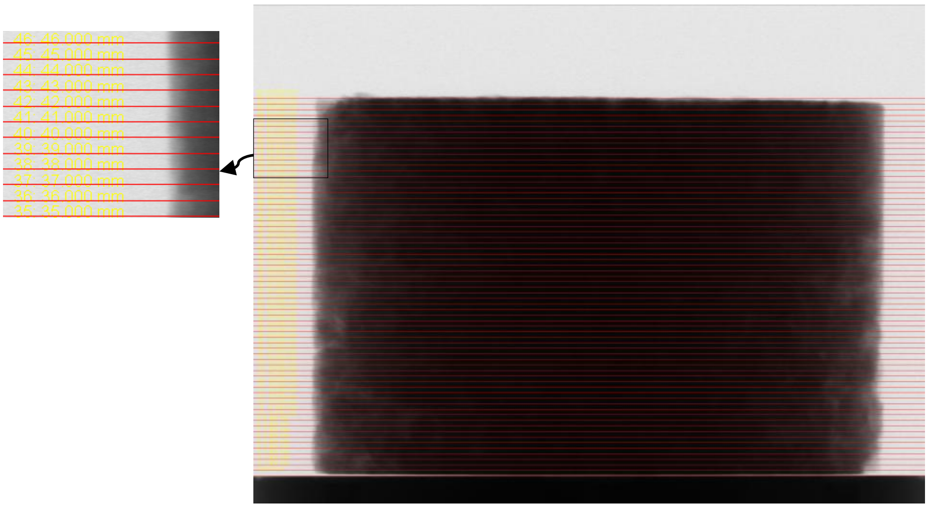


**Figure 3-8: Paint brush image for X-ray CT**

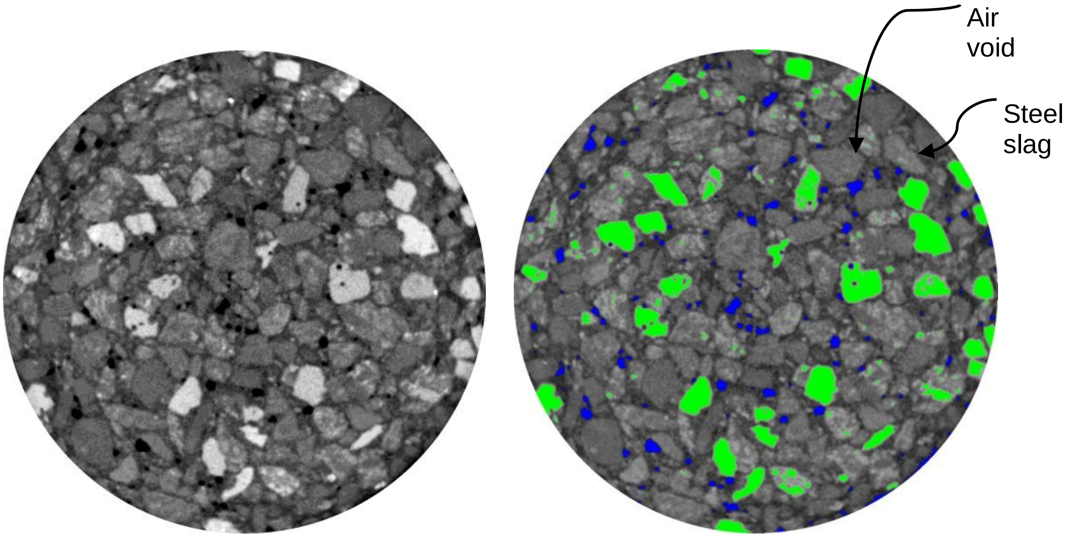



**Figure 3-9: 2D slice of a gyratory compacted specimen containing RA and steel** slag

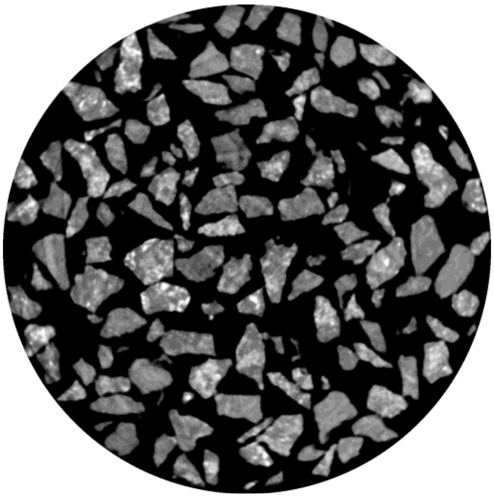


**Figure 3-10: Image of virgin aggregate**

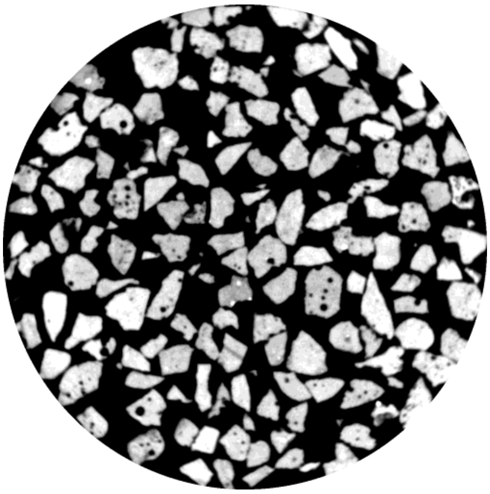


**Figure 3-11: Image of steel slag**

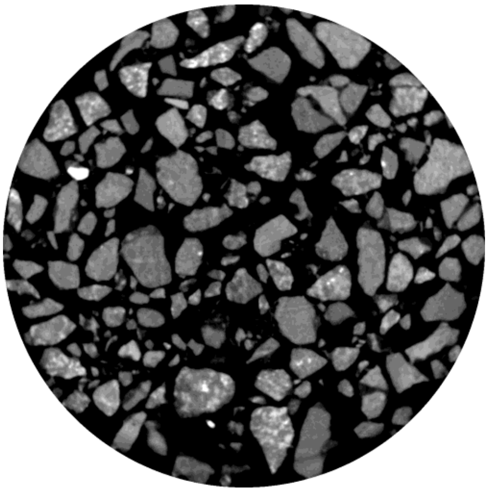


**Figure 3-12: Image from RA material**

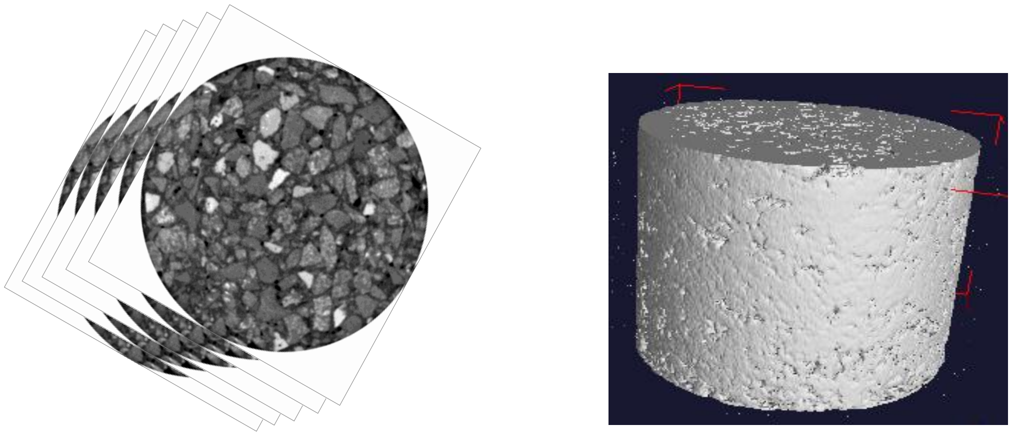


**Figure 3-13: Conversion of 2D images into a 3D image of the specimen**

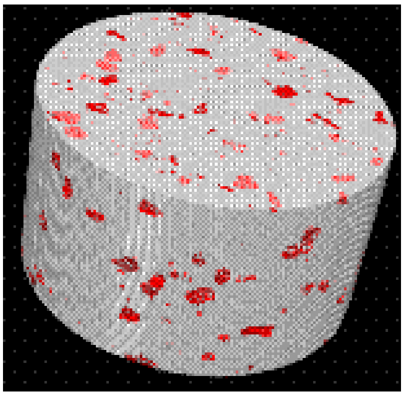


**Figure 3-14: Distribution of steel slag in a 3D image of a specimen**

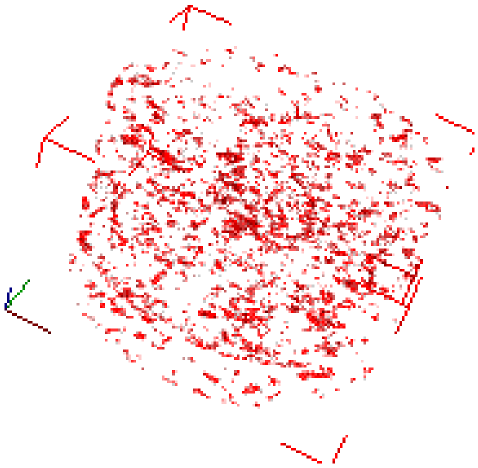


**Figure 3-15: Typical air void distribution from a 3D image of a specimen**

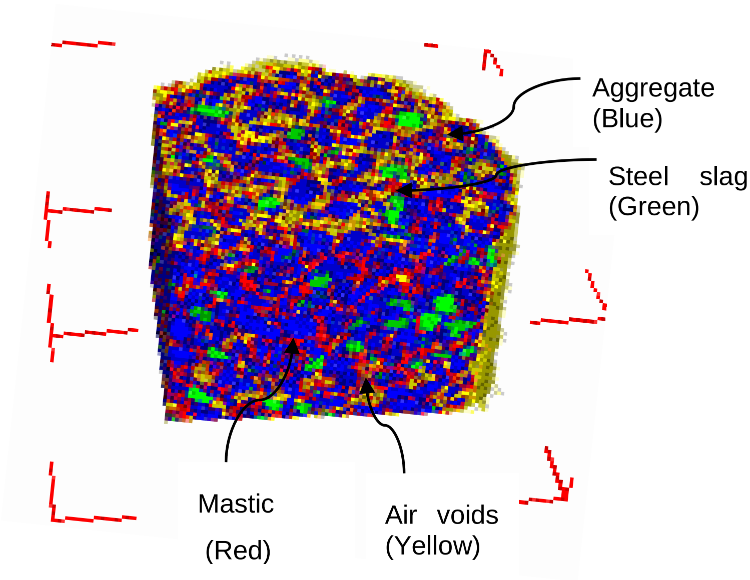



**Figure 3-16: Components of SMA mixture**

### *3.3.2* Optical Image Analysis

The methods presented here have been developed at DRI. There are two different methods: the thin layer method and the plane section method.

#### 3.3.2.1 Thin section method

The thin sections are all taken from a piece cut vertically from the middle of the samples as shown in Figure 3-17. Apart from the thin sections prepared from the specimens made in the gyrator compactor, thin sections have also been prepared from the RA material.

The standard thin sections are impregnated with epoxy resin containing fluorescent dye which fills all air voids, porous rocks and cracks. For polymer thin sections, the resin does not contain fluorescent dye. All thin sections have a thickness of approximately 20 μm.

The investigation of the standard thin section under the microscope has been carried out with transmitted light and the investigation of the polymer thin section has been performed with incident UV-light.

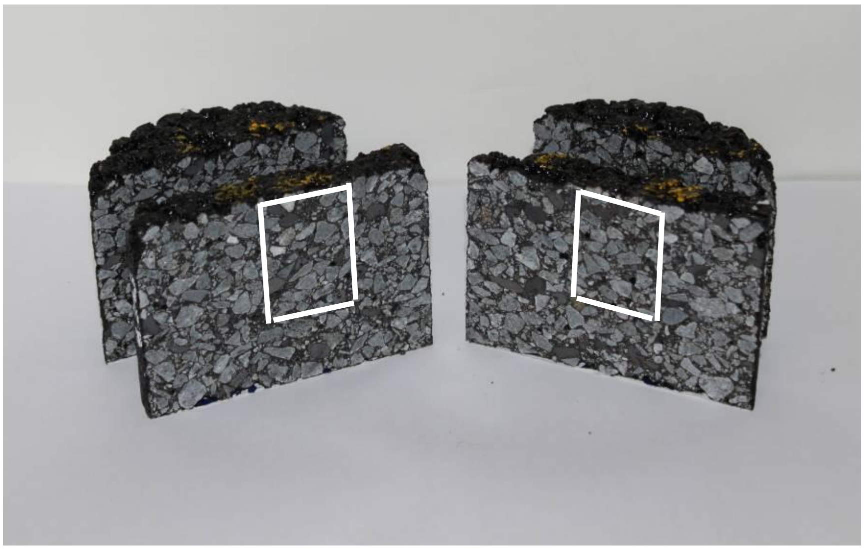


**Figure 3-17: Example of cutting thin sections from samples**

*Analysis and interpretation*

The photos of the standard thin sections are, unless otherwise stated, taken at a magnification of 25 times, so the photos correspond to a sample of approx. 1,93 x 2,57 mm and for the polymer thin sections the magnification used is 100 times, which corresponds to a sample of approx. 0,80 x 1,06 mm . In the description of the individual thin sections, the term mortar is used for binder, filler and small aggregates.

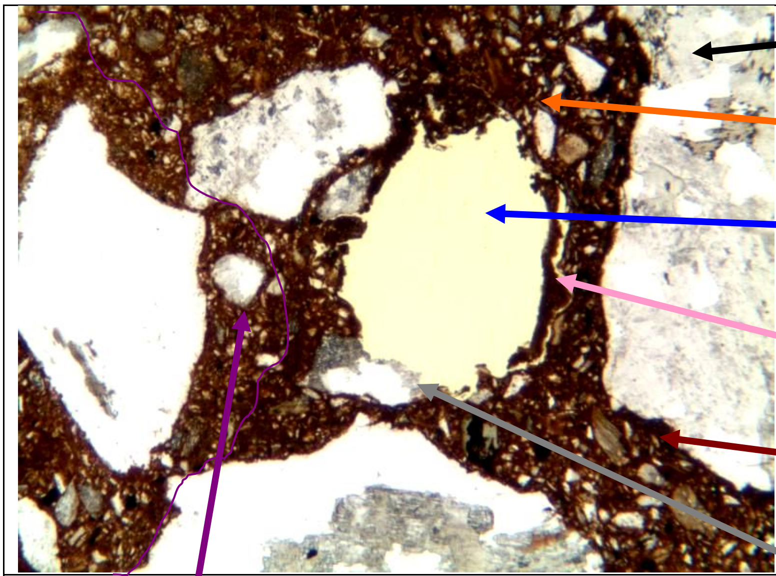
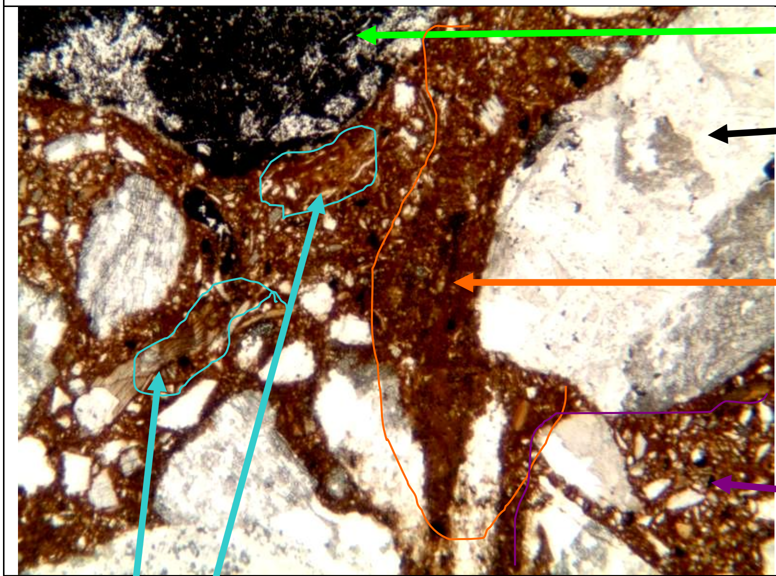
| | |
|---|---|
|  | Aggregate<br>RA material<br>Air void<br>The edge of the air void with dirt.<br>Presence of bitumen<br>Clean aggregate surface |
| New material with more filler in the mortar | |
|  | Steel slag<br>Aggregate<br>Area with RA material<br>New material with<br>more filler in the mortar |
| Lumps of fibre | |

**Figure 3-18: Examples of thin sections with mix material (Size 1,93 x 2,57 mm)**

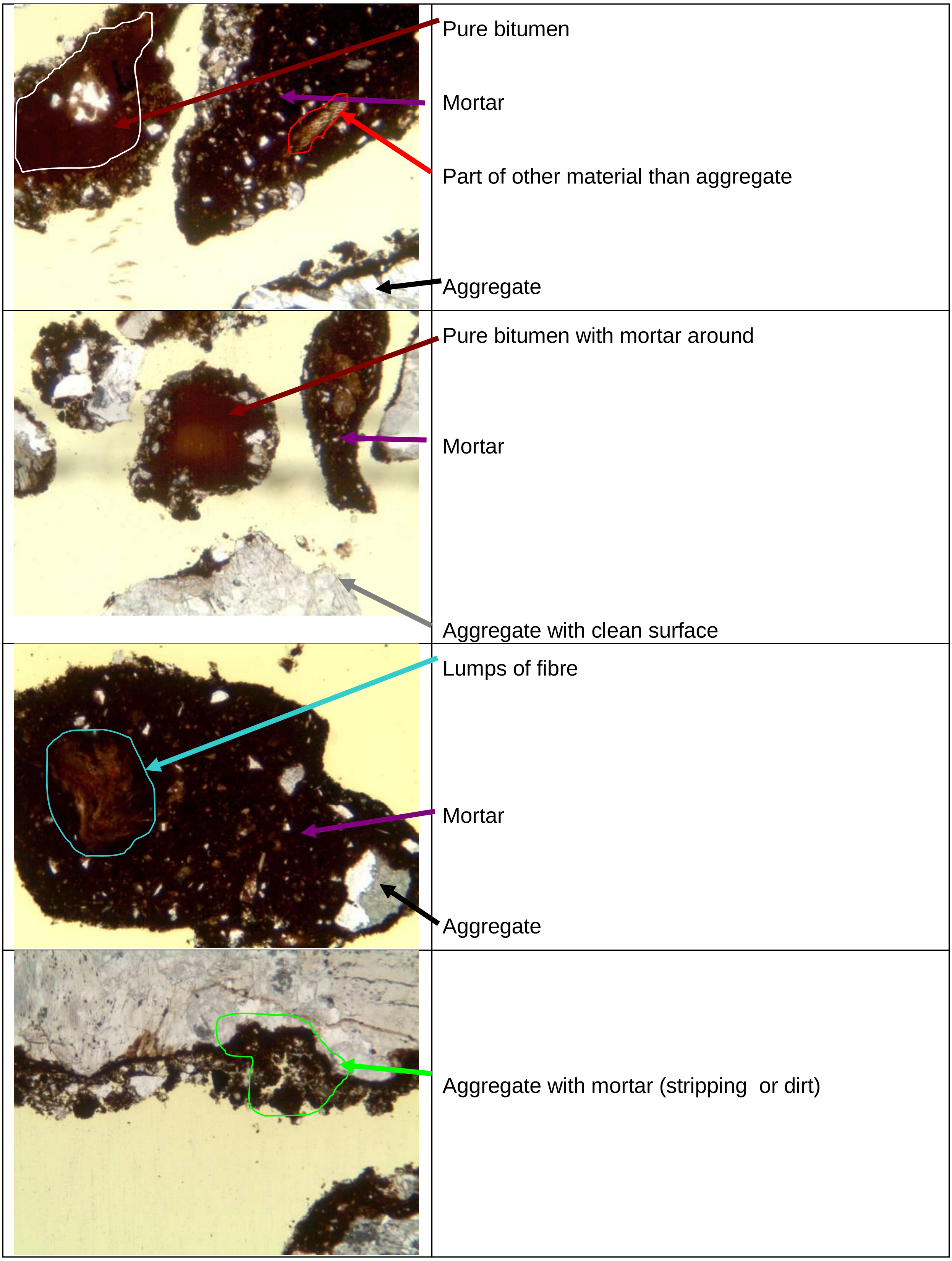



**Figure 3-19: Examples of thin sections of RA material (Size 1,93 x 2,57 mm)**

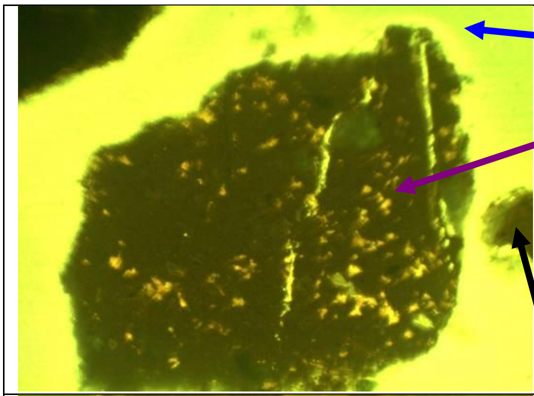
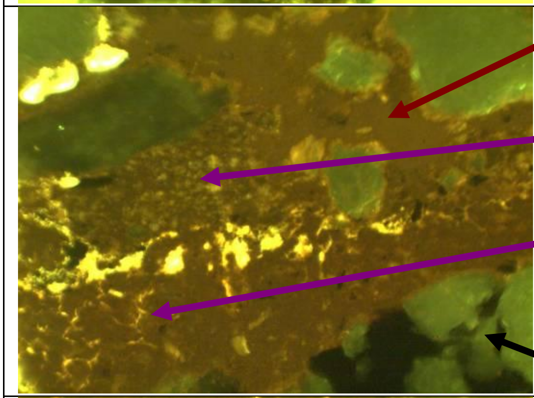
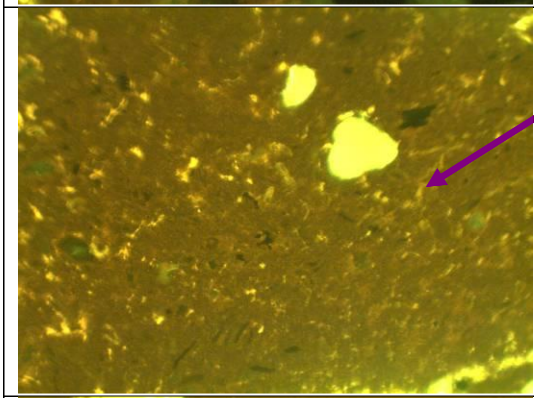
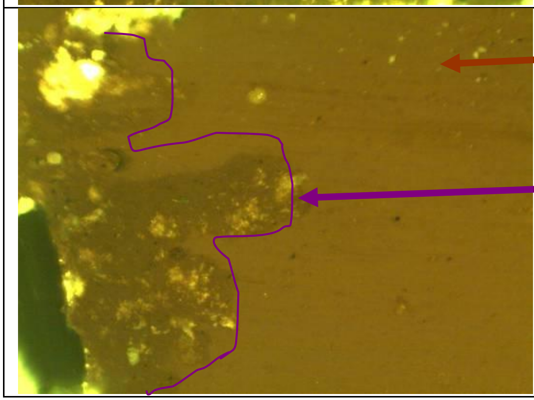
| | |
|---|---|
|  | Air<br>Mortar with presence of polymer (polymer is seen as small-sized yellow spots)<br>Aggregate |
|  | Pure bitumen<br>Polymer is seen as small-sized yellow spots<br>Mortar with presence of polymer (polymer is seen as yellow spots in a network)<br>Aggregate |
|  | Polymer network in mortar seen as small yellow spots |
|  | Pure bitumen<br>Bitumen with polymer seen as yellow spots |

**Figure 3-20: Examples of thin sections of RA material with focus on polymer (Size 1,93 x 2,57 mm)**

#### 3.3.2.2 Plane section method

The plane sections are also taken from the gyratory specimens cut both vertically and horizontally as can be seen in figures 3-21 and 3-22. The size of the plane sections corresponds to the width and height of the gyrator specimens and the thickness is approximately 10 mm. These pieces are impregnated with epoxy resin containing fluorescent dye.

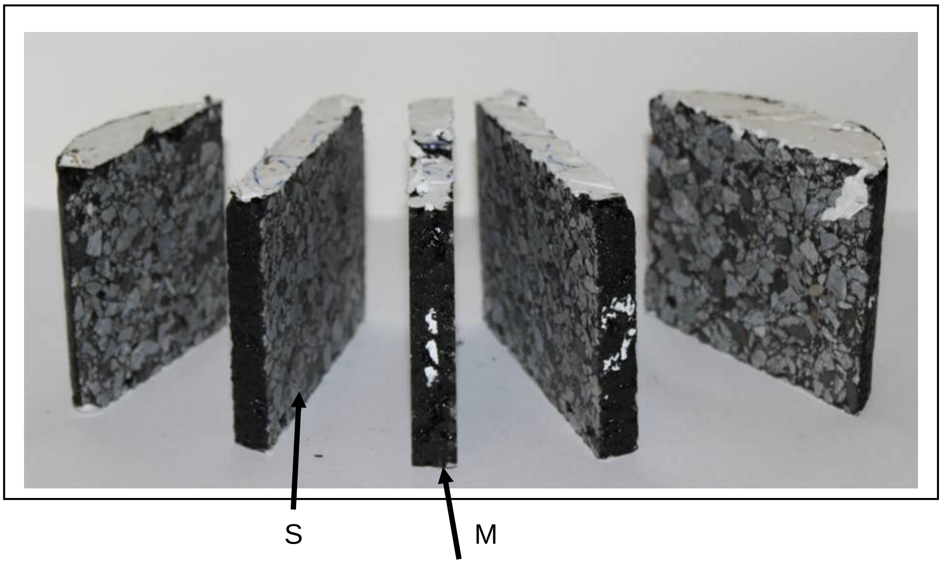



**Figure 3-21: Cutting samples for plane section method, vertical**

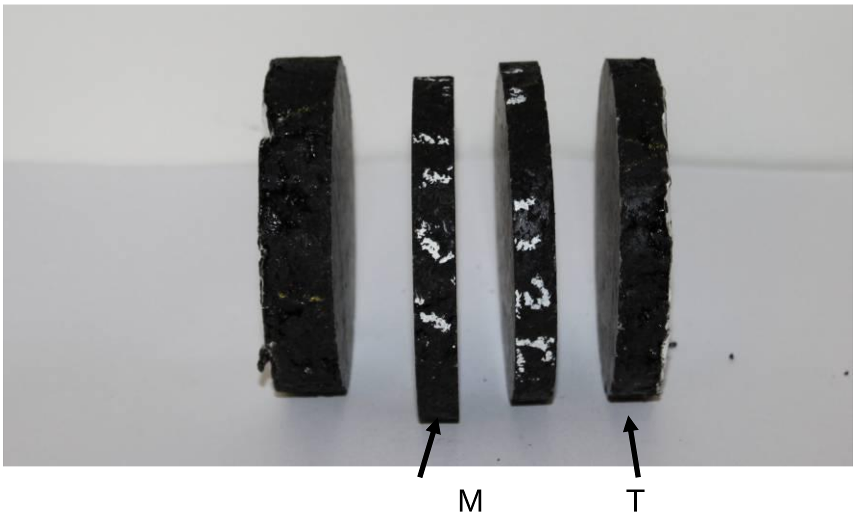



**Figure 3-22: Cutting samples for plane section method, horizontal**

*Analysis and interpretation*

The plane sections are examined in an automatic image analysis microscope/instrument to determine the content of air voids, there sizes and shape (Figure 3-23 and 3-24). The measurements have been performed inside the blue and white frame and the white and red frame respectively.

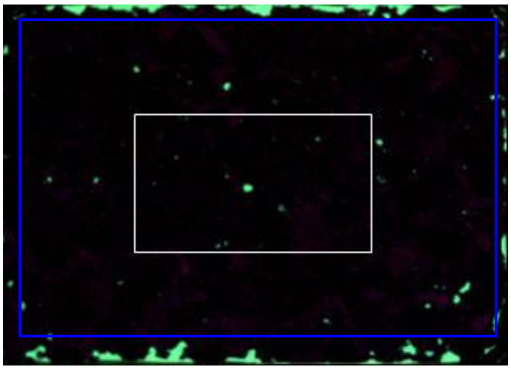


**Figure 3-23: Plane section from vertical cut**

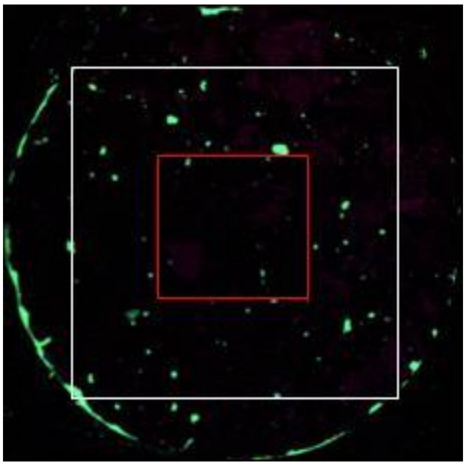


**Figure 3-24: Plane section from horizontal cut**

## *3.4 Mechanical test methods*

### *3.4.1* Compactability

#### 3.4.1.1 Compactability by gyratory compaction

For the lab mixing study, compactability of the mixes was measured using the gyratory compaction method according to EN 12697-31.

The principle of the compaction method is shown in Figure 3-25. Gyratory compaction subjects the material inside a cylindrical mould to simultaneous effects of a vertical pressure and shear stresses, induced by rotating the axis of the mould under a fixed angle $\alpha$. This results in a kneading action which orients the grains of the mineral skeleton and simulates the compaction process on the road. It allows high compacities to be reached with low compacting energies, thus minimizing effects like aggregate crushing or fragmentation. The curve of the density or void content versus the number of gyrations allows to evaluate the compactability of the mix and estimate the void content that can be reached on the road.

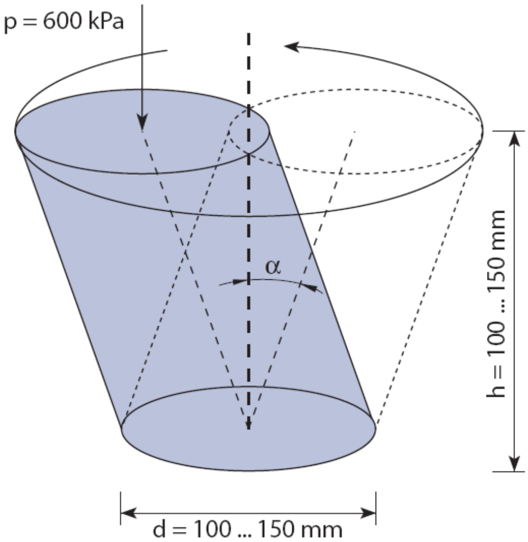



**Figure 3-25: Principle of gyratory compaction**

The European standard test method specifies the following test conditions:

Vertical pressure: 600 kPa
Angle (angle between the normal to the circular top and bottom plates and the axis of the mould): 0,82 °
Gyration speed: 30 gyrations per minute

Different devices were used by the different partners:

Both ISBS and BRRC used the same type of equipment, which is a pneumatic device (ELE-SERVOPAC, see Figure 3-26 and Figure 3-27).

**Figure 3-26: Gyratory compactor of ISBS**

**Figure 3-27: Gyratory compactor of BRRC**

IFSTTAR uses the PCG3 (from MLPC), shown in Figure 3-28.

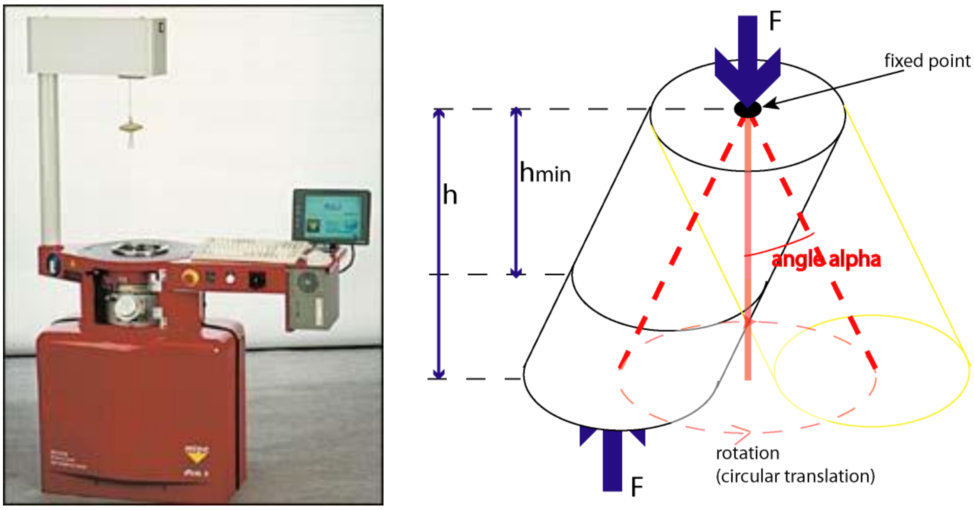



**Figure 3-28: Gyratory compactor of IFSTTAR**

The DRI gyratory compactor is a Troxler model 4140 constructed after SHRP specification but is able to run conditions according to EN 12697 – 31.

UNott has two gyratory compactors. The old compactor works according to AASHTO T321 and has a fixed external angle of 1,25 ° (See Figure 3-29 a). The new gyratory compactor can be set to an internal angle between 0,2 ° and 1,2 ° and complies with EN 12697-31 and BS standard (See Figure 3-29 b).


(a) (b)

**Figure 3-29: Gyratory compactors at UNott: a) old, b) new**

To compare the different gyratory compactors, a preliminary interlaboratory test was organised using the bulk material from the plant (see 3.1). This was described in deliverable D2.2.

Figure 3-30 shows the results.

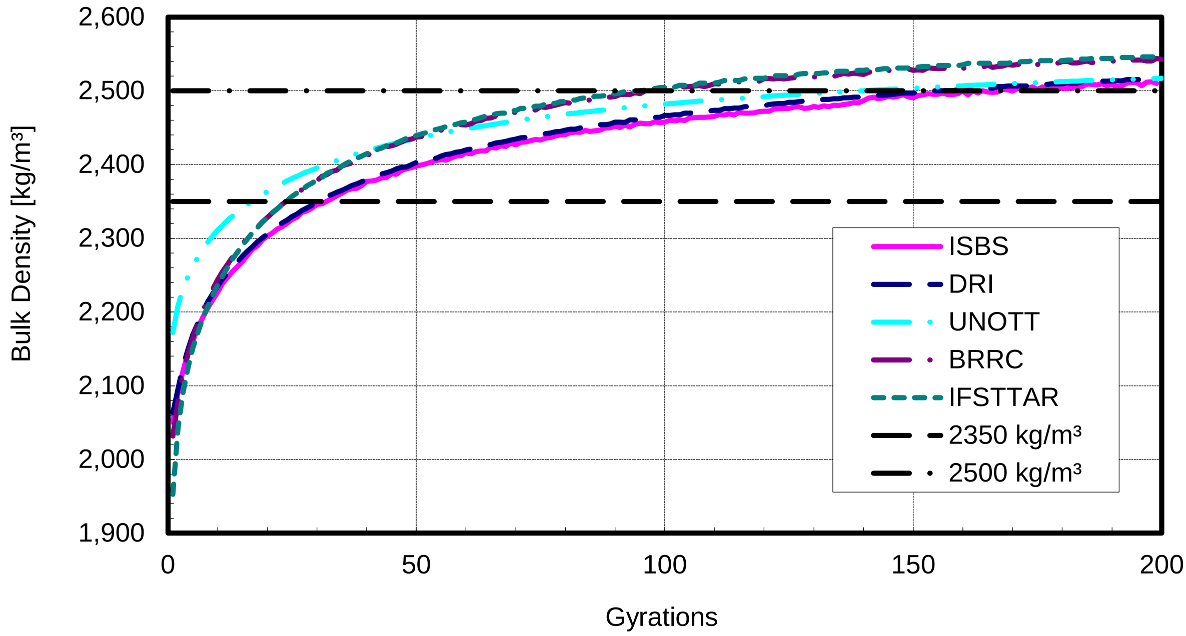



**Figure 3-30: Gyratory compaction of the plant mixed material: results from the 5 laboratories.**

As UNott didn't follow the EN and used the old compactor with the angle of 1,25 °, it is normal that the curve doesn't fit the other curves. For the other four partners, the results of BRRC and IFSTTAR coincide and the results of DRI and ISBS coincide, but the latter reach a lower density level. The explanation for the difference is the angle of rotation. Because of the finite stiffness of the apparatus, the internal angle between the normal to the base and bottom discs and the mould axis is always smaller than the externally set angle (which is the angle between the vertical direction and the mould axis). BRRC and IFSTTAR both worked with an internal angle of 0,82 ° (as specified in the European norm). The external angle to be set was determined by following the calibration procedure with the ILS-device (annex C of the EN). For ISBS and DRI, the external angle was set to 0,82 °. As the internal angle is always smaller than the external angle, it is normal that the densities reached are smaller because the compaction angle was smaller.

### 3.4.1.2 Compactability by impact compaction

For the multiple recycling study (see section 3.5.2) the impact compaction procedure was applied for evaluating the compactability of the asphalt mixtures according to EN 12697-30. During impact compaction, the specimen height is measured after each compaction blow. After 100 blows applied on one side of the specimen, it is rotated and 100 additional compaction blows are applied onto the other specimen side. Resulting from the falling height and the hammer weight, a compaction energy of 21 Nm is applied to the specimen during each compaction impact.

For evaluating the resistance against compaction, the specimen height is plotted versus the number of compaction blows. To evaluate the test, a regression is calculated according to equation 3.

An example for test evaluation is shown in Figure 3-31.

$$t(E_2) = \frac{1}{\frac{1}{t_\infty} - \left[\frac{1}{t_\infty} - \frac{1}{t_0}\right] \cdot e^{\left(\frac{-E_2}{T}\right)}} \qquad \textbf{Eq. 3}$$

where

$t(E_2)$ specimen thickness after $E_2$ compaction blows

$t_\infty$ regression parameter: calculated minimum specimen thickness [mm]

$t_0$ regression parameter: calculated specimen thickness at beginning of compaction process [mm]

T regression parameter: Compaction resistance [21 Nm]

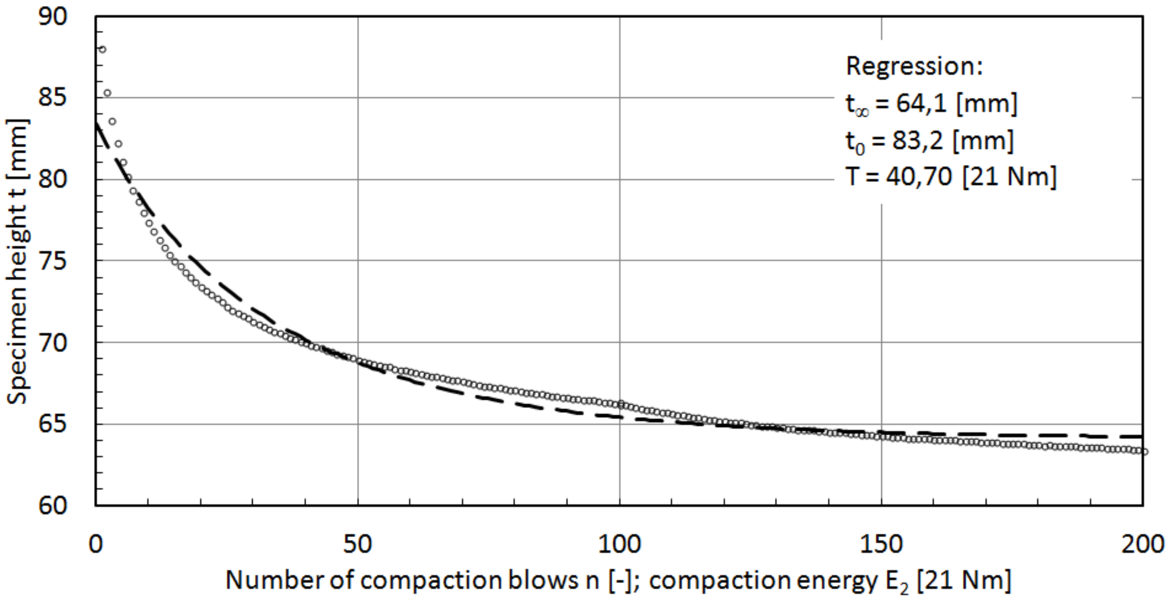



**Figure 3-31: Example of evaluation of compactability test by impact compaction according to EN 12697-10**

### *3.4.2* Water sensitivity

Water sensitivity was measured at BRRC using the European standard EN 12697-12. EN 12697-12 describes the conditioning procedure of the specimens, which consists of vacuum saturation (see Figure 3-32), followed by 72 hours of storage in a thermal bath at 40 °C.

The conditioned specimens, as well as a set of unconditioned specimens are then subjected to the Indirect Tensile Strength test according to EN 12697-23 (see Figure 3-33). The ITS of the conditioned specimens, expressed in % of the ITS of the unconditioned specimens, is a measure for the water sensitivity: the lower the ratio, the higher the water sensitivity.

**Figure 3-32: Vacuum saturation of the specimens**

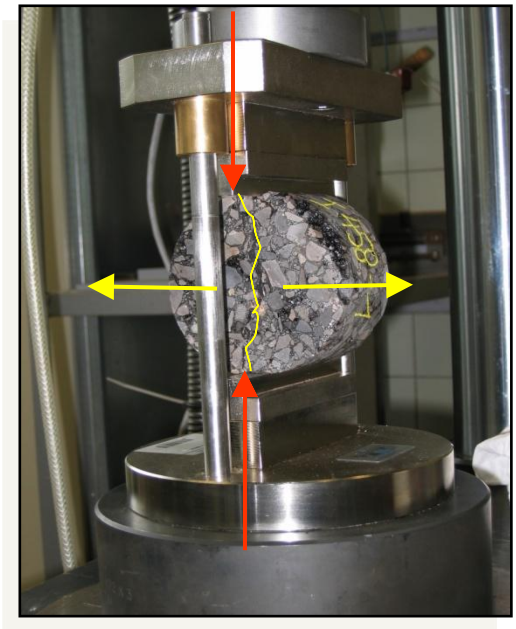


**Figure 3-33: Indirect Tensile Strength test**

### *3.4.3* Stiffness

#### 3.4.3.1 Stiffness modulus by Indirect Tensile Testing

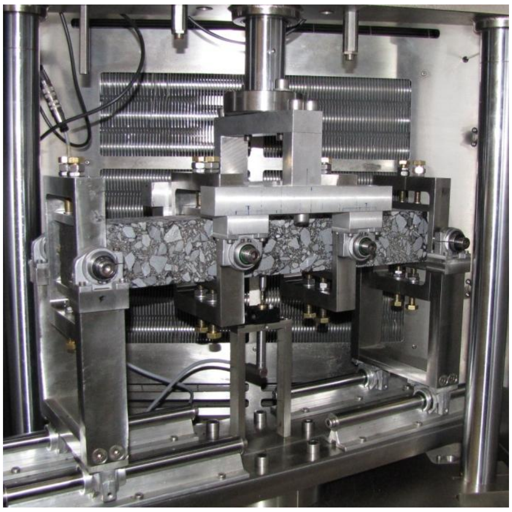
For the lab mixing study, the stiffness of the mixes was determined at BRRC using the European test method EN 12697-26, in indirect tension on cylindrical specimens (IT-CY method, see Figure 3-34). A series of 10 load pulses with a rise time of 124 ms and 3 s between the subsequent pulses is applied in the vertical direction and the deformation is measured in the horizontal direction. The stiffness modulus is calculated from the ratio of the applied force to the measured deformation.

**Figure 3-34: Stiffness measurement using the IT-CY method**

#### 3.4.3.2 Stiffness modulus by 4-point bending

For evaluating the stiffness of the asphalt mixes in the multiple recycling study, ISBS applied 4-point bending tests according to EN 12697-26. A prismatic specimen (40 x 40 x 260 mm) is cut from an asphalt slab compacted in laboratory according to EN 12697-33 (steel roller compaction). The specimen is mounted into the loading frame of the test device and conditioned to the test temperature of T = 20 °C. In the loading frame the specimen is clamped at its ends (outer clamps) and by 2 inner clamps. The distance between outer and inner clamps as well as between inner clamps is 80 mm. During 4-point bending tests the specimen location is fixed vertically by the outer clamps, whereas a vertical deflection is induced to the inner clamps, resulting in an area of constant bending moment between the inner clamps.

For evaluating the complex stiffness modulus, the specimen is subjected to a cyclic deflection-controlled load with varying load frequency. The deflection results in a bending strain of 50 µm/m between the inner clamps. During the stiffness test, the frequencies 0,1; 0,2; 0,5; 1; 2; 5; 10; 20; 50; and 60 Hz were applied. In Figure 3-35 the test device for 4PB tests and an example of stiffness values obtained are shown.



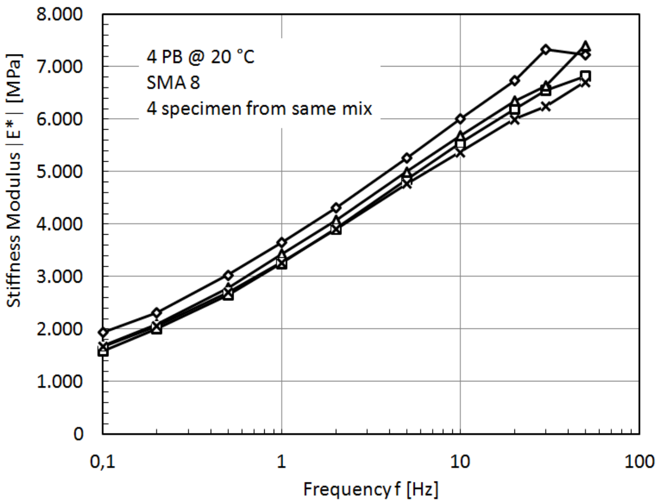



**Figure 3-35: Test device used for 4PB stiffness tests (left) and results obtained on four SMA 8 samples from the same laboratory compacted asphalt slab.**

### *3.4.4* Resistance against permanent deformation

For analysing the effect of various laboratory mixing procedures as well as the mixing time on the resistance against permanent deformation or rutting, cyclic triaxial stress tests (CTST) according to EN 12697-25 B were conducted. Figure 3-36 shows the test device used. A cylindrical specimen (diameter 100 mm, height 60 mm) is loaded into a pressure cell. By applying hydraulic oil pressure to the load cell, the specimen can be loaded by radial compressive stress $\sigma_C$. A static or cyclic dynamic radial stress up to a frequency of 10 Hz can be applied by close-loop control.

Independently of the radial confinement, the specimen is loaded axially by a cyclic compression stress with a frequency up to f = 10 Hz.

Axial deformation is measured symmetrically by two LVDT sensors of the range (± 2,5 mm). Radial deformation is measured at three levels (5 mm, 30 mm, 50 mm from bottom plate) by three LVDT sensors (±1.5 mm) for each level which are located at an angle of 0 °, 120 ° and 240 ° around the specimen.

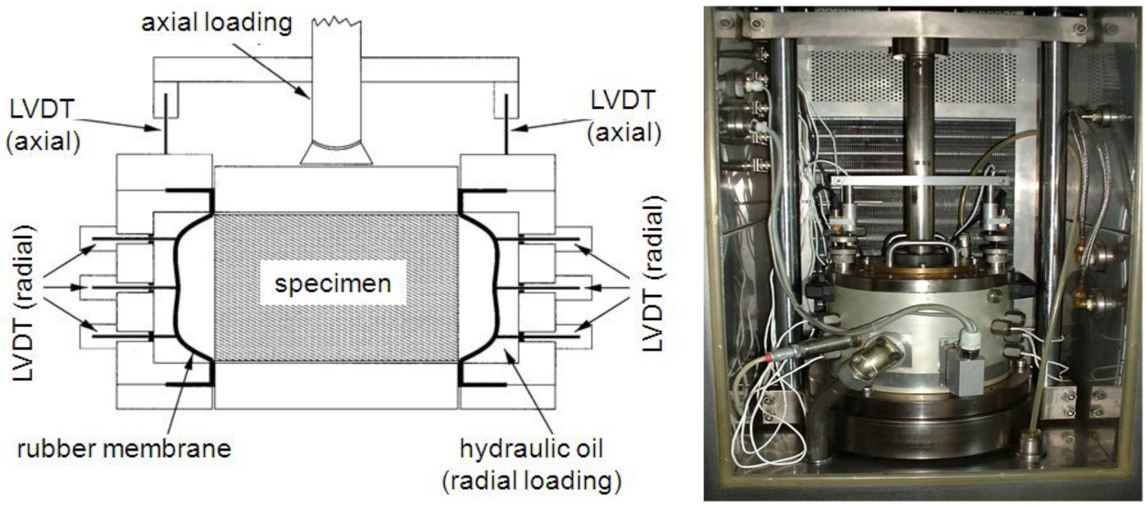



**Figure 3-36: CTST test device at ISBS**

In this study the loading conditions as described in EN 13108-20 for the test of asphalt concrete mixes were applied. Therefore, the specimen was loaded radially with a static confinement stress of $\sigma_C$ = 0,15 MPa. The same load is applied as axial bottom stress $\sigma_{ax,b}$ resulting in a static hydraulic stress state in the specimen. Additionally, a sinusoidal axial compression load with a loading frequency of f = 3 Hz and a stress amplitude of $\sigma_a$ = 0,3 MPa was applied. The test temperature was set to T = +50 °C. Loading conditions are summarized in Figure 3-37.

Before testing, bottom and top of the specimen were smoothly cut to reach even and parallel loading surfaces. Afterward the specimen's bulk density $\rho_{b,SSD}$ was measured according EN 12697-6, method B (saturated surface dry). After drying of the specimen for approximately 20 days, their dimensions were measured according EN 12697-29.

Before mounting the specimen into the load cell, silicone grease is applied to the up and bottom part to fix graphite flakes reducing the friction between specimen and steel load platens. To avoid sticking of the specimen to the rubber collar of the triaxial cell, a paper tissue is laid around the specimen.

Before testing, the prepared specimen is conditioned to the test temperature for (150 ± 30) minutes.

Test temperature: T = 50 °C

Axial loading frequency: $f_{ax}$ = 3 Hz

Radial confinement stress: $\sigma_c$ = 0,15 MPa

Axial bottom stress: $\sigma_{ax,b}$ = 0,15 MPa

Axial stress amplitude: $\sigma_a$ = 0,3 MPa

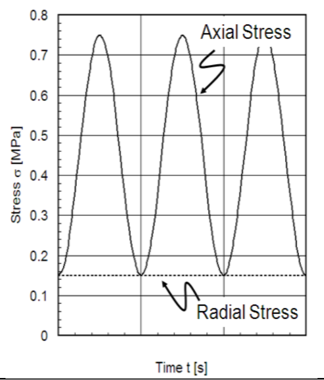



**Figure 3-37: Test conditions during CTST**

During the CTST the development of axial and radial deformation are recorded continuously with 10 measured data samples per load cycle. For analysing the rutting resistance the development of axial and radial permanent strains ε are evaluated and plotted versus the load cycle number as shown in Figure 3-38. Result for evaluating the resistance against rutting, the axial as well as the radial strain rate dε after 10.000 load cycles is applied.

Additionally the resilient strains after each load cycle were measured to evaluate the resulting strain amplitude εa. The stiffness modulus of the test specimen can be evaluated by applying equation 4.

Poisson ratio μ can be developed from the stress state and the axial and radial strains by equation 5 (see Figure 3-38).

$$S_{Mix} = \frac{\sigma_a}{\varepsilon_a} \qquad \textbf{Eq. 4}$$

$$\mu = \frac{\sigma_{ax} \cdot d\varepsilon_c - \sigma_C \cdot d\varepsilon_{ax}}{\sigma_C \cdot (2 \cdot d\varepsilon_c - d\varepsilon_{ax}) - \sigma_{ax} \cdot d\varepsilon_{ax}} \qquad \textbf{Eq. 5}$$

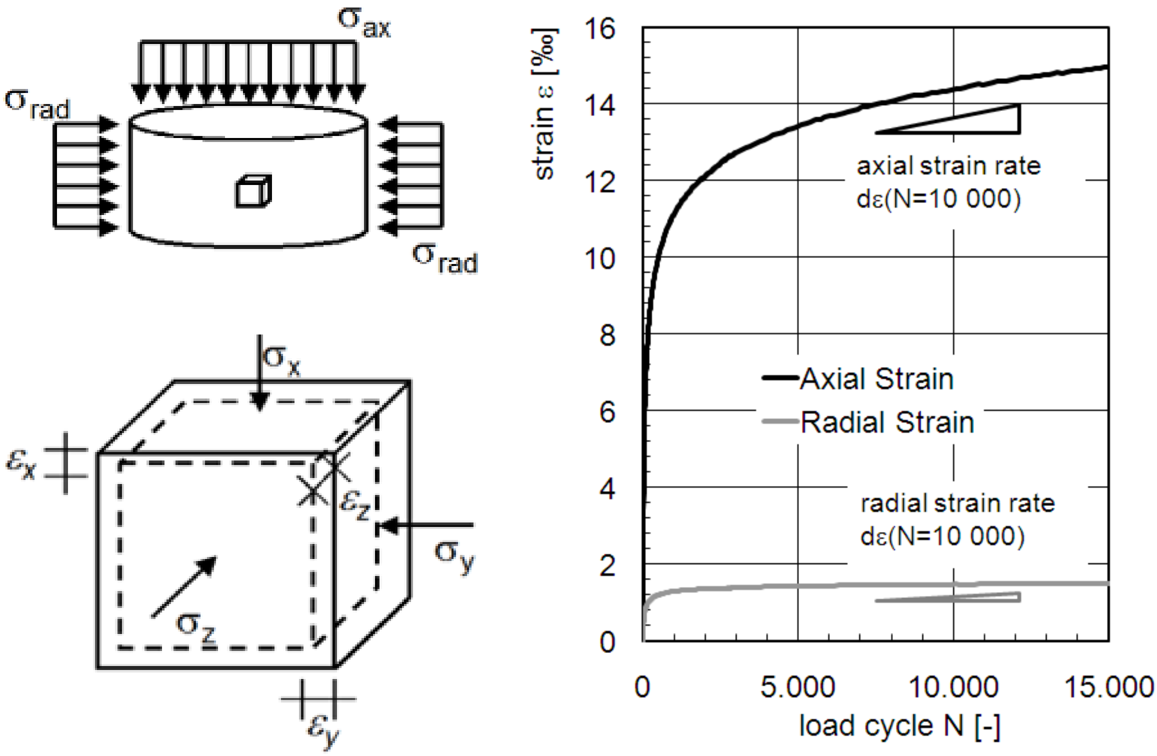


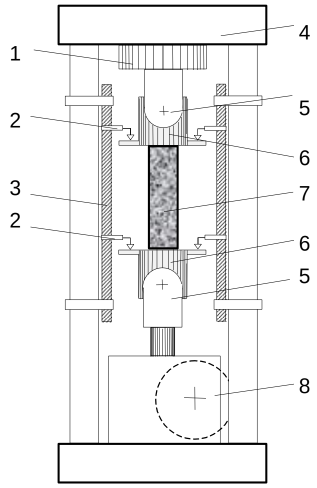

**Figure 3-38: Results of CTST**

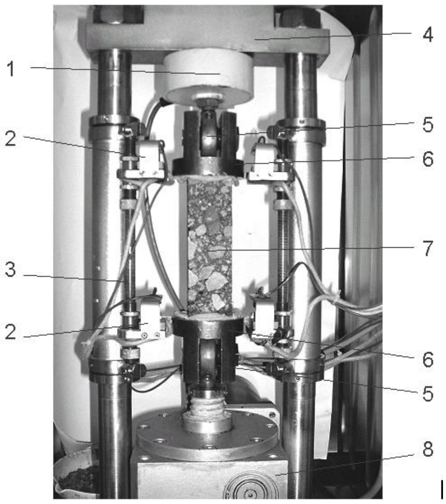
### *3.4.5* Low-temperature cracking

The asphalt mix resistance against low-temperature cracking was evaluated at ISBS by Thermal stress restrained specimen tests (TSRST) and uniaxial tensile stress tests (UTST) according to EN 12697-46. A layout of the test equipment, as used for static laboratory testing in uni-axial direction is shown in Figure 3-39. The beam specimen (40 x 40 x 160 mm³) is cut from a laboratory compacted asphalt slab and glued to steel adapters. After glue conditioning, the adapters are fixed into the loading device.

As the steel frame is exposed to the same thermal changes as the examined specimens, it reacts with thermal shrinkage and expansion. Thus, the correct measuring of the actual strain of the specimen requires a basis with constant length at various temperatures. Therefore, two measurement bases with thermal indifference made of carbon fibres, help to measure the real deformation of the test specimen and to counterbalance the thermal strain of the test equipment (see Figure 3-39).

During the test the force is recorded by a load cell fixed to the cross beam (1) whereas the specimen length of the specimen is measured by 4 displacement transducers (2).




| | | | |
|---|---|---|---|
| 1 | load cell | 5 | gimbal suspension |
| 2 | displacement transducer | 6 | adapter |
| 3 | thermal indifferent measurement base | 7 | specimen |
| 4 | crossbeam | 8 | gear box with stepping motor |

**Figure 3-39: Test device used for static low temperature tests as developed by ISBS**

### 3.4.5.1 Tensile stress restrained specimen test

The tensile stress restrained specimen test (TSRST) is a cooling test in which temperature is reduced at a constant rate. It simulates the weather-induced cooling of an asphalt pavement in the laboratory and aims at recovering the cryogenic tensile stresses in an asphalt mix specimen arising from temperature cooling as well as stress and temperature at fracture.

From the tensile force (F) and from the specimen's cross-section (A), the cryogenic tensile stress $\sigma_{cry}$ is calculated from $\sigma_{cry} = F/A$. The parameters resulting from the test are given in terms of the fracture stress $\sigma_F$ [MPa] and the corresponding fracture temperature $T_F$ [°C].

### 3.4.5.2 Uniaxial tensile stress test

The tensile strength of asphalt mixtures is a critical factor in cracking resistance. During the uniaxial tensile stress test (UTST), the asphalt specimen is loaded by a tensile displacement until fracture occurs, and strength is determined from the maximum load and the specimen dimensions.

The UTST is an isothermal process at a specified test temperature. After stress-free cooling of the specimen to the test temperature, a constant deformation rate of 1 mm/min is applied. The test is stopped as soon as the applied load has reached a maximum and fracture occurs. For each test temperature the tensile strength $\beta_t$ and the associated failure strain $\varepsilon_F$ is determined.

### 3.4.5.3 Tensile strength reserve

To evaluate the resistance against traffic loads at low temperatures at which the asphalt is already loaded by cryogenic stress, the tensile strength reserve $\Delta\beta_t$ can be calculated. Therefore the tensile strength measured at different temperatures are plotted versus the test temperature and fitted by a spline function. From this the cryogenic stress values measured at the test temperature during TSRST are substracted (see Figure 3-40. The resulting tensile strength reserve is characterized by a maximum value $\Delta\beta_{t,max}$ which is used together with the associated temperature $T(\Delta\beta_{t,max})$ to evaluate the resistance against traffic loads at low temperatures.

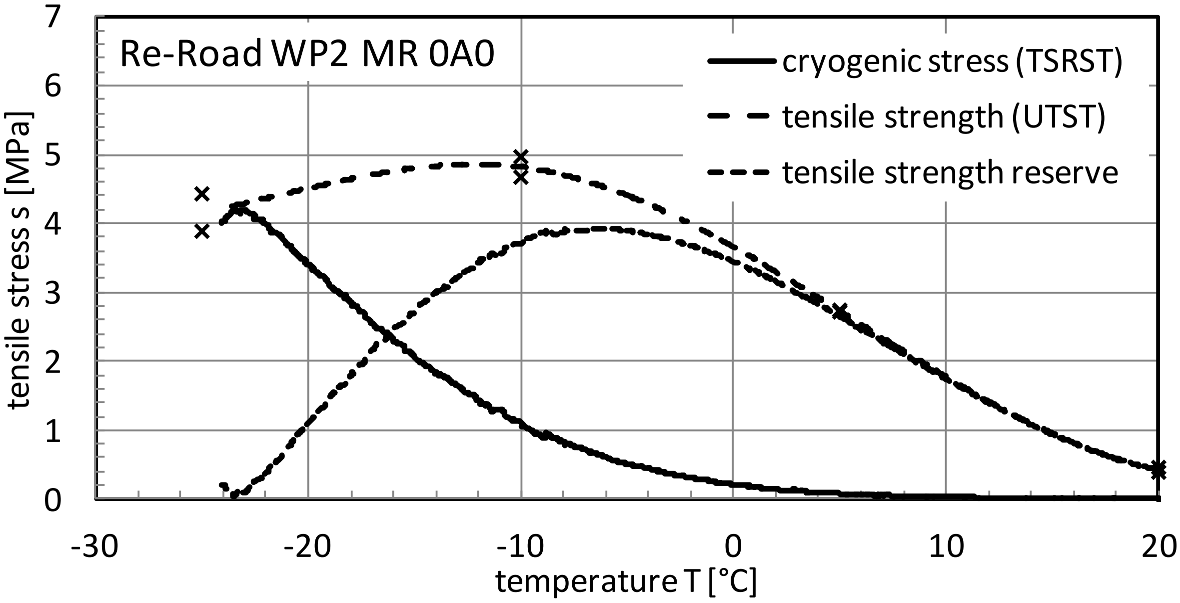



**Figure 3-40: Evaluation of tensile strength reserve from TSRST and UTST**

## *3.5 Test programs*

### *3.5.1* Lab mixing study

The lab mixing study was organized to obtain more insight in the impact of the lab mixing procedure on the performance of the resulting mix. Therefore, different lab mixing procedures were used to produce specimens for performance testing and visual analysis. The specimens prepared with plant mixed material were used as a reference.

With five participating laboratories, there were at least five different lab mixing procedures, since the laboratories use different mixers and different mixing times (see 3.2).

Besides the type of mixer, it is expected that the mixing time is one of the most important parameters, for the following reasons:

- Mixing time has an important impact on short term ageing, probably even more when the mix contains RA
- Mixing time has an effect on the aggregate shape and grading, due to grinding and crushing (especially the dry mixing time)

- Mixing time is a parameter that is not precisely specified in the Europe norm (because it depends on the type of mixer)

For these reasons, it was decided to consider, in addition to the type of mixer, also the mixing time as a variable mixing condition: every lab was asked to prepare one mix with “normal” mixing times (= the usual mixing times) and a second mix with longer (double) mixing times. This leads to a total of 10 different laboratory mixing procedures. To keep the other variables (besides the type of mixer and the mixing times) as constant as possible, a common mixing procedure was described (see D2.2 for the detailed mixing procedure).

The test specimens produced with the gyratory compactor with the 10 different lab mixing procedures (+ the plant mix) were intended for comparison on the basis of the following performance characteristics:

- Stiffness (performed by BRRC)
- Permanent deformation (performed by ISBS)
- Water sensitivity (performed by BRRC)

Test specimens were also made for visual assessment using the methods:

- X-ray CT scans (by UNott)
- Optical Image Analysis (by DRI)

It was essential to compact the specimens to the same densities. For the stiffness and permanent deformation tests, the laboratories were asked to compact the specimens to a density of 2500 kg/m³ (geometric density derived from the height measured in the gyratory compactor). This is representative for normal compaction. For the water sensitivity tests, the target density was only 2350 kg/m³, which means low compaction. With a low compaction level, the water sensitivity test becomes more discriminating, due to the higher void content which allows the water to penetrate deeper into the specimen. Preliminary gyratory compaction tests to 200 gyrations served to determine the number of gyrations needed to reach these density levels.

Every laboratory produced a set of specimens with normal and double mixing times for all tests mentioned above and sent the specimens to the different testing labs. Every test required 3 specimens. Since the X-ray CT scans by UNOTT are nondestructive tests, these specimens could also be used by DRI afterwards. So, DRI and UNott made their tests on the same sets of specimens.

In addition, 2 kg of uncompacted bulk material of each mix was sent to the laboratory of ZAG in Slovenia to measure grading, binder content, maximum density and some characteristics of the recovered binders.

A detailed procedure was described to do the laboratory mixing and produce the specimens (see annex 1). The aim was to keep all the conditions the same for all the laboratories, except for the type of mixer and the mixing times.

Some laboratories follow the practice of adding the filler at the end, after the wet mixing with the binder. This is supposed to improve the aggregate coating, because the binder is not yet stiffened by the filler. The effect of mixing sequence was therefore also verified in a small additional experiment conducted by BRRC. Only the impact on stiffness (IT-CY) was considered in this experiment.

### *3.5.2* Multiple recycling study

The service lifetime of asphalt surface layers (also called friction courses) is shorter compared to the service life of binder and base layers. Generally, the service lifetime varies between 10 and 26 years (FGSV 2002), depending on the type of mix and traffic loading applied (comp. Table 3-3).

Usually the first major rehabilitation procedure during the lifetime of a road structure is the removal and repaving of the surface layer. In future time, when the road network will not grow any further, the demand for these high-quality asphalt layers will increase. At the same time, large amounts of reclaimed asphalt from surface courses will have to be recycled during the rehabilitation process where the option of “down-cycling” in asphalt base layers is not available anymore because of the lack of new road construction works. If surface course materials already contain RA, this material will be recycled in new asphalt surface mixes an additional time after 10 to 25 years.

**Table 3-3: General service lifetime for asphalt surface courses according to traffic load (FGSV 2002)**

| Asphalt surface mix type | General service lifetime [a] | |
|---|---|---|
| | high traffic loads | low traffic loads |
| asphalt concrete AC | 12 | 18 |
| stone mastic asphalt SMA | 16 | 22 |
| mastic asphalt MA | 19 | 26 |
| porous asphalt PA | ~10 | |

In order to evaluate the effect of multiple recycling cycles on the performance of an asphalt mix, a laboratory produced asphalt mix was subjected to laboratory long-term ageing in order to simulate a mix with similar properties as RA. As ageing protocol, the so-called “RILEM”-ageing procedure as applied in task 2.1 of the Re-Road project was applied (see De la Roche et al. 2009, Mollenhauer et al. 2010a, 2012), where the loose asphalt mix is spread on a metal tray and stored for 9 days inside a heating cabinet at a temperature of 85 °C.

After simulated long-term ageing, the aged material was added as RA into new stone mastic asphalt (SMA) variations. This recycling cycle was repeated twice. The lay-out of this study is shown in Figure 3-41.

As surface course material, SMA 8 mixes were used. The grading of these SMA variants was kept constant and is shown in Figure 3-2 (see section 3.1). During the study 12 SMA variants were produced.

After mixing and ageing (for MR-RA1, MR-RA2 and MR-RA3), the binder was extracted from the mixture by applying automatic extraction and recovery using trichloro-ethylene as a solvent according to EN 12697-1 and -3. From the loose mixes, asphalt slabs were compacted according to EN 12697-33 and specimens were cored or cut from the slabs.

The mix composition of the asphalt mixes was controlled in order to check the aggregate grading and binder content. Further, the compactibility of the mixes was evaluated by measuring the specimen height during impact compaction according to EN 12697-10 (see section 3.4.1).

On specimens cut from the asphalt slabs, following mechanical properties were measured:

- stiffness modulus |E*| at 20 °C for a range of frequencies between 0,1 Hz and 60 Hz by 4-point bending tests according to EN 12697-26,
- failure temperature TF [°C] and failure stress $\sigma$F [MPa] by TSRST and tensile strength $\beta$t [MPa] and failure strain $\varepsilon$F [‰] by UTST at +5 °C and -10 °C according to EN 12697-46.
- dynamic axial and radial creep rate fC [µm/m], stiffness modulus |E| [MPa] and Poisson ratio µ [-] by cyclic triaxial stress tests CTST at a temperature of 50 °C according to EN 12697-25.

In addition to these tests, the binders extracted from each asphalt sample were tested by means of conventional and performance tests. These results are presented in Re-Road deliverable D2.3 (Mollenhauer et al. 2012).

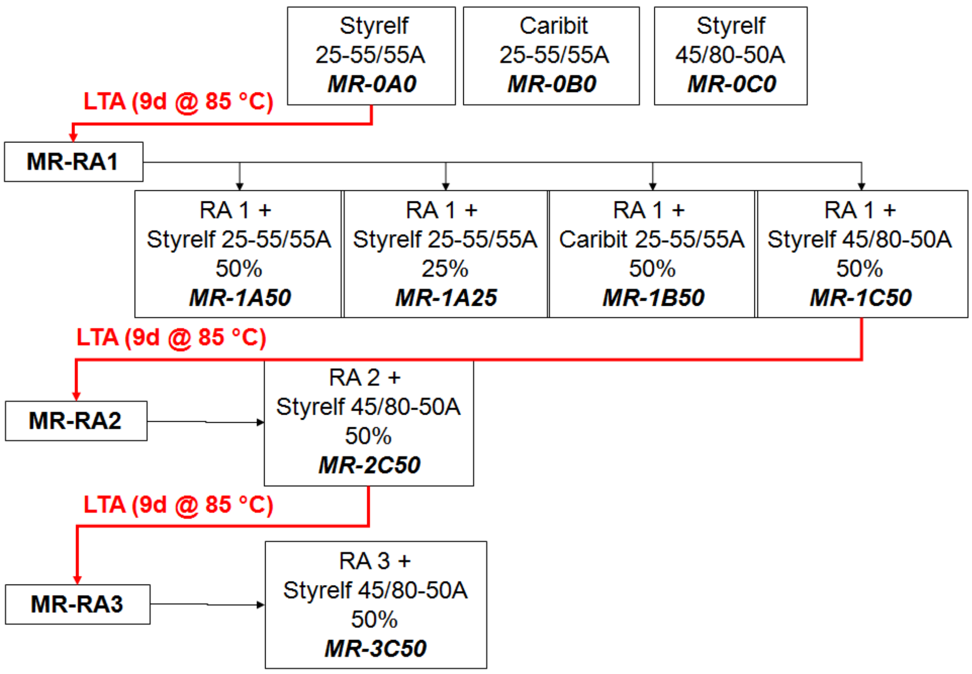



**Figure 3-41: Lay-out of multiple recycling study**

# 4 Test results

## 4.1 Results of lab mixing study

### *4.1.1* Mix control

From all the mixes prepared for the lab mixing study, ZAG received loose bulk mixtures. They were numbered as follows:

1. UNott, normal mixing times
2. UNott, double mixing times
3. BRRC, normal mixing times
4. BRRC, double mixing times
5. DRI, normal mixing times
6. DRI, double mixing times
7. ISBS, normal mixing times
8. ISBS, double mixing
9. IFSTTAR, normal mixing times
10. IFSTTAR, double mixing times
11. ISBS, reference plant mix

Recovery of the binder was performed according standard EN 12697-3 (Bitumen recovery: Rotary evaporator).

Table 4-1 shows the results of the mix control tests and the grading of the 11 mix variants.

For the grading, there are no significant differences between the laboratory mixes. The mixes made with double mixing times do not show a systematically higher amount of fines (percentage passing the 0.063 mm sieve), which means that doubling the mixing times did not cause any significant additional grinding or crushing of the aggregates. The percentage of fines is slightly higher for the laboratory mixes than for the reference mix.

For the binder properties, the penetration was higher and the softening point slightly lower for the binders recovered from the ISBS mixtures (laboratory mixed). This may be an indication of less short term ageing during the mixing process and agrees with the fact that ISBS is the laboratory which uses the shortest mixing times. The type of mixer may also be a parameter that influences short term ageing, since one type of mixer may introduce more oxygen into the mix than another.

The maximum density of the mixtures from ISBS was lower than for the other mixtures, but more similar to the results from the plant mix. To verify these results, ISBS also measured the maximum density and their results confirmed the results from ZAG (2596 kg/m³ for normal and 2604 kg/m³ for double mixing times). A possible explanation could be that depending on the type of mixer and the mixing times, more or less large aggregates are broken. The steel slag consists of mostly large aggregates. When steel slag aggregates are broken, the porosities are opened to the surface and this may lead to higher density values, as the internal voids become more accessible to the water. But this explanation is not confirmed by the grading, since the mixtures from ISBS have a similar grading than the other mixtures.

**Table 4-1: Mix control tests of the mix variants of the lab mixing study**

| | UNott | | BRRC | | DRI | | ISBS | | IFSTTAR | | ISBS plant mix |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of mix | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |

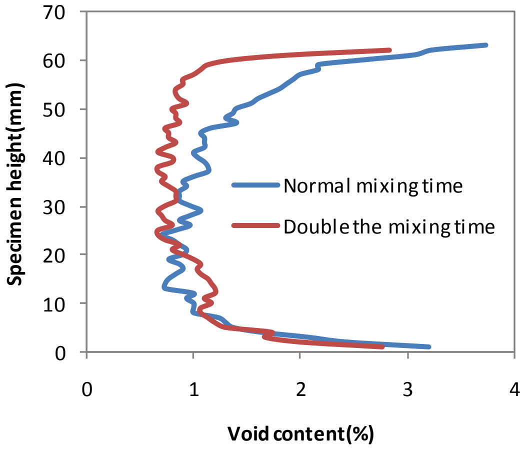
| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Penetration at 25 ºC [0.1mm] | 18 | 19 | 17 | 18 | 19 | 16 | 24 | 22 | 17 | 17 | 18 |
| Softening point [ºC] | 70,6 | 71,4 | 72,6 | 71,4 | 72,8 | 72,6 | 68,6 | 70,2 | 71,8 | 72,2 | 71,2 |
| Fraass point [ºC] | -7 | -6 | -6 | -7 | -6 | -2 | -8 | -6,8 | -5 | -5,8 | -7 |
| Bitumen content % (m/m) | 6,9 | 6,8 | 6,9 | 7,0 | 6,9 | 6,9 | 6,9 | 6,9 | 7,2 | 7,0 | 6,9 |
| Maximum density [kg/m³] | 2628 | 2630 | 2631 | | 2625 | 2629 | 2602 | 2607 | 2620 | 2623 | 2607 |
| Sieve passing (in % of mass) | | | | | | | | | | | |
| 0,063 [mm] | 10 | 10,4 | 11,1 | 11,7 | 12,8 | 11,2 | 10,6 | 10,7 | 11,2 | 11,5 | 9,6 |
| 0,25 [mm] | 14 | 14,1 | 14,9 | 15,5 | 17,0 | 16,0 | 14,2 | 14,4 | 15,0 | 15,0 | 14,3 |
| 0,71 [mm] | 18,2 | 18,4 | 19,2 | 19,9 | 21,4 | 20,4 | 18,2 | 18,4 | 19,5 | 19,2 | 19,2 |
| 2,0 [mm] | 26,5 | 26,3 | 26,8 | 28,5 | 28,2 | 28,2 | 25,5 | 26,1 | 28,0 | 27,4 | 27,2 |
| 4,0 [mm] | 35,5 | 34,3 | 34,5 | 37,1 | 38,1 | 37,5 | 33,8 | 34,3 | 39,0 | 37,7 | 34,7 |
| 8,0 [mm] | 95,5 | 96,3 | 96,3 | 95,3 | 96,5 | 96,4 | 94,7 | 95,6 | 95,5 | 95,6 | 96,7 |
| 11,2 [mm] | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 99,0 | 100 | 99,8 |
| 16,0 [mm] | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |

### *4.1.2* Visual properties

#### 4.1.1.1 CT scan results

Results for void content in the specimens from all five labs are shown in Figure 4-1 to Figure 4-3). These figures show that the void content is variable through the specimen and a high content is concentrated at top and bottom of the specimen. A similar trend was found for all the specimens.

Results of steel slag distribution in the compacted specimens are shown in Figure 4-4 to Figure 4-6. The percentage of steel slag was calculated from X-ray images and the distribution along the samples height was plotted. Similarly the values were calculated for specimens made with twice the normal mixing time and the values were plotted. From these results it can be seen that the distribution of steel slag is more or less uniform through the specimens. Because of the small difference in density value between the old and new aggregate, the threshold grey level for the RA could not be identified.



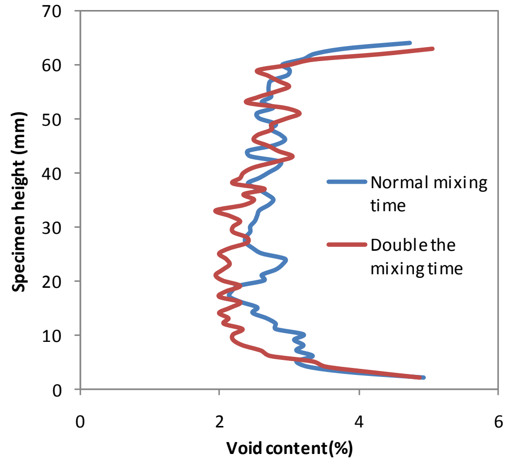
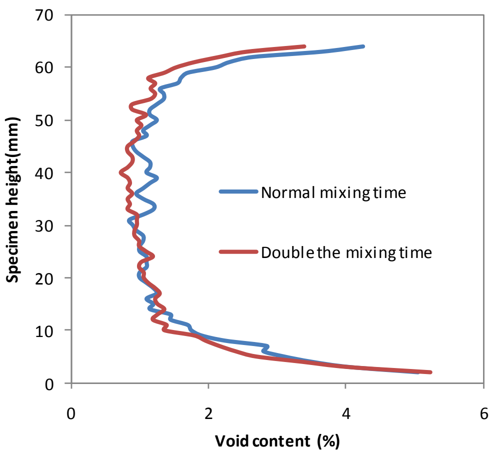




**Figure 4-1: Distribution of air void (left: DRI; right: ISBS)**



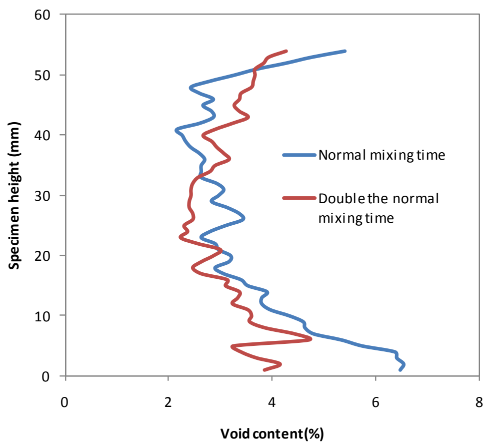




**Figure 4-2: Distribution of air void (left: BRRC; right: UNott)**

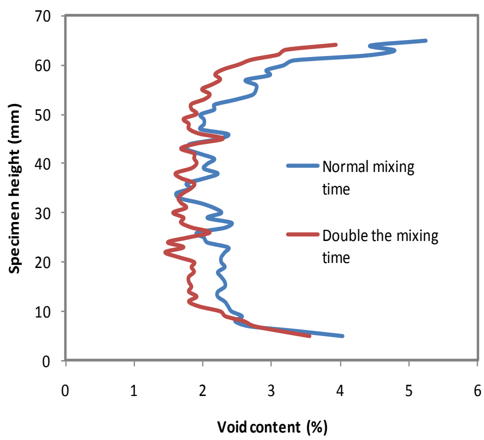



**Figure 4-3: Distribution of air void (IFSTTAR )**

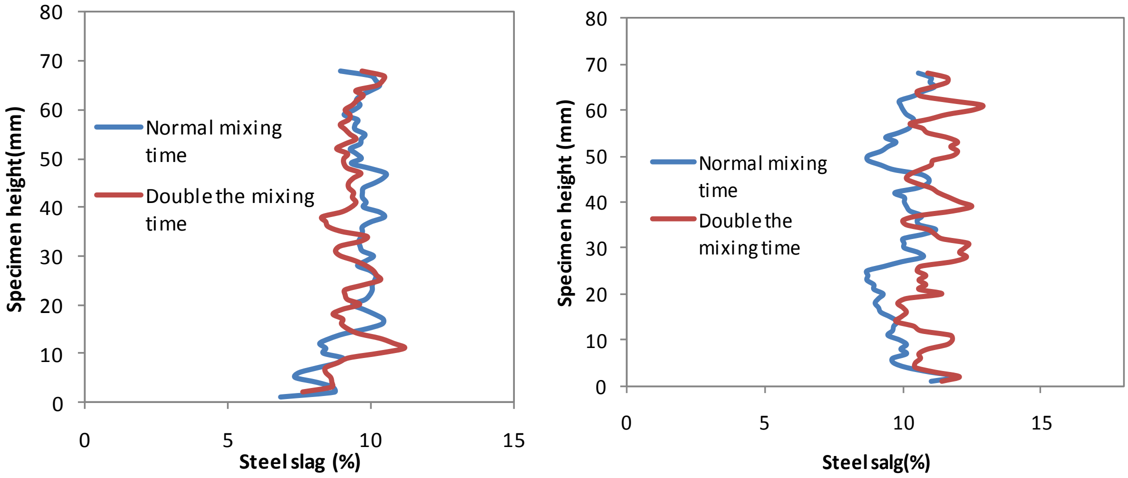



Figure 4-4: Distribution of steel slag (left: DRI, right: ISBS)

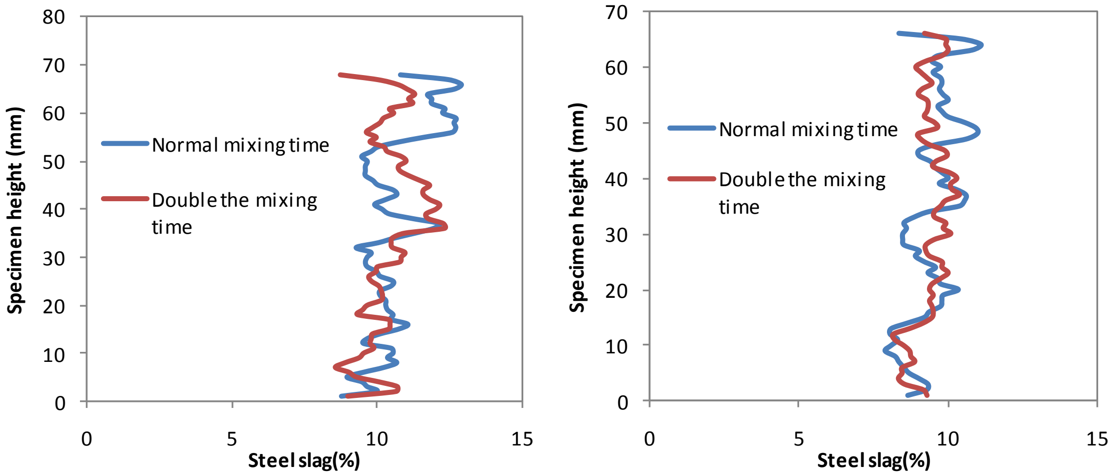



Figure 4-5: Distribution of steel slag (left: BRRC, right: UNott)

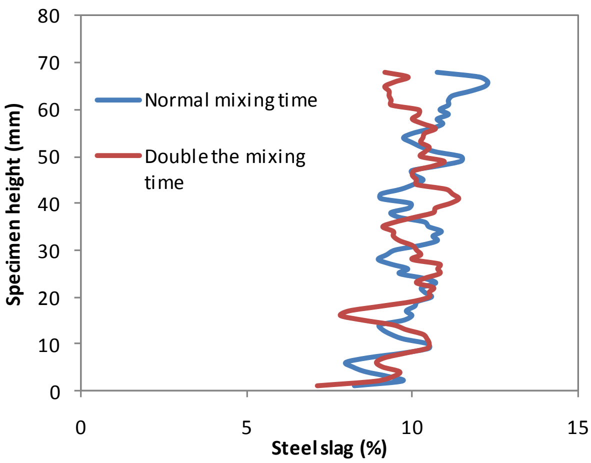



Figure 4-6: Distribution of steel slag (IFSTTAR)

#### 4.1.1.2 *Optical Image Analysis results*

Tables 4-2 to 4-6 give a summary of the most characteristic observations under the microscope for plain sections and thin sections.

**Table 4-2: Observations on specimens from BRRC**

| **BRRC** | | **Normal mixing time** | **Double mixing time** |
|---|---|---|---|
| Plane section | Distribution of: | | |
| | - Air voids | Several, regularly | Several, regularly |
| | - Steel slag | A lot, slightly irregularly | A lot, slightly irregularly |
| PMB thin section | Mixing between RA and New | Large areas with respectively RA/New | Large areas with respectively RA/New |
| | Distribution of: | | |
| | - Polymer | Only slightly dispersed in the mix | Only slightly dispersed in the mix |
| | - Lumps of fibres | few small lumps | few small lumps |
| Thin section | Mixing between RA and New | Good to less good | Good |
| | Presence of bitumen | Less to some | Less |
| | Clean aggregates surface | Few | None |
| | Distribution of: | | |
| | - Air voids | Few | Some |
| | - Steel slag | Few | More |
| | - Lumps of fibres | Some | Few |

**Table 4-3:** Observations on specimens from DRI

| **DRI** | | **Normal mixing time** | **Double mixing time** |
|---|---|---|---|
| Plane section | Distribution of: | | |
| | - Air voids | Some, regularly | More, slightly irregularly |
| | - Steel slag | Irregularly | Irregularly |
| PMB thin section | Mixing between RA and New | Good | Less good |
| | Distribution of: | | |
| | - Polymer | Only slightly dispersed in the mix | Only slightly dispersed in the mix |
| | - Lumps of fibres | Some lumps | More and larger lumps |
| Thin | Mixing between RA | Good | Good to less good |

| | | | |
|---|---|---|---|
| section | and New | | |
| | Presence of bitumen | Less | Some |
| | Clean aggregates surface | Few | None |
| | Distribution of:<br>- Air voids | Few | Few to some |
| | - Steel slag | Some | Few |
| | - Lumps of fibres | Some | Few lumps |

**Table 4-4: Observations on specimens from IFSTTAR**

| IFSTTAR | | Normal mixing time | Double mixing time |
|---|---|---|---|
| Plane section | Distribution of:<br>- Air voids | Some, regularly | Few, regularly |
| | - Steel slag | irregularly (large areas without any) | irregularly (large areas without any) |
| PMB thin section | Mixing between RA and New | Less good | Less good |
| | Distribution of:<br>- Polymer | Only slightly dispersed in the mix | Slightly to regularly dispersed in the mix |
| | - Lumps of fibres | few lumps | One smaller lumps |
| Thin section | Mixing between RA and New | Less good | Less good |
| | Presence of bitumen | Less | Less |
| | Clean aggregates surface | None | Few |
| | Distribution of:<br>- Air voids | Few | Few |
| | - Steel slag | Few | Few |
| | - Lumps of fibres | Few | Some |

**Table 4-5: Observations on specimens from ISBS**

| ISBS | | Normal mixing time | Double mixing time |
|---|---|---|---|
| Plane section | Distribution of:<br>- Air voids | Few, regularly (less in the middle of the specimen) | More, slightly irregularly (most in the middle of the specimen) |
| | - Steel slag | A lot but irregularly (most in the middle and "top" of the specimen) | A lot but irregularly (most in the side and "top" of the specimen) |
| PMB thin section | Mixing between RA and New | Good | Less good |
| | Distribution of:<br>- Polymer | Good dispersed in the mix | Slightly to regularly dispersed in the mix |
| | - Lumps of fibres | None | More larger lumps |
| Thin section | Mixing between RA and New | Good to less good | Good to less good |
| | Presence of bitumen | Some | Less |
| | Clean aggregates surface | More | Few |
| | Distribution of:<br>- Air voids | More | Few |
| | - Steel slag | Few | Few |
| | - Lumps of fibres | Few | Some (larger) |

**Table 4-6: Observations on specimens from UNott**

| **UNott** | | **Normal mixing time** | **Double mixing time** |
|---|---|---|---|
| Plane section | Distribution of:<br>- Air voids | Few to some, irregularly | Some, irregularly |
| | - Steel slag | irregularly (large areas without any) | irregularly (large areas without any) |
| PMB thin section | Mixing between RA and New | Less good | Good |
| | Distribution of:<br>- Polymer | Only slightly dispersed in the mix | Slightly to regularly dispersed in the mix |
| | - Lumps of fibres | One lumps | One lumps |
| Thin section | Mixing between RA and New | Less good | Good to less good |
| | Presence of bitumen | Less to some | Less to some |
| | Clean aggregates surface | Few | Few |
| | Distribution of:<br>- Air voids | Some | Few |
| | - Steel slag | Some | One |
| | - Lumps of fibres | Some but separate | Few lumps |

Results for the air void content from optical image analysis of the plane sections can be seen in Table 4-7.

"W" means that the whole area has been analysed and "C" that only the centre was measured.

**Table 4-7: Air void content (in %) from optical image analysis.**

Normal mixing time

| | Vertical slices | | | | Horizontal slices | | | |
|---|---|---|---|---|---|---|---|---|
| | Middle | | Side | | Middle | | Top | |
| | W | C | W | C | W | C | W | C |
| BRRC | 1,5 | 0,9 | 1,4 | 1,1 | 1,4 | 3,1 | 0,6 | 1,0 |
| DRI | 1,2 | 0,5 | 0,9 | 1,4 | 1,0 | 2,8 | 1,2 | 1,1 |
| IFSTTAR | 0,9 | 0,9 | 0,9 | 1,2 | 0,6 | 0,6 | 0,2 | 0,0 |
| ISBS | 0,3 | 0,6 | 0,6 | 0,8 | 0,3 | 0,3 | 0,1 | 0,1 |
| UNott | 1,1 | 1,0 | 0,6 | 0,2 | 0,3 | 0,8 | 2,4 | 1,0 |

Double mixing time

| | Vertical slices | | | | Horizontal slices | | | |
|---|---|---|---|---|---|---|---|---|
| | M | | S | | M | | T | |
| | W | C | W | C | W | C | W | C |
| BRRC | 1,4 | 1,0 | 1,3 | 0,6 | 1,1 | 1,2 | 1,2 | 0,6 |
| DRI | 1,2 | 1,2 | 1,1 | 1,0 | 1,1 | 0,4 | 0,7 | 0,4 |
| IFSTTAR | 1,0 | 0,5 | 0,6 | 0,8 | 0,3 | 0,3 | 0,2 | 0,2 |
| ISBS | 0,9 | 1,0 | 1,0 | 1,4 | 1,4 | 1,8 | 0,3 | 0,7 |
| UNott | 2,2 | 2,3 | 1,7 | 1,1 | 1,0 | 0,8 | 0,9 | 0,7 |

A comparison between the figures in the tables above and the CT scans of UNott will be interesting and presented in the final report.

DRI's analysis of the gyratory specimens has been carried out to test if it is possible to prepare specimens in the laboratory which are homogeneous and if there is an impact from the mixing procedure (mixer type and mixing times) or gyratory compaction device .

Each of the five laboratories has produced two mixes of the SMA with two different mixing times (normal for the mixer and twice that time). The mixers which have been used, are constructed by different manufacturers and this also applies to the gyratory compactors.

DRI has received three specimens from each mix and two of these were used for the plane section method (horizontal and vertical slices) and one for the thin section method. The conclusion drawn from the analysis is therefore based on very few samples.

The objective was to analyse if the laboratory mixing procedures could simulate the various mixing processes in asphalt plants. Another interesting point was also if it is possible to see whether the RA has been well mixed into the rest of the material, so the mixes could be considered homogeneous.

In general both plane and thin sections show that the specimens, both those mixed with normal time and those mixed with twice the time, have very few air voids and they are not regularly distributed.

If steel slag is used as a kind of indicator of how well the mixture has been homogenized, plane sections show that even with a doubling of the mixing time it was not possible to achieve a satisfactory structure.

Using twice the mixing time seems not to give a better distribution of the fibres, RA or the polymer. In one parameter, however, it seems that increasing the mixing time will have a positive influence: the number of clean aggregate surfaces decreases.

### *4.1.3* Results of mechanical tests

#### 4.1.3.1 Compactability

To see the effect of the mixing time, only the results of BRRC are discussed here. BRRC used two different mixing times:

1. Normal mixing times (30 s dry + 30 s with RA + 90 s with binder)
2. Double mixing times (60 s dry + 60 s with RA+ 180 s with binder)

The following specimens were compacted (for each of the mixing times):

- 3 specimens @ 200 gyrations for compactability
- 3 specimens to a density of 2350 kg/m³ and a height of 100 mm for water sensitivity (ITS-R) by BRRC
- 9 specimens to a density of 2500 kg/m³ and a height of 70 mm for stiffness:
    - 3 for stiffness (IT-CY) by BRRC
    - 3 for Cyclic Triaxial Stress Test (CTST) by TUBS
    - 3 for Optical Image Analysis and X-ray CT by DRI and UNott

Figure 4-7 shows the curves for the samples compacted to 200 gyrations (average of 3), for the two mixing times and for the plant mixed bulk material that was compacted for the preliminary interlaboratory test.

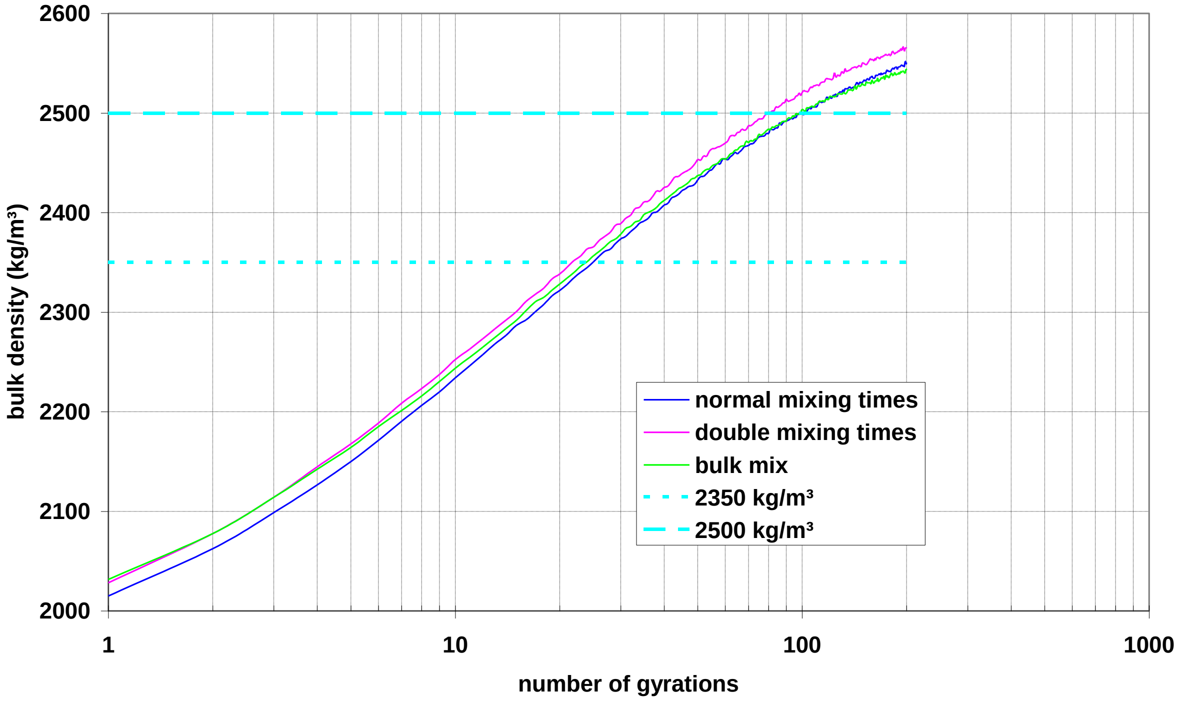



**Figure 4-7: Gyratory compaction of plant bulk mix and mixes with normal and double mixing times**

The following observations are made:

- The differences between the curves are small (20 kg/m³ at 100 gyrations) but not insignificant compared to the standard deviation calculated from the repeated tests (which is less than 10 kg/m³).
- The compaction curve of the plant mixed material is more flat, in other words, the plant mix is harder to compact than the freshly made laboratory mixes.
- Doubling the mixing times leads to a denser mix, from the start to the end of compaction. The shape of the curve is the same as for the normal mixing times.

The difference between the plant mix and the lab mix could be explained by hardening of the plant mix due to ageing and reheating. The difference between the normal and double mixing times could be explained by a better coating or aggregate grinding. The analysis of the grading of the mixes by ZAG indeed showed that for BRRC, the fines content was a little higher which may again be explained by grinding. However, the differences are of the same order as the precision of the test results, so the conclusion is that doubling the mixing times has no significant effect and compactability of the laboratory mixes is the same as for the plant mix.

The compaction curves in Figure 4-7 were used to determine the number of gyrations needed for a target density of 2350 and 2500 kg/m³ respectively, for the fabrication of the test specimens. For the normal mixing times, 25 and 100 gyrations were needed, while for the double mixing times, only 22 and 80 gyrations were needed.

Figure 4-8 shows the compaction curves of all the specimens (average of 3 for 25 and 200 gyrations, average of 9 for 100 gyrations)

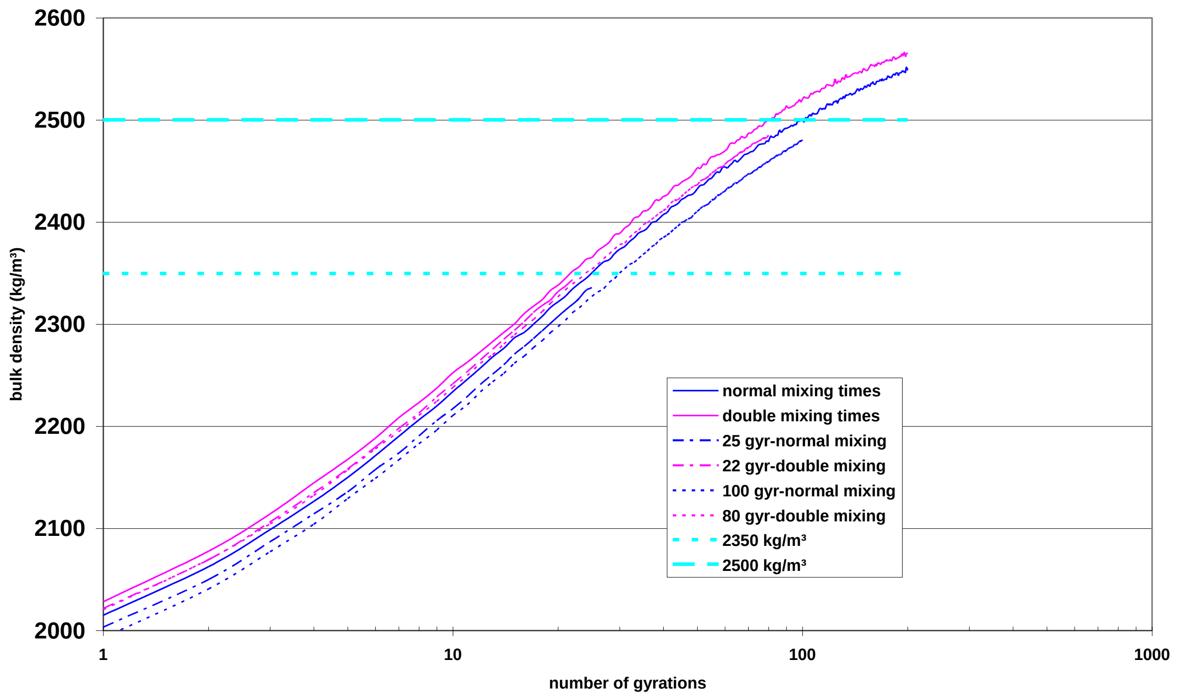



**Figure 4-8: Gyratory compaction curves of specimens prepared by BRRC for the lab mixing study**

The following observations are made:

- Doubling the mixing times consistently leads to a denser mix, from the start to the end of compaction. The shape of the curve is the same as for the normal mixing times.
- The density at a given number of gyrations is systematically higher for the specimens compacted to 200 gyrations.

Note that only two mixes were made (normal times and double times) in the large mixer and that all the test specimens were made in the following days after reheating the subdivided mix. The specimens compacted to 200 gyrations were made first, while the others were made a few days later (so longer storage of the mixed material).

Note also that there were differences in specimen target height, depending on the test for which the specimens were meant. The specimens compacted to 200 gyrations (for compactability) had a target height of approximately 77 mm. The specimens compacted to 80 or 100 gyrations (for stiffness and cyclic triaxial stress tests) had a target height of 70 mm. The specimens compacted to 22 or 25 gyrations (for water sensitivity) had a target height of 100 mm. This also has a small effect on the compaction curves.

#### 4.1.3.2 Water sensitivity

The specimens were compacted by the different laboratories using the gyratory compactor. The number of gyrations had to be chosen to reach a density of 2350 kg/m³ (geometrical density in the gyratory compactor). All ITS-R tests were done by BRRC.

Following the procedure for the water sensitivity test (EN 12697-12), the bulk density of the samples was measured, following EN 12697-6 (Saturated Surface Dry method). Table 4-8 and Figure 4-9 show the results. Considering the standard deviations (error bars) on the measured bulk densities of the specimens, there are no significant differences. There can be no relation between the density of the specimens and the mixing times, because the intention was to reach the same density (so the number of gyrations may be different depending on the mixing times).

**Table 4-8: Bulk density of the specimens (EN 12697-6, proc. B(SSD))**

| bulk density (kg/m³) | | BRRC | DRI | ISBS | IFSTTAR | UNott | average |
|---|---|---|---|---|---|---|---|
| average | normal mix time | 2464 | 2467 | 2469 | 2445 | 2431 | 2453 |
| | double mix time | 2470 | 2477 | 2442 | 2456 | 2446 | 2458 |
| | plant mix | | | 2452 | | | |
| stdev | normal mix time | 13 | 16 | 23 | 17 | 26 | |
| | double mix time | 11 | 11 | 5 | 35 | 14 | |
| | plant mix | | | 8 | | | |

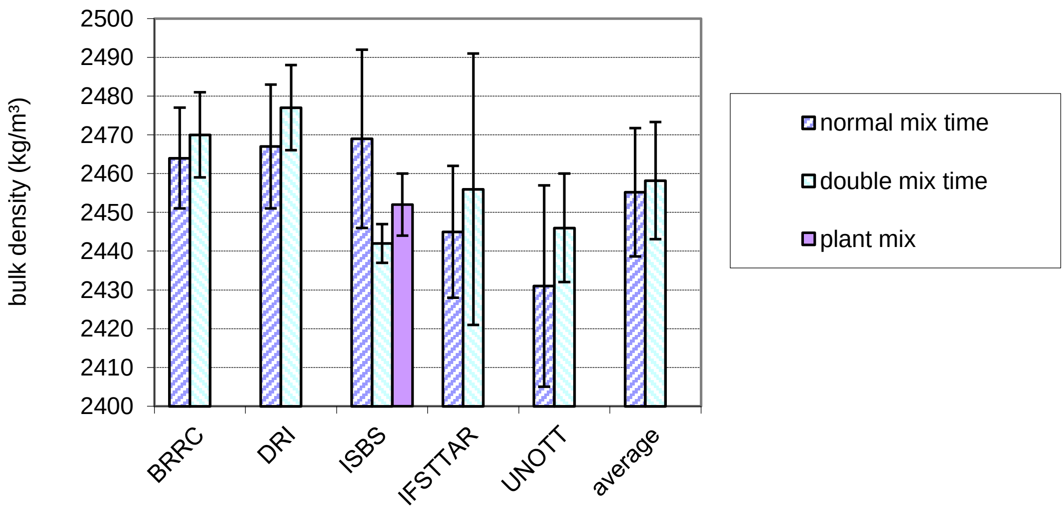



**Figure 4-9: Bulk density of the specimens (EN 12697-6, proc. B(SSD))**

Figure 4-10 and

Table 4-9: Indirect Tensile Strength of the unconditioned specimensshow the results of the indirect tensile strength (ITS) of the unconditioned specimens. The differences between the laboratories and the mixing times are small compared to the standard deviations of the measurements. The average results are very close to the result of the plant mixed specimens.

**Table 4-9: Indirect Tensile Strength of the unconditioned specimens**

| ITS (MPa) | | BRRC | DRI | ISBS | IFSTTAR | UNott | average |
|---|---|---|---|---|---|---|---|
| average | normal mix time | 2,39 | 2,38 | 2,36 | 2,35 | 2,09 | 2,26 |
| | double mix time | 2,39 | 2,63 | 2,35 | 2,47 | 2,15 | 2,40 |
| | plant mix | | | 2,25 | | | |
| stdev | normal mix time | 0,10 | 0,30 | 0,23 | 0,18 | 0,09 | 0,16 |
| | double mix time | 0,13 | 0,15 | 0,01 | 0,19 | 0,16 | 0,17 |
| | plant mix | | | 0,04 | | | |

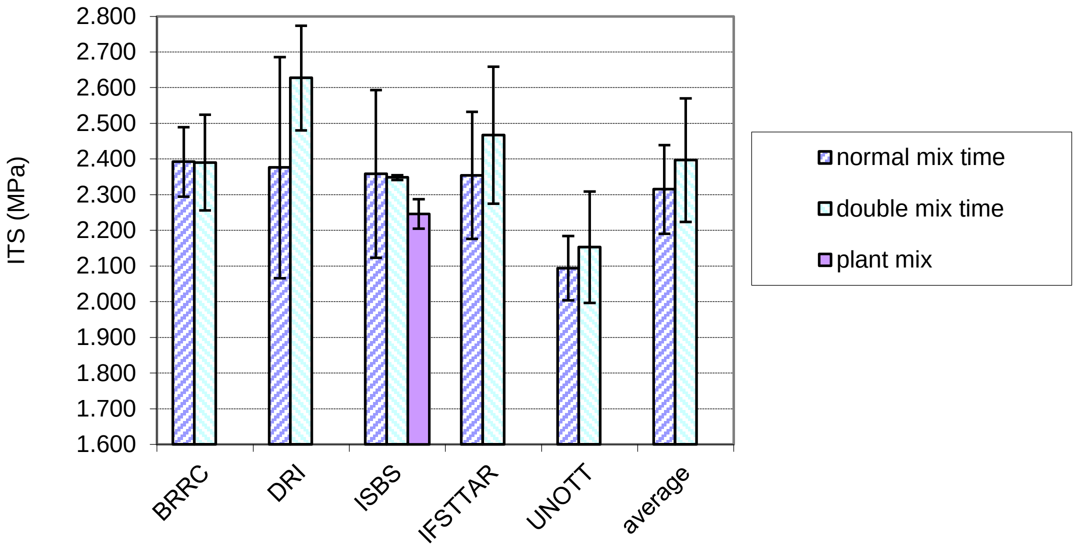



**Figure 4-10: Indirect Tensile Strength of the unconditioned specimens**

Table 4-10 and Figure 4-11 show the results of ITSR, which is a measure for water sensitivity. The following observations are made:

ITSR is high for all laboratories, around 90 %, with a minimum of 85 %. This is typical for SMA-mixtures.

All the laboratories have either no impact of doubling the mixing times, or a small positive impact. This could theoretically be explained by a better coating, but the differences in this experiment are too small to draw this conclusion.

The average results are very close to the result of the plant mixed specimens.

**Table 4-10: ITSR-results**

| ITSR (%) | BRRC | DRI | ISBS | IFSTTAR | UNott | average |
|---|---|---|---|---|---|---|
| normal mix time | 90 | 92 | 85 | 86 | 91 | 89 |
| double mix time | 93 | 92 | 91 | 86 | 94 | 91 |
| plant mix | | | 91 | | | |

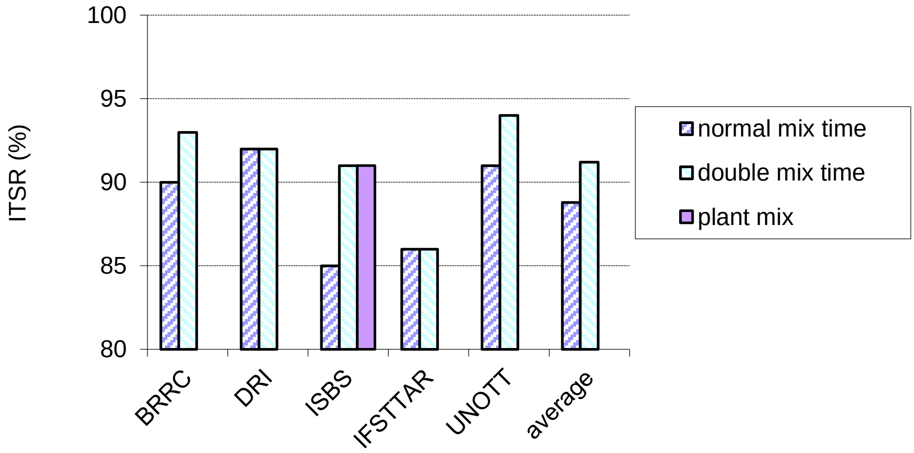



**Figure 4-11: ITSR-results**

### 4.1.3.3 Stiffness

The specimens were compacted by the different laboratories using the gyratory compactor. The number of gyrations had to be chosen to reach a density of 2500 kg/m³ (geometrical density in the gyratory compactor). All ITS-CY stiffness tests were done by BRRC.

The bulk density of the samples was measured, following EN 12697-6 (Saturated Surface Dry method). Table 4-11 and 4-12 and Figure 4-13 show the results (average and standard deviations of 3 specimens).

**Table 4-11: Bulk density of the specimens (EN 12697-6, proc. B(SSD))**

| | BRRC | | DRI | | ISBS | | IFSTTAR | | UNott | |
|---|---|---|---|---|---|---|---|---|---|---|
| mix time | normal | double | normal | double | normal | double | normal | double | normal | double |
| AVG (kg/m³) | 2579 | 2584 | 2566 | 2561 | 2566 | 2565 | 2551 | 2559 | 2556 | 2547 |
| STDEV (kg/m³) | 13 | 6 | 10 | 2 | 4 | 9 | 6 | 10 | 21 | 17 |

**Table 4-12: Bulk density of the specimens compacted by ISBS from plant mix (EN 12697-6, proc. B(SSD))**

| | ISBS-plant mix |
|---|---|
| AVG (kg/m³) | 2556 |
| STDEV(kg/m³) | 4 |

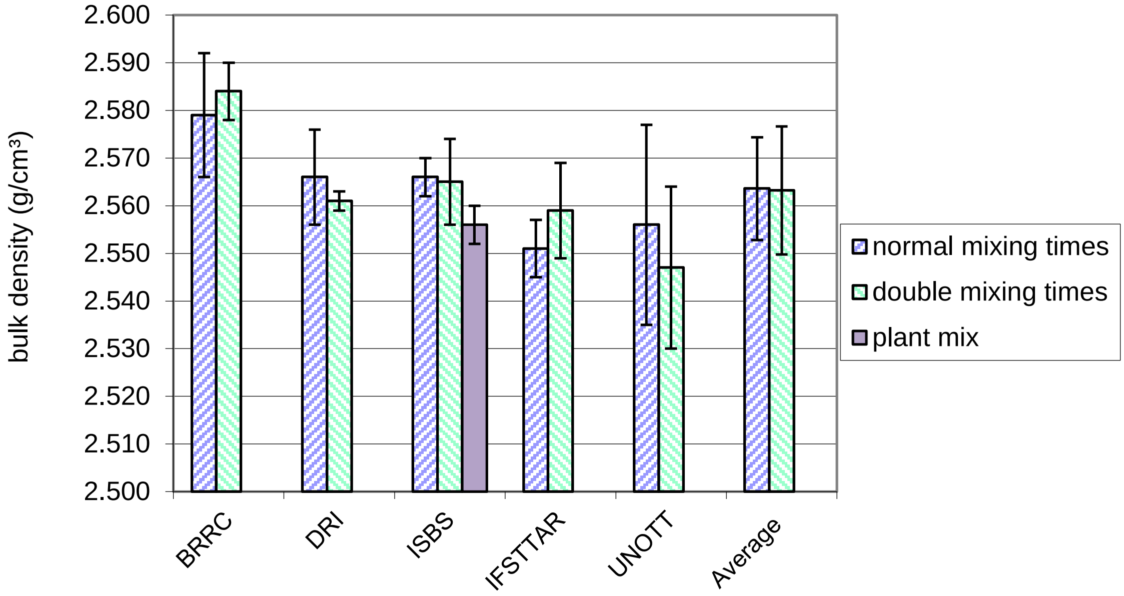



**Figure 4-12 : Bulk density of all mixes (EN 12697-6, proc. B(SSD))**

The stiffness as measured using the IT-CY method is shown in Table 4-13 for the laboratory mixes and in Table 4-14 for the plant mix. All tests were done at a temperature of 20 °C. The results are expressed as the average and standard deviation of 3 specimens. Note that there are no precision data given for this test in the European standard EN 12697-26, so the rounding of the results is based on the standard deviations.

**Table 4-13: Overview of individual results for IT-CY stiffness on laboratory mixes**

| | BRRC | | DRI | | ISBS | | IFSTTAR | | UNott | |
|---|---|---|---|---|---|---|---|---|---|---|
| mix time | normal | double | normal | double | normal | double | normal | double | normal | double |
| AVG (GPa) | 6,36 | 6,77 | 7,24 | 6,89 | 5,70 | 6,24 | 5,53 | 5,26 | 5,96 | 6,06 |
| STDEV(GPa) | 0,19 | 0,30 | 0,52 | 0,21 | 0,18 | 0,08 | 0,18 | 0,54 | 0,32 | 0,18 |

**Table 4-14: Individual results for IT-CY stiffness on plant mixed material (specimens compacted by ISBS)**

| | ISBS - plant mix |
|---|---|
| AVG (GPa) | 6,43 |
| STDEV(GPa) | 0,23 |

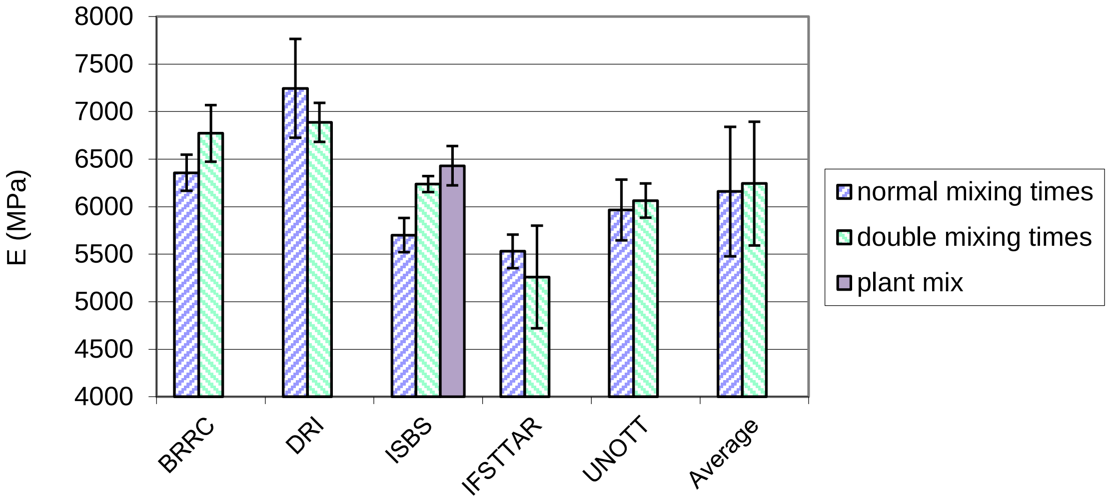



**Figure 4-13: IT-CY stiffness of all mixes**

For BRRC, ISBS and UNott, the stiffness is higher with the double mixing times, while for DRI and IFSTTAR, it is lower. On average, there is no significant effect of doubling the mixing times, as seen in Table 4-15. Note that the standard deviation shown in this table is not associated with the repeatability of the IT-CY stiffness test (all the tests were done by BRRC), but with the reproducibility of the specimen preparation that was done by the different laboratories.

**Table 4-15: Average IT-CY stiffness over all labs**

| | Average over all labs | |
|---|---|---|
| | normal mix.time | double mix.time |
| AVG (GPa) | 6,16 | 6,24 |
| STDEV(GPa) | 0,68 | 0,65 |

For the normal mixing times, the ranking in stiffness by laboratory is:

DRI>BRRC>UNott>ISBS>IFSTTAR

For the double mixing times, the ranking remains the same (except for ISBS and UNott switching places, but the difference between these two results is within precision limits). The laboratory by which the specimens have been prepared therefore seems to have more impact on stiffness than the mixing times.

The differences in stiffness could partly be explained by the differences in bulk density of the specimens. When comparing Figures 4-13 and 4-12, there is indeed a trend that the specimens with lower density have a lower stiffness.

The analysis of the mixes done by ZAG shows no differences that may explain the results, except for the binder content of the IFSTTAR mixes, which was approximately 0.2 % higher. This may be an explanation for the lower stiffness of the IFSTTAR specimens.

As a general conclusion however, it can be said that the differences are not very large as compared to the precision of the test and that the average over all lab mixing procedures is practically the same as the result from the plant mix.

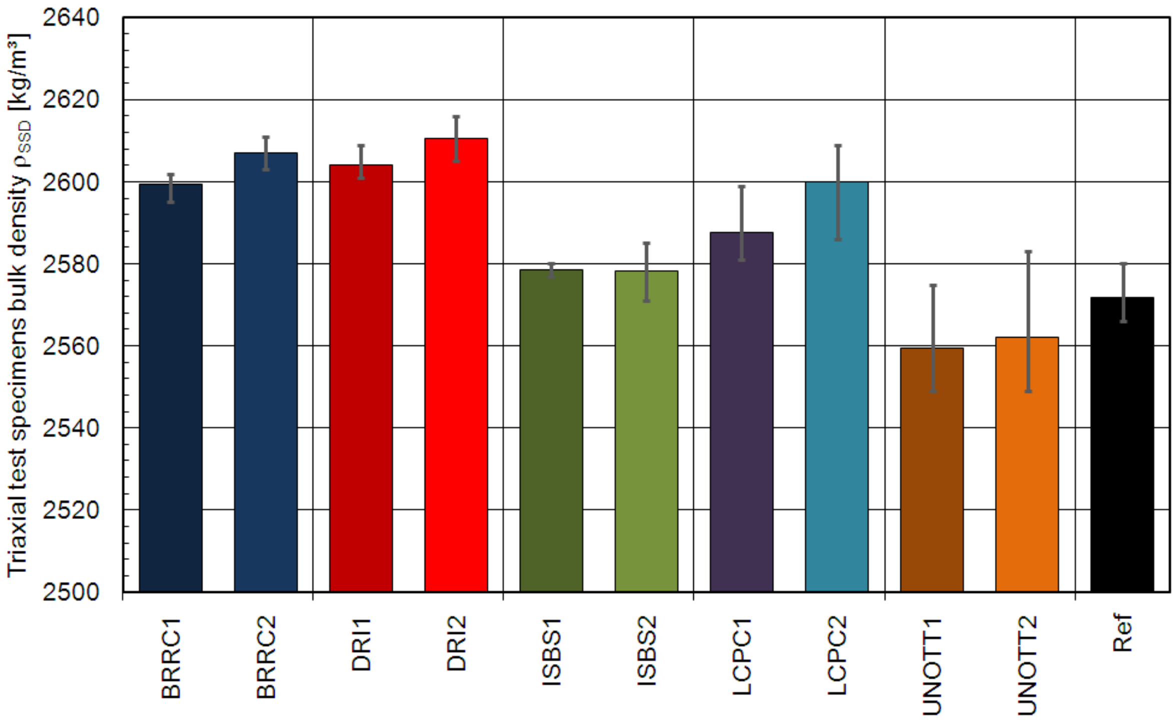
#### 4.1.3.4 Permanent deformation

Table 4-16 contains the bulk density and dimensions of each tested specimen. Further the actual stress levels measured during each CTST are given.

As indicated in Figure 4-14, the specimen's bulk densities, as measured using EN 12697-6, proc. B (SSD), vary between 2 549 kg/m³ and 2 616 kg/m³. For all laboratories, the prolonged mixing time results in the same or slightly higher bulk density. The same trend was observed for the specimens for water sensitivity and IT-CY stiffness tests discussed above: the majority of data showed a small increase of the density for longer mixing times.

**Table 4-16. Specimen properties and measured loading parameters**

| Specimen | Bulk density $\rho_{b,SSD}$ [kg/m³] | Height H [mm] | Diameter D [mm] | Axial bottom stress $\sigma_{ax,b}$ [MPa] | Axial stress amplitude $\sigma_{a,ax}$ [MPa] | Radial confinement stress $\sigma_c$ [MPa] |
|---|---|---|---|---|---|---|
| BRRC131 | 2602 | 60,4 | 100,0 | 0,155 | 0,303 | 0,149 |
| BRRC132 | 2601 | 60,5 | 99,8 | 0,157 | 0,307 | 0,150 |
| BRRC133 | 2595 | 60,5 | 99,7 | 0,156 | 0,308 | 0,149 |
| BRRC243 | 2611 | 60,5 | 99,9 | 0,156 | 0,307 | 0,149 |
| BRRC244 | 2603 | 62,4 | 99,9 | 0,156 | 0,307 | 0,150 |
| BRRC245 | 2607 | 60,7 | 99,9 | 0,156 | 0,307 | 0,150 |
| DRI112 | 2602 | 60,9 | 99,9 | 0,155 | 0,305 | 0,149 |
| DRI114 | 2609 | 60,8 | 99,9 | 0,156 | 0,306 | 0,150 |
| DRI18 | 2601 | 60,8 | 99,9 | 0,156 | 0,307 | 0,149 |
| DRI226 | 2605 | 60,9 | 99,8 | 0,156 | 0,307 | 0,148 |
| DRI227 | 2611 | 60,8 | 99,7 | 0,157 | 0,307 | 0,149 |
| DRI229 | 2616 | 60,9 | 99,8 | 0,156 | 0,308 | 0,149 |
| ISBS111 | 2579 | 60,3 | 99,8 | 0,157 | 0,307 | 0,149 |
| ISBS115 | 2580 | 61,0 | 99,9 | 0,157 | 0,307 | 0,150 |
| ISBS17 | 2577 | 60,5 | 99,7 | 0,157 | 0,308 | 0,150 |
| ISBS210 | 2585 | 60,5 | 99,9 | 0,156 | 0,305 | 0,150 |
| ISBS212 | 2571 | 60,6 | 99,8 | 0,157 | 0,307 | 0,150 |
| ISBS28 | 2579 | 60,5 | 99,8 | 0,156 | 0,307 | 0,149 |
| IFSTTAR14 | 2599 | 60,8 | 99,8 | 0,156 | 0,308 | 0,133 |
| IFSTTAR15 | 2581 | 60,9 | 99,8 | 0,157 | 0,307 | 0,149 |
| IFSTTAR16 | 2583 | 60,8 | 99,4 | 0,156 | 0,308 | 0,148 |
| IFSTTAR24 | 2586 | 60,9 | 99,9 | 0,156 | 0,304 | 0,150 |
| IFSTTAR25 | 2609 | 60,5 | 99,9 | 0,157 | 0,307 | 0,148 |
| IFSTTAR26 | 2605 | 60,8 | 99,8 | 0,157 | 0,307 | 0,149 |
| UNott11 | 2575 | 61,1 | 99,9 | 0,156 | 0,307 | 0,150 |
| UNott12 | 2554 | 62,3 | 99,9 | 0,155 | 0,304 | 0,150 |
| UNott17 | 2549 | 61,5 | 99,9 | 0,156 | 0,307 | 0,150 |
| UNott217 | 2554 | 61,6 | 100 | 0,157 | 0,302 | 0,150 |
| UNott220 | 2549 | 61,0 | 100 | 0,157 | 0,302 | 0,150 |
| UNott222 | 2583 | 60,5 | 100 | 0,156 | 0,302 | 0,150 |
| Ref7 | 2566 | 60,5 | 99,9 | 0,155 | 0,307 | 0,150 |
| Ref14 | 2569 | 60,1 | 99,6 | 0,157 | 0,307 | 0,150 |
| Ref15 | 2580 | 60,1 | 99,8 | 0,155 | 0,306 | 0,150 |




note: index 1 stands for normal mixing times and 2 for double mixing times

**Figure 4-14: Mean bulk densities of triaxial test specimens**

The test results of the cyclic triaxial stress tests are summarized in Table 4-17.

The strain graphs measured on the specimens made of the plant mix reference material are shown in Figure 4-15 besides the resulting strain rates after 10 000 load cycles. The graph of axial strain shows a fast increase at the beginning of the test. The strain rates decrease continuously resulting in a typical convex cyclic creep curve. After an increase of the radial strain at the beginning of the test (indicating an increase of the diameter of the specimen), it reaches a maximum after approximately 100 load cycles. After that, the radial strain decreases indicating a decrease of diameter. Specimen Ref14, which shows the highest strains, reaches a diameter at the end of the test which is even smaller than its initial diameter. Despite the axial deviatoric compression stress, the loading results in a negative radial strain rate. This behaviour can be found for all specimens as indicated in Table 4-17.

This phenomenon can be explained by the anisotropy of the specimen. The vertical (axial) loading combined with gyratory movements during compaction results in a horizontal arrangement of the aggregates. During compaction the specimen receives radially much lower loading which results in a smaller stiffness.

As shown in Figure 4-15, specimen REF14 results in significantly higher strain values. Nevertheless, as especially the axial strain rate after 10 000 load cycles reaches comparable values as the other specimens, the strain difference is due to effects happening at the beginning of the loading.

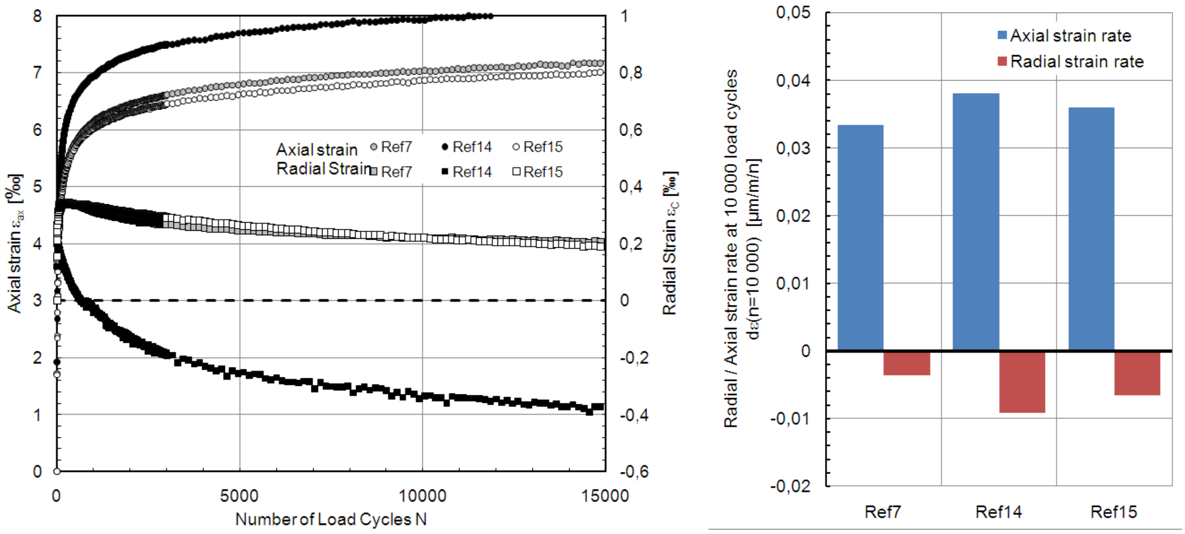


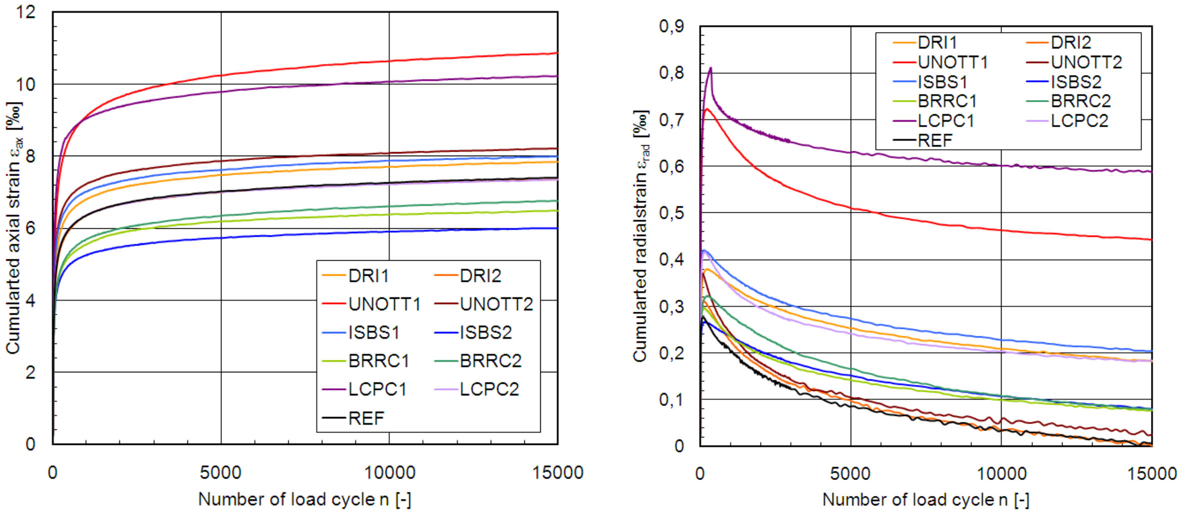

**Figure 4-15: Strain graphs (left) and strain rates after 10 000 load cycles (right) of reference mix specimens**

Figure 4-16 shows the plots of the development of axial and radial strain during CTST. Each curve is the mean of three tests. For cumulated axial strain, the tests result in following ranking:

UNott1>IFSTTAR1>UNott2>ISBS1>DRI1>REF>DRI2>IFSTTAR2>BRRC2>BRRC1>ISBS2

For the standard mixing times only: UNott1>IFSTTAR1> ISBS1>DRI1>BRRC1

For the double mixing times only: UNott2> DRI2>IFSTTAR2>BRRC2>ISBS2




note: index 1 stands for normal mixing times and 2 for double mixing times

**Figure 4-16: Plots of axial (left) and radial (right) cumulated strain in CTST**

**Table 4-17. Results of Cyclic Triaxial Stress Tests**

| | Axial strain rate | Axial strain | Radial strain rate | Radial strain | Stiffness Modulus | Poisson Ratio |
|---|---|---|---|---|---|---|
| | $d\varepsilon_{ax}$ | $\varepsilon_{ax}$ | $d\varepsilon_{rad}$ | $\varepsilon_{rad}$ | $S_{Mix}$ | µ |
| Specimen | [(µm/m)/n] | [‰] | [(µm/m)/n] | [‰] | [MPa] | [-] |
| BRRC131 | 0,02883 | 5,990 | -0,00283 | 0,0355 | 646 | 0,25 |
| BRRC132 | 0,01977 | 7,407 | -0,00789 | 0,1356 | 643 | 0,38 |
| BRRC133 | 0,01955 | 5,721 | -0,00539 | 0,1265 | 679 | 0,33 |
| BRRC243 | 0,03529 | 5,862 | -0,00613 | 0,1775 | 688 | 0,28 |
| BRRC244 | 0,05075 | 7,597 | -0,00813 | 0,1065 | 614 | 0,28 |
| BRRC245 | 0,02261 | 6,338 | -0,00792 | 0,0412 | 554 | 0,36 |
| DRI112 | 0,03552 | 7,632 | -0,00621 | 0,2307 | 709 | 0,28 |
| DRI114 | 0,02739 | 7,449 | -0,00496 | 0,2990 | 705 | 0,29 |
| DRI18 | 0,03282 | 8,028 | -0,00805 | 0,0975 | 731 | 0,31 |
| DRI226 | 0,03218 | 7,084 | -0,01332 | -0,1528 | 760 | 0,39 |
| DRI227 | 0,03116 | 7,346 | -0,00489 | 0,2740 | 701 | 0,27 |
| DRI229 | 0,02694 | 7,259 | -0,00292 | -0,0080 | 706 | 0,25 |
| ISBS111 | 0,02762 | 7,516 | -0,00597 | 0,1270 | 641 | 0,30 |
| ISBS115 | 0,03397 | 8,280 | -0,00463 | 0,3952 | 658 | 0,27 |
| ISBS17 | 0,02628 | 7,818 | -0,00777 | 0,1626 | 694 | 0,34 |
| ISBS210 | 0,02019 | 5,283 | -0,00509 | 0,0973 | 691 | 0,32 |
| ISBS212 | 0,02728 | 6,220 | -0,00509 | 0,1183 | 676 | 0,29 |
| ISBS28 | 0,01682 | 6,216 | -0,00839 | 0,1061 | 678 | 0,42 |
| IFSTTAR14 | 0,03911 | 9,854 | -0,00205 | 0,6869 | 659 | 0,21 |
| IFSTTAR15 | 0,03818 | 9,911 | -0,00255 | 0,6595 | 606 | 0,23 |
| IFSTTAR16 | 0,04017 | 10,410 | -0,00507 | 0,4569 | 570 | 0,26 |
| IFSTTAR24 | 0,04593 | 9,045 | -0,00175 | 0,5240 | 583 | 0,22 |
| IFSTTAR25 | 0,01072 | 5,717 | -0,00851 | 0,0270 | 646 | 0,52 |
| IFSTTAR26 | 0,02679 | 6,937 | -0,00668 | 0,0565 | 662 | 0,32 |
| UNott11 | 0,05577 | 15,056 | -0,00697 | 0,5913 | 613 | 0,26 |
| UNott12 | 0,05982 | 7,952 | -0,00329 | 0,7472 | 538 | 0,23 |
| UNott17 | 0,04012 | 8,900 | -0,00530 | 0,0505 | 659 | 0,26 |
| UNott217 | 0,03096 | 7,714 | 0,00008 | -0,0175 | 614 | 0,20 |
| UNott220 | 0,03833 | 7,563 | -0,00667 | -0,0469 | 624 | 0,28 |
| UNott222 | 0,03342 | 8,955 | -0,00583 | 0,2245 | 615 | 0,28 |
| Ref7 | 0,03342 | 7,025 | -0,00355 | 0,2202 | 688 | 0,25 |
| Ref14 | 0,03810 | 7,935 | -0,00912 | -0,3361 | 709 | 0,31 |
| Ref15 | 0,03597 | 6,869 | -0,00655 | 0,2186 | 665 | 0,29 |

The mean values of the three single results for each applied mixing method are plotted in Figure 4-17 to Figure 4-20.

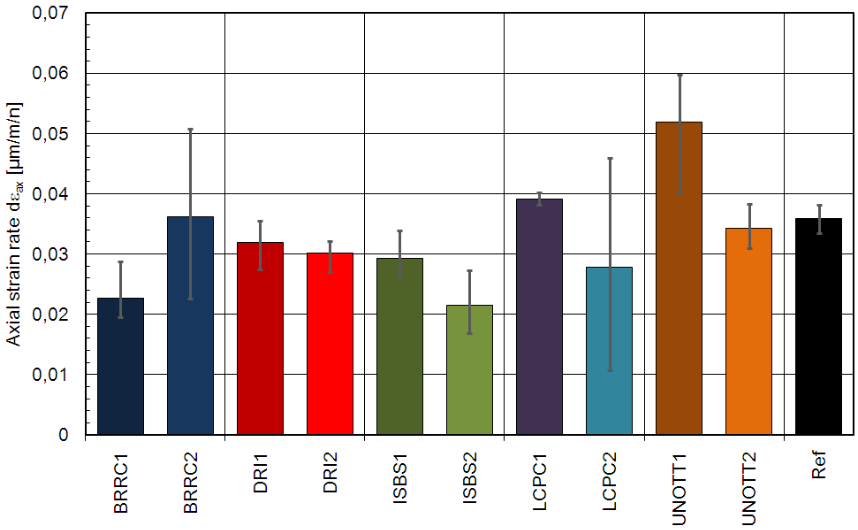
For the axial strain rate $d\varepsilon_{ax}$ (compare Figure 4-17), the prolonged mixing time results generally in lower mean axial strain rates. Only for BRRC results, the longer mixing times results in a higher strain rate. However, the three replicates for the samples BRRC2, IFSTTAR2 and UNott1 show high scattering of the test results.

For axial strain rate the tests result in following ranking:

UNott1>IFSTTAR1>BRRC2>Ref>UNott2>DRI1>DRI2>ISBS1>IFSTTAR2>BRRC1>ISBS2

For the standard mixing times only: UNott1>IFSTTAR1>DRI1> ISBS1 >BRRC1

For double mixing time: BRRC2> UNott2> DRI2> IFSTTAR2> ISBS2

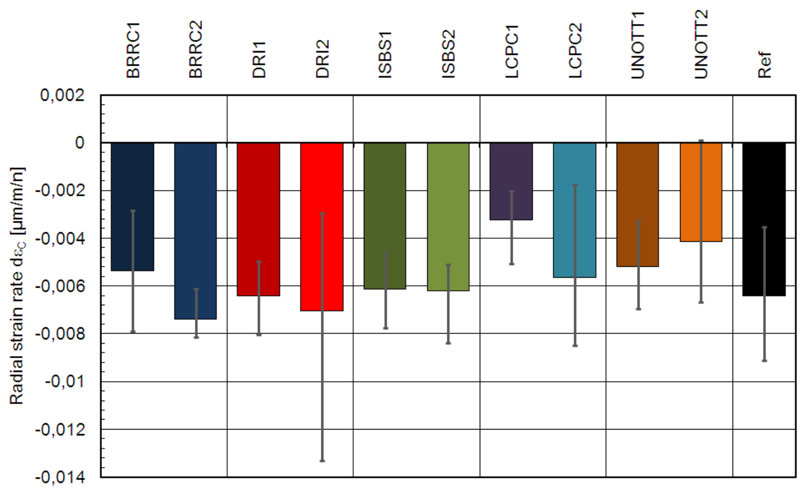



note: index 1 stands for normal mixing times and 2 for double mixing times

**Figure 4-17: Mean axial strain rate results**

Figure 4-18 shows the mean values of the measured radial strain rate. Generally the prolonged mixing time results in lower strain rates (negative!). Thus, the specimens compacted after prolonged mixing times result in a faster decrease of diameter, with exception of the UNott specimens. Though, the scattering of the results is considerably high.

Figure 4-19 indicates the mean stiffness moduli of the tested specimen. Generally, the prolonged mixing time result in higher stiffness values, except for BRRC specimens.




note: index 1 stands for normal mixing times and 2 for double mixing times

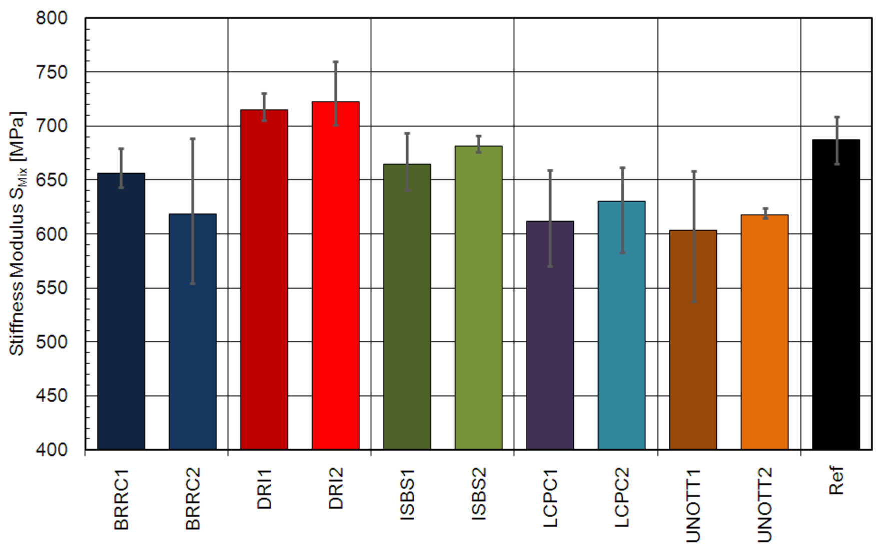
**Figure 4-18: Mean radial strain rate results**

The ranking of stiffness modulus results is as follows:

DRI2>DRI1>Ref>ISBS2>ISBS1>BRRC1>IFSTTAR2>BRRC2>UNott2>IFSTTAR1>UNott1

For the standard mixing times only: DRI1>ISBS1>BRRC1>IFSTTAR1>UNott1

For double mixing time: DRI2> ISBS2>IFSTTAR2>BRRC2>UNott2

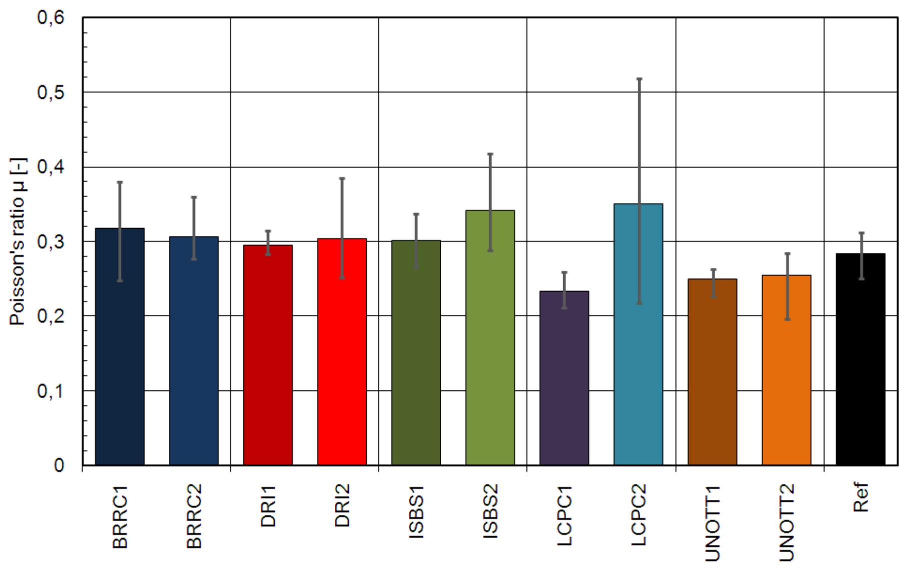



note: index 1 stands for normal mixing times and 2 for double mixing times

**Figure 4-19: Mean stiffness modulus results**

The Poisson ratio calculated from the axial and radial stresses and the axial and radial strain rates, as shown in Figure 4-20, varies between 0,20 and 0,52. Except for ISBS and IFSTTAR, the mixing time doesn't influence the value of µ. For ISBS and

IFSTTAR, the mean values measured on specimens after prolonged mixing time are higher compared to standard mixing time.




note: index 1 stands for normal mixing times and 2 for double mixing times

**Figure 4-20: Mean Poisson ratio results**

As indicated in Figure 4-21 both axial strain rate and stiffness modulus are slightly dependent on the bulk density of the specimen. A higher bulk density will result in a slightly higher stiffness modulus (measured at 50 °C) and a lower axial strain rate, though the overall scatter of the test results is rather high.

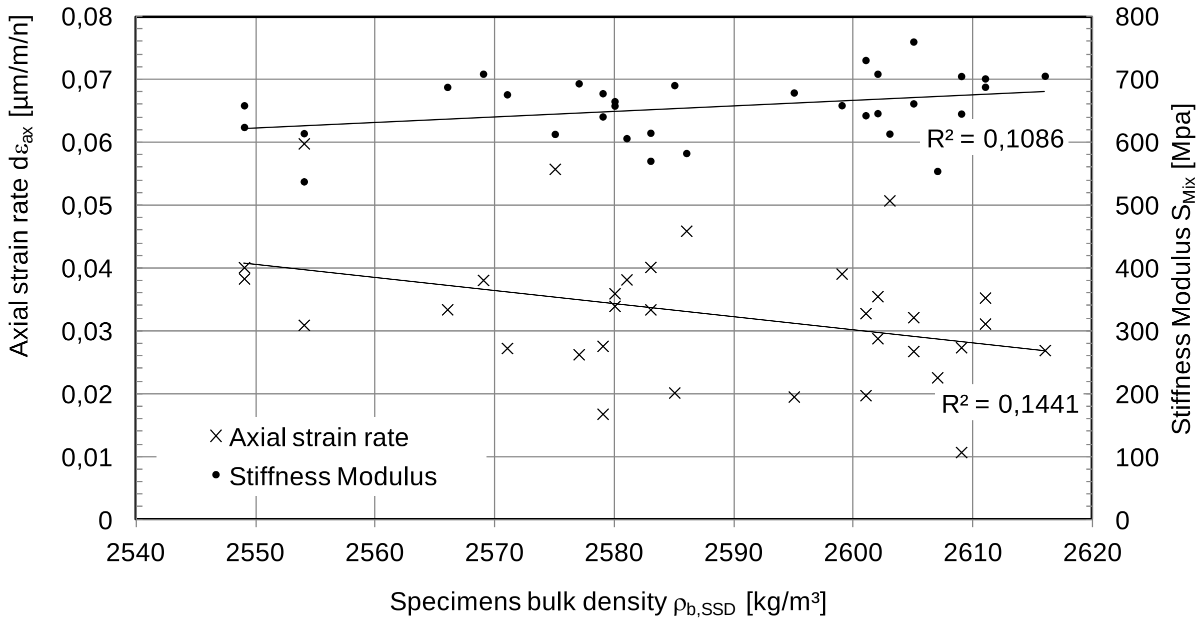



**Figure 4-21: Axial strain rate and stiffness modulus versus specimens bulk density**

#### 4.1.3.5 Effect of mixing sequence on stiffness

The aim of the following tests was to assess the impact of this difference in mixing sequence.

Two mixing sequences were used by BRRC:

1. Adding filler before the binder:
   - Pour the dry aggregates (including fibres and filler!) in the mixer and mix for 30 s.
   - Add the RA and mix for another 30 s.
   - Add the new binder and mix for another 90 s.
2. Adding filler after the binder:
   - Pour the dry aggregates (except for fibres and filler!) in the mixer and mix for 30 s.
   - Add the RA and mix for another 30 s.
   - Add the new binder and mix for another 30 s.
   - Add the fibres and filler and mix for another 60 s.

Note that the total mixing time was the same for both sequences.

The comparison was made using the stiffness measurements (IT-CY) at 20 °C. The samples were produced and tested at BRRC. Because of the small quantities needed to prepare these specimens, the mixtures were prepared in a small Hobart mixer instead of the large MLPC mixer.

The results are summarized in Table 4-18. The mix density increases slightly when the filler is added at the end. The impact on stiffness is less than 10 %, but this difference is significant when compared to the standard deviation. This single experiment does not allow to draw a general conclusion or to recommend one of the two sequences as preferable. However, being aware that there may be an impact, it is important for every laboratory to control the mixing sequence and to make sure it is always the same.

**Table 4-18: Impact of mixing sequence on stiffness (IT-CY)**

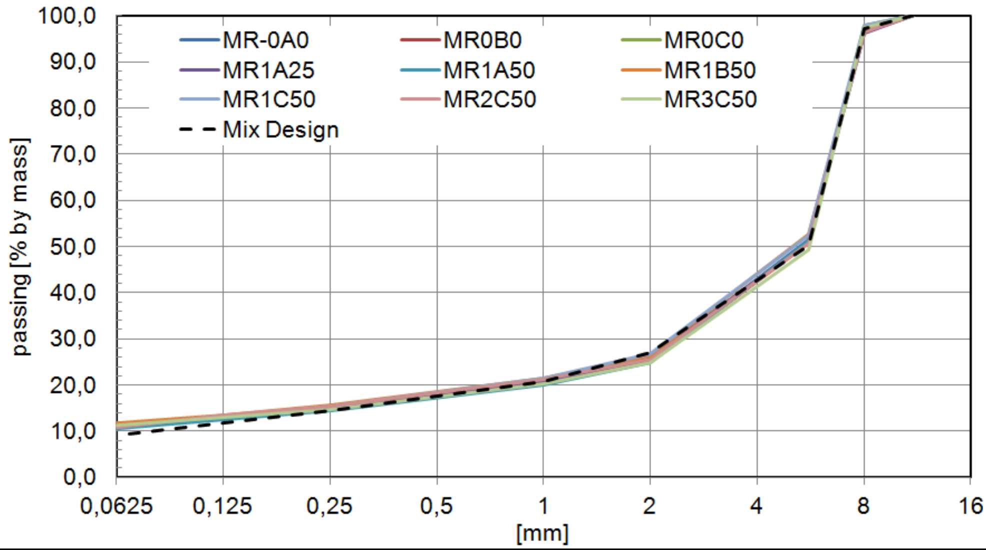
| Mixing sequence | Filler added before binder | Filler added after binder |
|---|---|---|
| Total mixing time | 2 min 30 s | 2 min 30 s |
| Density (SSD) (kg/m³) | 2573 | 2584 |
| E avg (GPa) | 5,70 | 6,17 |
| Stdev (GPa) | 0,18 | 0,12 |

## 4.2 Multiple recycling study

### 4.2.1 Mix control

The results of the asphalt mix control tests applied to the various SMA mixes prepared in laboratory are summarized in Table 4-19.

**Table 4-19: Results of mix control tests applied to SMA 8 mix samples of multiple recycling study**

| | Design | 0A0 | 0B0 | 0C0 | 1A25 | 1A50 | 1B50 | 1C50 | 2C50 | 3C50 |
|---|---|---|---|---|---|---|---|---|---|---|
| Composition of aggregates: grading | | | | | | | | | | |
| Fines [%] | 9 | 11,1 | 11,3 | 11,3 | 11,4 | 10,6 | 11,7 | 11,2 | 10,8 | 11,2 |
| >0,063; ≤ 2 mm | 18 | 14,2 | 14,0 | 14,8 | 14,4 | 14,2 | 14,6 | 15,6 | 14,9 | 13,6 |
| >2 mm | 73 | 74,7 | 74,7 | 73,9 | 74,2 | 75,2 | 73,7 | 73,3 | 74,4 | 75,2 |
| |  | | | | | | | | | |
| Mix composition | | | | | | | | | | |
| Binder content [%] | 7,0 | 6,47 | 6,48 | 6,94 | 6,87 | 6,72 | 6,91 | 6,84 | 7,06 | 6,79 |
| $T_{R\&B}$ [°C] | - | 61,6 | 64,6 | 55,2 | 61,3 | 64,1 | 65,9 | 58,9 | 56,9 | 57,3 |
| max. density $\rho_m$ [kg/m³] | - | 2586 | 2575 | 2552 | 2576 | 2566 | 2560 | 2568 | 2556 | 2554 |
| | | Mean: 2563 (used for calculating specimen void content) | | | | | | | | |
| Specimen characteristics (40 x 40 x 160 mm³) | | | | | | | | | | |
| bulk density $\rho_b$ [kg/m³] | | 2503 | 2512 | 2530 | 2530 | 2522 | 2522 | 2533 | 2519 | 2510 |
| Void content V [%] | | 2,4 | 2,0 | 1,3 | 1,3 | 1,6 | 1,6 | 1,2 | 1,7 | 2,1 |

### *4.2.2* Results of mechanical tests

#### 4.2.2.1 Results of compactability tests

For evaluating the compactability of the mixes, the decrease of specimen height was measured during impact compaction. From the resulting measurements, the compaction resistance T [21 Nm] as well as the theoretical minimum specimen height $t_\infty$ and the specimen height at the beginning of the compaction process $t_0$ are estimated.

The results of the compactability tests are summarized in Table 4-20. For 2 mixes the test data recording was not working and the test results got lost.

The results of compaction resistance T are shown in Figure 4-22 as mean values shown by columns and the range between the smallest and highest values as the error bars. For the control mixes without addition of RA (0A0, 0B0, 0C0) it can be seen, that the mix 0A0 has the highest resistance against compaction. The T-Value for mix 0C0 is the smallest, indicating the effect of the binder with lowest viscosity. Also for the mixes containing 50 % of RA the same ranking between the three virgin binders is shown. Multiple recycling slightly increases the resistance against compaction T , as shown for 0C0, 1C50 and 2C50 mixes.

Note, that the value T (the resistance against compaction) indicates the number of compaction blows needed to reduce the thickness of the specimen for 1/e = 36,8 % of the calculated total height reduction ($t_0$ - $t_\infty$).

**Table 4-20: Results of compactability tests**

| Mix Sample | $t_0$ [mm] | $t_\infty$ [mm] | T [21 Nm] |
|---|---|---|---|
| **0A0** | 83,70 | 64,42 | 42,03 |
| **0B0** | 85,41 | 65,76 | 38,94 |
| **0C0** | 82,94 | 64,45 | 37,89 |
| **1A25** | - | - | - |
| **1A50** | 83,76 | 65,07 | 40,70 |
| **1B50** | 85,02 | 66,06 | 39,14 |
| **1C50** | 83,05 | 64,40 | 38,15 |
| **2C50** | 82,68 | 64,60 | 38,74 |
| **3C50** | - | - | - |
| -: test data got lost due to computer problems | | | |

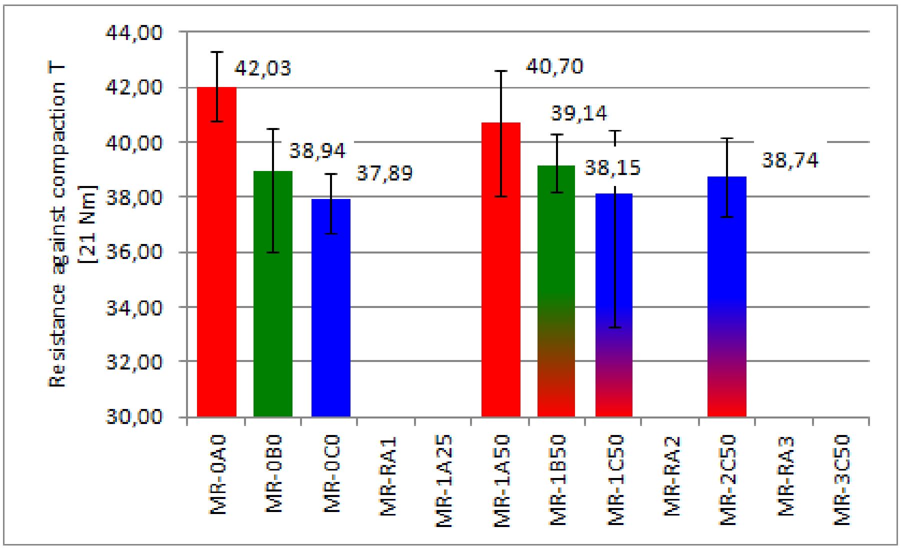



**Figure 4-22: Resistance against compaction T measured on SMA mixes**

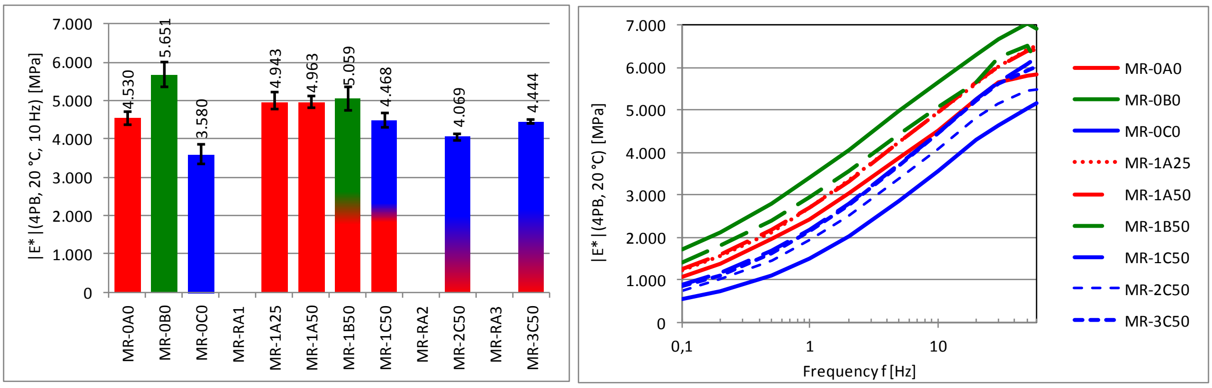
#### 4.2.2.2 Stiffness modulus

The stiffness of the specimens compacted from the asphalt mixtures was obtained by 4-point bending tests at 20 °C. The results are depicted in Figure 4-23. The left plot shows the mean values of stiffness moduli obtained at a test frequency of f = 10 Hz as columns and the range between lowest and highest value measured as error bars. For the control mixes without RA addition, the influence of binder viscosity is significant. The binder 25/55-55 used in mix 0B0 results in the highest mix stiffness, whereas mix 0C0 containing the binder of lower viscosity (45/80-50) shows the lowest stiffness. These differences are significant as indicated by the error bars and can be observed for all frequencies tested as shown in the plot of frequency-sweeps (compare Figure 4-23, right).

The same effect of virgin binder viscosity can be observed for the mixes containing 50 % of simulated reclaimed asphalt (RA1), though the difference between the stiffness moduli of 1A50 and 1B50 is not significant.

There is no effect observed of RA content between the mixes 1A25 and 1A50. Both mixes reach practically the same stiffness moduli at all frequencies as shown in the frequency-sweep where the lines are on top of each other.

By using the binder 45/80-50 with lower viscosity the stiffness modulus doesn’t increase significantly after multiple recycling steps. All the mixes containing 50 % of RA after 1, 2 or 3 recycling cycles reach lower stiffness values compared to mixture 0B0, which is designed according the German specifications for SMA mixes. The effect of long-term ageing acting on asphalt can fully be compensated in the recycling process by adding a binder of a softer type even for polymer modified bitumens.




at 10 Hz as function of frequency

**Figure 4-23: Stiffness moduli |E*| obtained in 4-point bending tests on specimens prepared from MR mixes**

#### 4.2.2.3 Resistance against permanent deformation

The results of cyclic triaxial stress tests (CTST) obtained from specimens compacted from the mixes as well as from the reheated long-term aged mixes RA1 and RA2 are depicted in Figure 4-24 and Figure 4-25. For the axial strain rate there is very little difference between the creep rates measured. Just the specimens compacted from the aged mix RA2 indicate significant higher strain rates.

A reason for the little differences of axial strain rate can be the fact, that for SMA mixes the aggregate skeleton has the main effect on the resistance against deformation. For all mixes analysed the aggregate skeleton is actually the same. Furthermore, during CTST the specimen is fixed horizontally by the radial stress which will further decrease the effect of binder viscosity on the axial deformation. In the CTST also the radial strain was measured. The results as shown in Figure 4-24 (right) indicate larger differences between the specimens compacted from the various mixes compared to the axial strain rate. Mixes indicating high radial strain are characterized by the ability to allocate the vertical loads horizontally. The combination of axial and radial strain rate enables to evaluate the Poisson ratio as shown in Figure 4-25 (right). Small values of Poisson ratio µ indicate that the specimen was further compacted during the triaxial loading, whereas high values of µ point to volume-constant deformation.

If axial, radial strain rate and the Poisson ratio are taken into account, there is no significant effect of RA percentage when the mixes 0A0, 1A25 and 1A50 are compared. During multiple recycling it seems that the mixes resistance against rutting is decreased, indicated by increasing axial and radial strain rates of mixes 1C50, 2C50 and 3C50.

For the stiffness modulus obtained from the elastic responses during the CTST as shown in Figure 4-25 (left) similar observations can be done compared to the stiffness moduli obtained from 4-point bending tests (compare Figure 4-23). The differences between the control mixes clearly indicate the use of softer binder type in 0C0 compared to 0A0 and 0B0 with the same ranking for the mixes containing 50 %

of RA1 (1A50, 1B50 and 1C50). The differences obtained on the mixes after multiple recycling cycles (1C50, 2C50 and 3C50) are not significant.

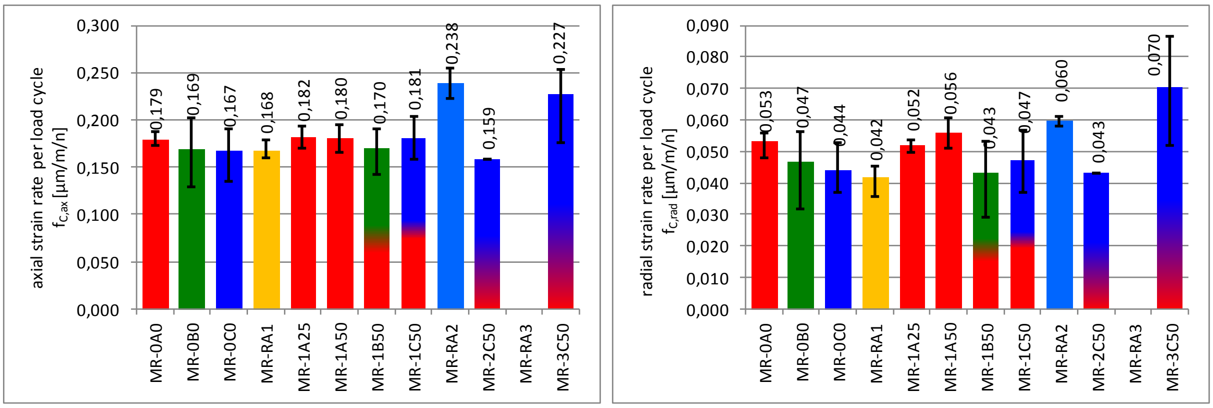



**Figure 4-24: Results of cyclic triaxial stress tests on specimens compacted from MR mixes: axial (left) and radial (right) strain rate per load cycle**

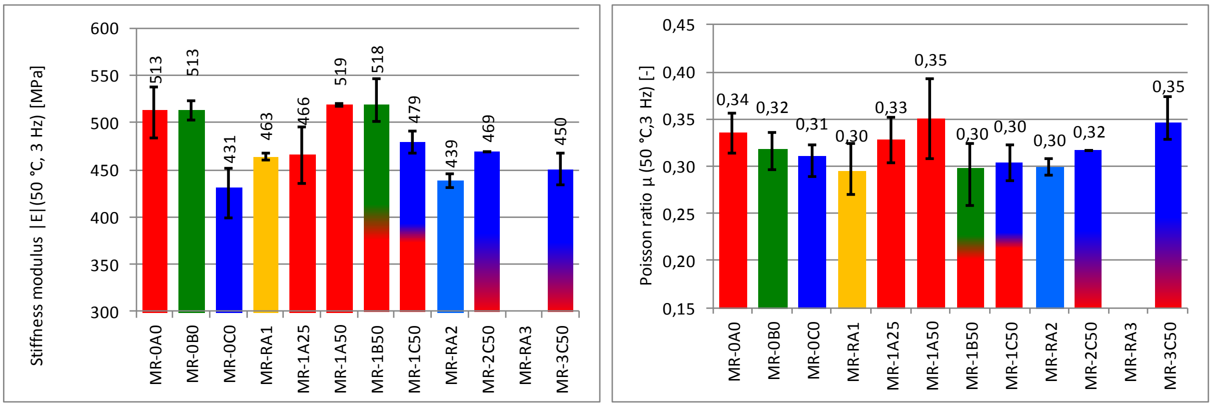



**Figure 4-25: Results of cyclic triaxial stress tests on specimens compacted from MR mixes: stiffness modulus (left) and Poisson ratio (right)**

#### 4.2.2.4 Resistance against low-temperature cracking

For evaluating the resistance against low-temperature cracking, TSRST and UTST tests were conducted.

In Figure 4-26 the results of TSRST are depicted. The left plot indicates the failure temperatures obtained on the specimens compacted from the various mixes analysed.

The control mixes 0A0, 0B0 and 0C0 indicate significant differences in their failure temperatures. 0C0 mixed with the softer binder type reaches the lowest failure temperature, whereas the mix 0B0 shows the highest value of $T_F$ and therefore the lowest resistance against low-temperature cracking. The same ranking with reduced differences is obtained for the mixes containing 50 % of RA (1A50, 1B50, 1C50).

During the recycling cycles, all the mixes obtained indicate failure temperatures lower than the value measured on the control mix 0B0. Only the specimens compacted from the RA mixes (RA1, RA2, RA3) indicate a lower resistance against low-temperature cracking.

If compared to the stiffness moduli obtained in 4PB tests it is clearly shown that low failure temperatures correlate well with low stiffness moduli.

For failure stress as shown in Figure 4-26(right) the differences between the mixes are less significant compared to failure temperature.

Again, the differences in failure stress obtained during the multiple recycling cycles are not significant (1C50, 2C50, 3C50). The increasing rigidity caused by ageing as indicated by higher failure temperatures and higher failure stresses can be levelled by adding a soft type of binder to the mixes.

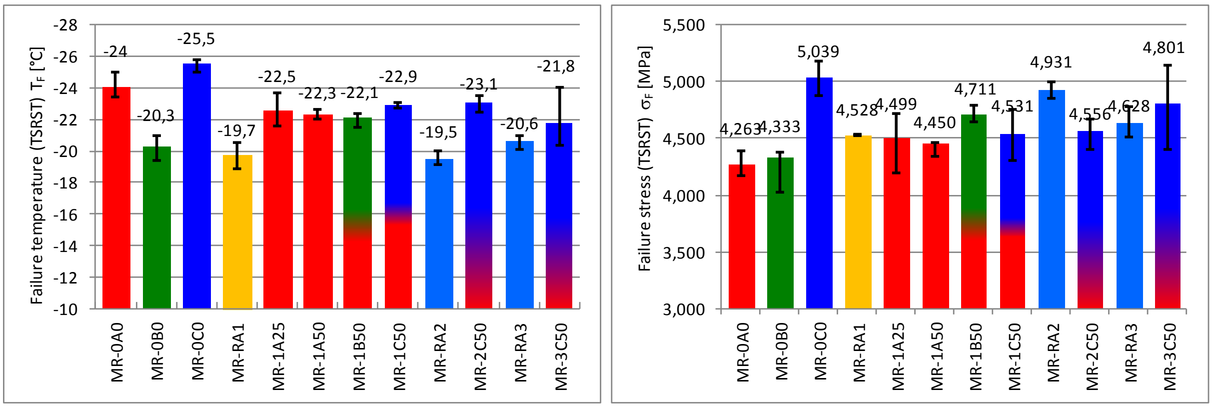



**Figure 4-26: Results of TSRST: Failure temperature TF (left) and Failure stress σF (right)**

The effect of flexibility of the mix also predetermines the results of uniaxial tensile stress tests (UTST) as shown in Figure 4-27. The control mixes 0A0, 0B0 and 0C0 show significant differences in tensile strength and failure strain. By ageing, the increased rigidity leads to an increase of tensile strength and decrease of failure strain obtained at 5 °C (0A0 -> RA1, 1C50 -> RA2, 2C50 -> RA2). Again the increased rigidity due to ageing can be compensated by the use of a softer virgin binder as shown by the same results obtained for the mixes 1C50, 2 C50 and 3C50.

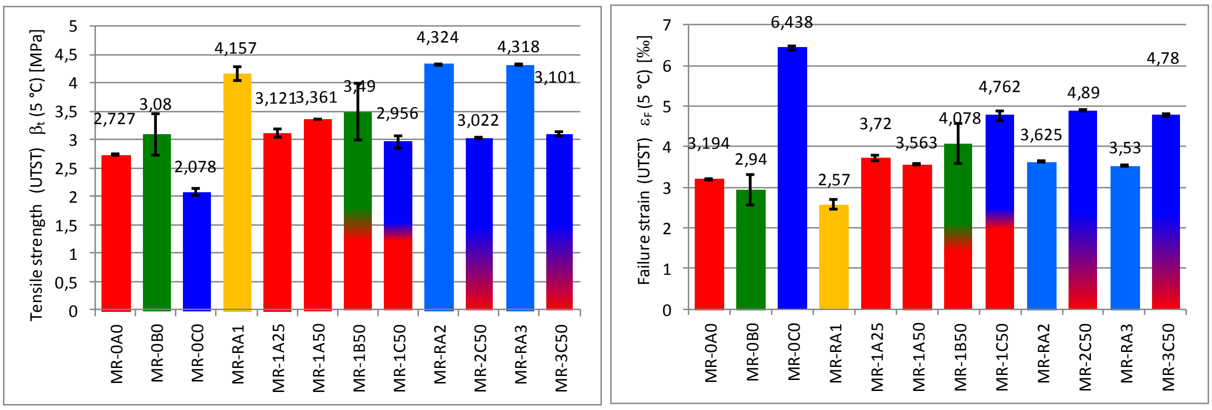



**Figure 4-27: Results of UTST: Tensile strength βt (left) and Failure strain εF (right)**

By combining the results of TSRST and UTST the tensile strength reserve can be estimated indicating the ability of asphalt pavement to be loaded by traffic induced loading at low temperatures where already considerable high cryogenic stress occurs. The higher the strength reserve $\Delta\beta_{t,max}$ and the lower the corresponding temperature, the higher is the materials resistance against cracks occurring by high traffic loads at low temperatures. As shown in Figure 4-28, the mixes containing RA with contents of 25 % and 50 % reach higher tensile strength reserves compared to the control mixes 0A0 and 0B0, which are in correspondence to German mix design specifications, whereas the temperatures of maximum strength reserve are very similar. The mixes containing RA exhibit the same or even better resistance against low-temperature cracking compared to the control mixes.

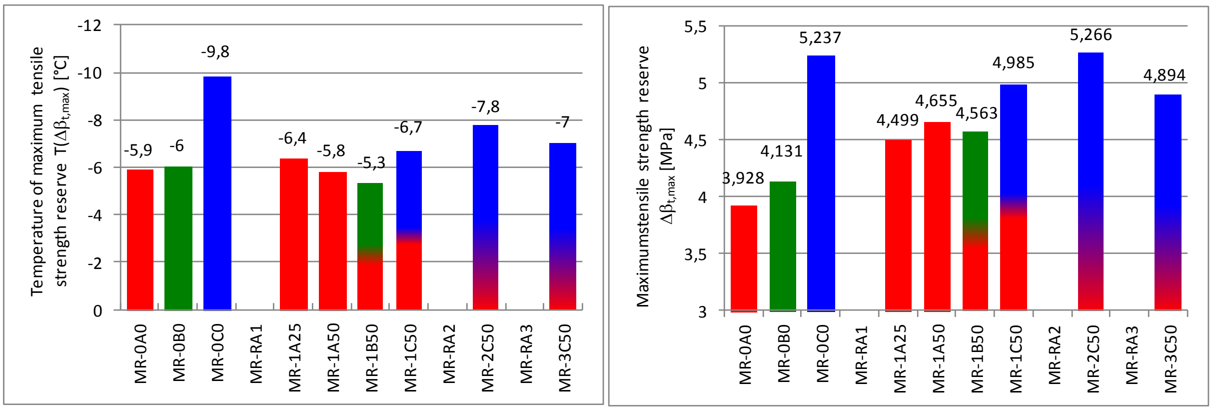



**Figure 4-28: Tensile strength reserve results: Temperature (left) and value (right) of maximum tensile strength reserve $\Delta\beta t,max$**

In summary, the performance test results obtained in this study indicate the possibility of multiple recycling of SMA mixes with RA content of approximately 50 %. For stiffness as well as resistance against low-temperature cracking, the test results obtained for the mixes after up to 3 recycling cycles indicate adequate properties compared to these of the control mixes composed according to German mix design specification. Though, for resistance against permanent deformation, the mix in the third recycling cycle shows significant higher strain rates compared to control mixes. This may be caused by a higher binder content resulting from the mix design or by some double coating effect, where the soft virgin binder added to the RA predetermines the mix performance.

### *4.2.3* PmB compatibility on asphalt properties

The presented results of the multiple recycling study allow some conclusions on the compatibility of PmB and the influence of combining different kinds of PmB in a new mix. In the study, three different PmB products were applied:

- A: 25/55-55A (SBS-chemically cross-linked PmB)
- B: 25/55-55A (SBS physically mixed PmB)
- C: 45/80-50A (SBS-chemically cross-linked PmB)

The choice for elastomer modified binders of the type 25/55-55A (A and B) was made because these are applied in German mix design for SMA mixes and are the most common in practice in all European countries . As seen in all test results, there are no indications showing problems of compatibility of the evaluated binder products. The mix 1B50 containing two different PmB products from different suppliers shows very similar results to the mix 1A50 where the same binder was applied in the simulated RA as well as virgin binder.

However, in daily road construction practice several other types of binders and modifiers are currently in use, for instance

- thermoplastic modifiers,
- natural asphalts,
- waxes for reducing mixing temperatures or
- rejuvenator agents.

To evaluate compatibility of recycled and virgin binders, the previously described test procedures can be used to verify the effect on the mix performance.

### *4.2.4* Mixing law for asphalt properties

The results presented allow the validation of mixing law equations applied in mix design practice for calculating resulting binder properties, in which the small range of variation in binder properties has to be considered. In theory, the aged RA binder interchanges its properties completely with the properties of the virgin binder during the hot mixing process (comp. Mollenhauer et al. 2012). Note that the mix law equations were originally validated on binders extracted from asphalt mix. In this case the mixing of binders does not only occur during the asphalt mixing process but also during extraction and recovery of the binders. To evaluate the validity of the mixing law on the actual mix properties, the results of the performance tests obtained during the multiple-recycling study can be used.

For validating the mixing law on asphalt properties, it is checked if the results of the performance tests can be calculated by applying the mixing laws according to equations 1 and 2 (compare page 20). For the test program conducted, this can be checked for following six mix variations, where results of performance tests are available for the control mixes as well as for the simulated RA:

- 1A25: 23,7 % RA1 and 76,3 % 0A0 (TSRST, UTST, CTST)
- 1A50: 48,2 % RA1 and 51,8 % 0A0 (TSRST, UTST, CTST)
- 1B50: 48,2 % RA1 and 51,8 % 0B0 (TSRST, UTST, CTST)
- 1C50: 48,2 % RA1 and 51,8 % 0C0 (TSRST, UTST, CTST)
- 2C50: 48,2 % RA2 and 51,8 % 1C50 (TSRST, UTST, CTST)
- 3C50: 48,2 % RA3 and 51,8 % 2C50 (TSRST, UTST)

If the aged RA bitumen is not completely mixed with the virgin binder added, double coating will occur. This will result in RA granulates which are coated by a first layer of old binder and a second layer of virgin binder. The first layer is very hard and behaves as part of the aggregate, while the second layer behaves as the active binder. It has to be noted that this is a simplified model, because in reality there is always partial mixing of the binders at the interface.

In double coating theory, the obtained mechanical properties of the resulting mix containing double-coated RA granulate will be predominately controlled by the virgin binder viscosity. Furthermore, the binder film thickness covering the virgin aggregate will be reduced because less active binder is available in the mix. To evaluate if double coating theory can be observed, the mechanical properties of the mixes containing RA will be compared to the properties of the mixes composed of only virgin materials.

- 1A25: 0A0 (TSRST, UTST, CTST)
- 1A50: 0A0 (TSRST, UTST, CTST)
- 1B50: 0B0 (TSRST, UTST, CTST)
- 1C50: 0C0 (TSRST, UTST, CTST)
- 2C50: 0C0 (TSRST, UTST, CTST)
- 3C50: 0C0 (TSRST, UTST, CTST)

In Figure 4-29 to Figure 4-31 the calculated performance test results according to mixing law application (linear and log type) as well as the expected test results if double-coating effects are considered are plotted versus the actual test results for the six mixes. In Table 4-21 the resulting coefficients of correlation $R^2$ are summarized.

For the results of TSRST (failure temperature and stress) neither the theory of mixing laws nor the double coating theory can be validated. The scatter of values as well as the deviation from the line of equality is slightly less for the mixing laws compared to the double-coating results (compare Figure 4-29).

For the results of uniaxial tensile stress tests (UTST) conducted at T = 5 °C the application of mixing laws gives good results as indicated in Figure 4-30. For the tensile strength $\beta_t$ and failure strain $\varepsilon_F$ values the data points are close to the line of equality and coefficients of correlation higher than 0,85 are reached. The double coating theory is not applicable for the tensile strength $\beta_t$ obtained from UTST as indicated by large deviations from the line of equality. For the results of cyclic triaxial stress tests (CTST), in Figure 4-31 shown for the stiffness modulus and Poisson ratio, both theories results in a scattering of values which are somehow near the line of equality but with low coefficients of correlation.

In summary, for the properties showing a wide range of test results combined with low test scatter (here: UTST results), the mixing law for estimating the expected mix performance seems to be applicable. Though for properties with only little difference between the test results (e. g. TSRST) the mixing law applicability couldn't be proven in this research study.

Whereas the double coating theory doesn't seem to be applicable for the test results of TSRST and UTST, the results of CTST for evaluation of the resistance against permanent deformation (here shown for creep Poisson ratio µ) may be an explanation for the high strain rates observed for the mixes 1C50, 2C50 and 3C50 (compare Figure 4-24) containing the virgin binder C in addition to RA.

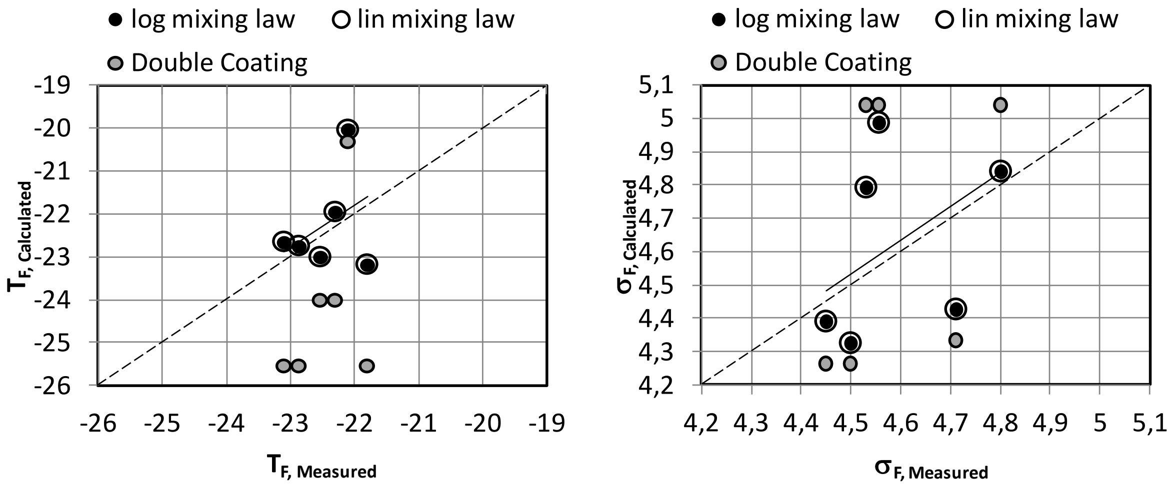



**Figure 4-29: Comparison of measured and calculated results for validating the mixing laws for results of TSRST**

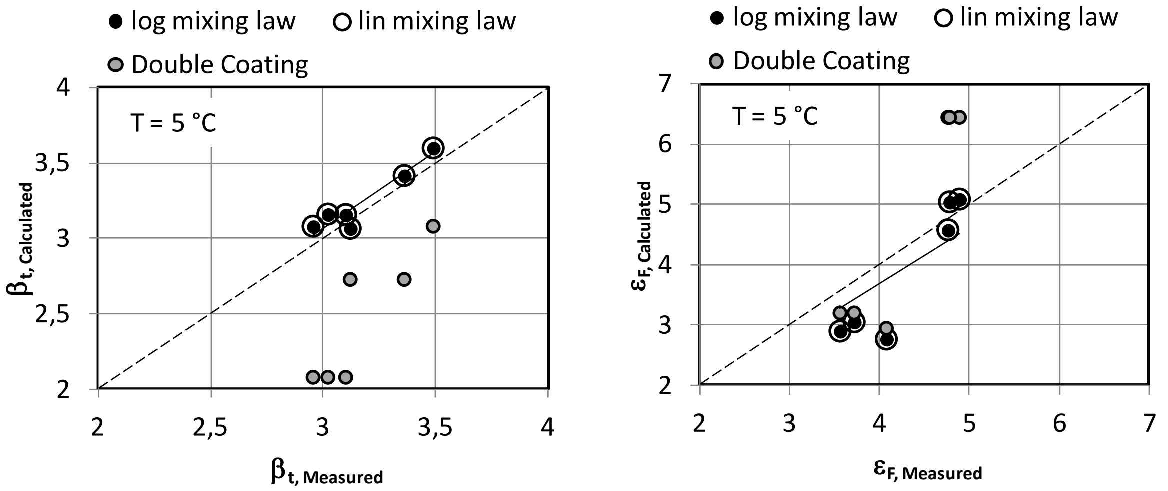



**Figure 4-30: Comparison of measured and calculated results for validating the mixing law equation for results of UTST (left: tensile strength, right: failure strain)**

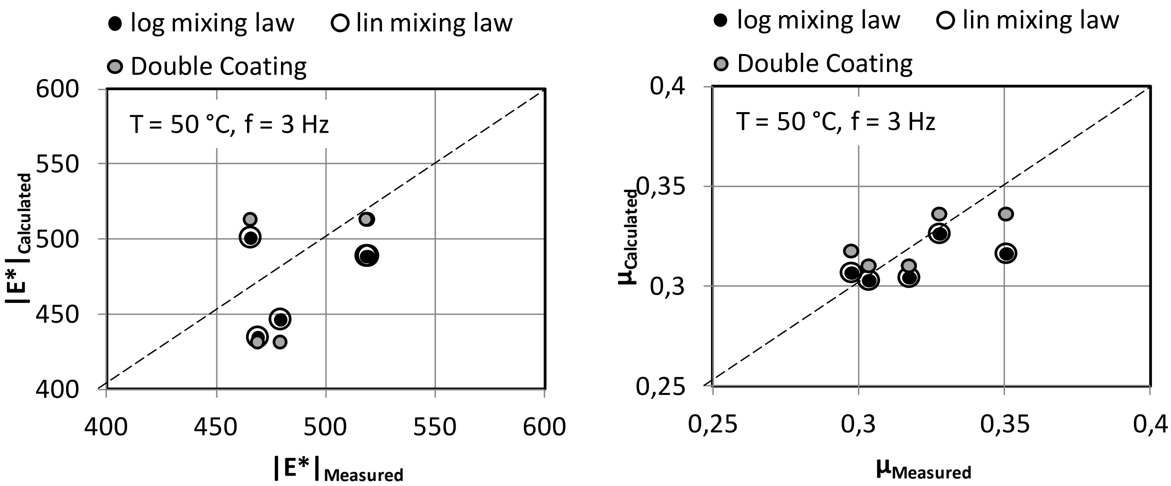



**Figure 4-31: Comparison of measured and calculated results for validating the mixing law equation for results of CTST (left: stiffness modulus, right: Poisson ratio)**

**Table 4-21: Coefficients of correlation R² for comparison of measured and calculated mix properties when mixing theory or double-coating theory is applied**

| Mix property | linear mixing law | logarithmic mixing law | double coating |
|---|---|---|---|
| | $R^2$ | $R^2$ | $R^2$ |
| $T_F$ | 0,07 | 0,07 | 0,16 |
| $\sigma_F$ | 0,10 | 0,10 | 0,12 |
| $\beta_t$ | 0,89 | 0,89 | 0,78 |
| $\varepsilon_F$ | 0,87 | 0,87 | 0,85 |
| $\lvert E^*\rvert_{CTST}$ | 0,18 | 0,18 | 0,44 |
| $\mu_{CTST}$ | 0,40 | 0,40 | 0,19 |

# 5 Proposal of design methodology

The effect of RA and multiple recycling on the asphalt mix performance will depend on the type of mixture, the characteristics of RA and virgin materials, the mix formula, the type of asphalt plant and the mixing procedure. A proposal for a general design methodology is presented in this section. This methodology describes the different steps to be followed for designing mixtures, while evaluating their long term performance and maximizing the amount of recycling. The methodology is in many aspects identical to the methodology for mix design with only new materials, so the following description is focussed on the particularities for mixtures with RA containing PmB.

## 5.1 Step 1: Characterization of the constituents

Besides the characterization of the virgin materials, the RA needs to be characterized. It is important to emphasize that the methodology depends on the results of this step, which implies that the characterization has to be made with samples from a homogeneous stockpile of RA, the same stockpile that will be used for the production at the plant. If the homogeneity of the stockpile cannot be assured, the heterogeneity of RA properties has to be considered by reducing the percentage of RA in the mix (see also Ipavec et al. 2012).

The following characteristics are essential for the mix design:

*Grading of the RA aggregates (after extraction of the binder)*

The grading of the dry aggregates of the RA has an impact on the grading of the resulting mix. When a very high percentage of RA is used, the impact is so large that it is recommended to use RA from a similar mix as the new mix.

*Binder content of RA*

The binder content of the RA has to be known exactly in order to determine the amount of new binder needed. This methodology assumes that the old binder is entirely reactivated, an assumption that could be questioned when the old binder is extremely aged and therefore hard to mix with the new binder ("double coating effect").

*RA binder characteristics*

The characteristics of the recovered binder are important for the selection of the new binder. In some cases, the RA could be refused on the basis of the characteristics of the recovered binder, depending on specifications existing in some countries (see for example Figure 2-1). When the old binder is not polymer modified, PEN and R&B softening point are sufficient characteristics for the mix design. For a PmB, the complex modulus G* is more interesting from a rheological point of view.

## 5.2 Step 2: Selection of new materials

As the binder in the mix will be a mixture of old and new binder, the binder properties shall be optimized by selecting an appropriate new binder, compatible with the old binder. For the verification of the compatibility of the binders, one is referred to deliverable D2.3.

In general, the new binder will be softer to compensate the harder aged binder. The logarithmic law of mixtures for PEN provides a simple rule to select the grade of the new binder.

When recycling RA with PmB, the new binder shall also be a PmB. If not, the effect of polymer modification will be lost and the RA is not used for its full potential. On the other hand, using a new PmB binder for a mix with RA without PmB also makes no sense, since the polymer will be diluted and have less or no effect in the binder mixture. It may be however be possible to use binders containing higher contents of polymers to compensate this dilution effect.

## 5.3 Step 3: Theoretical mix design

This step determines the mix formula using only calculations. Therefore, an optimisation tool is required which calculates the needed amounts of virgin aggregates and binder according to the grading of RA as well as the grading of the various aggregates used for mixing.

Commercial software solutions are available, e. g. BRRC’s software PradoWin: Programs for Road Asphalt Design and Optimization. This software allows to calculate and optimize the resulting grading, the volumetric composition and void content of the mix and the quantity of new binder to be added. PEN and R&B softening point of the resulting binder mix are predicted using simple mixture laws (logarithmic law for PEN and linear law for R&B softening point).

When designing a mixture with RA, the target volumetric composition shall be the same as for a mix with only new materials. This imposes a limit on the percentage of RA that can be used. When the grading curve of the RA is close to the target grading of the mixture, the percentage of RA can be very high. This is the main argument for a more selective milling of surface courses and a separation into stockpiles according to the type of mixture.

## 5.4 Step 4: Performance testing

In this step, the mix design is further optimized on the basis of performance test results. The advantage of using laboratory mixtures instead of plant produced mixtures is the smaller scale, which allows more flexibility to optimize the composition. For performance testing it is recommended to measure following mix properties:

- resistance against deformation (EN 12697-25 or -22)
- water sensitivity (EN 12697-12)
- stiffness (EN 12697-26)
- resistance against low temperature cracking (EN 12697-46)

The laboratory mixing study described in the previous sections has shown that, for the SMA mix with 15 % of RA containing PmB, the performance test results are not significantly dependent on the laboratory, the type of mixer or the exact mixing times.

The European norm for laboratory mixing EN 12697-35 is thus sufficiently precise. It is recommended to mix long enough to avoid effects like double coating, but not longer than the maximum times given in the norm in order to limit aggregate grinding and excessive ageing.

Initial type testing consists of testing the final mix design in order to determine the performance categories to which the mix belongs. This is usually done at this stage with the laboratory mix.

### *5.5 Step 5: Determination of plant mix formula*

As for a mix without RA, the mix formula at the plant shall be tuned to obtain a mix with the same grading as the mix used for initial type testing.

For a mix with only virgin materials, this is sufficient to ensure the same performance as demonstrated by initial type testing. For a mix with RA, especially with PmB, the uncertainty is higher because of the question of binder mixing, which may be different in the plant than in the laboratory. Therefore, it is recommended to do additional performance tests on the plant mix and to validate the results obtained in step 4 on the laboratory mix. A test for permanent deformation is recommended, since it is expected that an adverse effect like double coating has a negative impact on the resistance to permanent deformation. Indications for that phenomenon were seen for example in the multiple recycling study.

# 6 Conclusions

Two extensive experimental programs were set up to investigate mix design and performance of asphalt mixes with RA containing PmB.

The laboratory mixing study was made to investigate the effect of the laboratory mixing procedure on the performance characteristics of asphalt with RA and PmB.

This is a very important question, since mix design is usually based on, or validated by an initial type testing study. As discussed in the state of the art, this study is in most cases done with laboratory prepared mixes and performance based. Therefore, we need to be sure that the laboratory mixing procedure leads to a mix with the same performance characteristics as the plant mix.

The experimental program considered 10 different laboratory mixing procedures in 5 different laboratories. The performance testing consisted of compactability, stiffness, water sensitivity and permanent deformation. A mix type SMA 8 with 15 % of RA containing PmB from a German asphalt plant was used as test case.

The main conclusions of this study are the following:

- Considering the 10 different laboratory mixing procedures, the mixing times are not as critical as expected since they don't have a significant impact on the test results. There was however a weak trend observed that the longer mixing times lead to higher densities caused by increased compactibility. Several possible explanations were given: a better coating of the aggregates and/or more grinding of the aggregates. This latter explanation could play a particular role in this mix because of the steel slag which contains internal pores that may become accessible when the stones are subjected to grinding. The visual techniques (X-ray CT scans and Optical Image Analysis) also gave some qualitative indications that the longer mixing times slightly improve the homogeneity of the mixes (this was seen in the distribution of the steel slag aggregate) and improve the aggregate coating.

- The differences between the 5 laboratories were larger than the variations due to mixing times. This was expected, since the laboratories used different types of mixers and different gyratory compactors to compact the specimens. These differences should be accounted for when imposing specifications on the test results.
- For the SMA 8 mix considered in the experimental program, there was no significant difference seen between the average results of the laboratory prepared mixtures on one hand and the plant mix on the other hand in any of the performance tests. This shows that it is valid to do an initial type testing study with laboratory prepared mixes, when the correct procedure for laboratory mixing is followed.

The multiple recycling study was made to investigate the effect of recycling a mixture containing PmB more than once on the performance of the resulting mixtures. Other important issues like compatibility of the new PmB with the old PmB and the validity of mixing laws for predicting the properties of a mixture with up to 50 % RA were also addressed in this study. These are very important and urgent questions to be solved, since we have come to a point where high quantities of RA that become available nowadays for recycling are coming from the rehabilitation of surface layers, mostly containing PmB and often already containing RA.

The experimental program considered up to 3 recycling cycles and 3 different PmB with different properties. The performance testing consisted of compactability, stiffness, permanent deformation and low temperature cracking measurements.

The main conclusions of this study are:

- The multiple recycling of 50 % RA in new asphalt mixes in 3 recycling cycles with optimal laboratory conditions results in asphalt performance comparable to the properties of SMA mixes containing 100 % virgin material. This conclusion is valid for the laboratory conditions applied, where the influence of different grading in RA and new mix was not considered and “pure” simulated RA without any other materials (e. g. other layers, rehabilitation patches) was added to the new mixes. In terms of binder reactivation the laboratory ageing simulating long-term site ageing won’t affect the recyclability of surface course SMA if virgin binder of reduced viscosity is added to the mixes.
- Between the binders analysed, no sign of incompatibility between aged and fresh polymer modified binders could be observed. This conclusion can be drawn for the analysed combinations of binders (chemically and physically linked SBS-modified binders).
- The mixing law as applied during mix design may be also valid for some asphalt mix properties. Though, most performance test results show only little differences between the analysed mix variations in this study. Only for the uniaxial tensile stress tests (UTST) the tests on the mixes resulted in a wide range of test results.

For these results, the logarithmic and linear mixing law results in a good agreement between calculated and measured properties. For the other test results the properties between the analysed mixes didn't vary considerably, which doesn't allow the interpretation of validity of mixing law.

The experience gained while carrying out these experimental programs leads to the following recommendations for an advanced mix design procedure:

- The RA shall be correctly characterized and these characteristics shall be used to design the new mixtures. This becomes more and more important, because of the high quality of the materials used in surface layers. Instead of "down-cycling" this material, their good characteristics shall be used in an optimal way and this starts by knowing and controlling these characteristics. This also implies that measures shall be taken to ensure that the RA used in the plant is from the same stockpile as the RA used for the initial type testing.
- Knowing and controlling the grading of the RA, it is possible to determine correctly the grading of the new mixture and consequently also the volumetric composition of the mix. This is very important because of the impact of the volumetric composition on the performance characteristics. Throughout the experimental work done in this task 2.2 of WP2, the various mixtures with RA were designed in such a way that the grading was the same and the performance tests made on the various mixes showed the success of this approach.
- No problems of incompatibility were encountered in the multiple recycling study. When using binders of a very different nature, binder compatibility shall be investigated more thoroughly.
- Performance testing is necessary to validate the mix design. Preparing the test specimens with laboratory mixed material was acceptable for the mix studied in the lab mixing study. The validity of predicting the asphalt performance using mixing laws was less convincing as shown in the multiple recycling study. It may be acceptable as a first estimation, but performance testing on the final mix remains necessary.

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# List of abbreviations

| | |
|---|---|
| AC | Asphalt concrete |
| BRRC | Belgian Road Research Centre |
| CTST | Cyclic Triaxial Stress Test |
| DRI | Danish Road Institute |
| HMA | Hot mix asphalt |
| IFSTTAR | Institut français des sciences et technologies des transports, de l' aménagement et des réseaux |
| ISBS | Institut für Straßenwesen der TU Braunschweig |
| ITS | Indirect Tensile Strength |
| LVDT | Linear variable differential transformer |
| MR | Multiple recycling |
| PmB | Polymer modified binder |
| RA | Reclaimed asphalt |
| SMA | Stone mastic asphalt |
| TSRST | Thermal Stress Restrained Specimen Test |
| UNott | University of Nottingham |
| UTST | Uniaxial Tensile Stress Test |

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**THE RE-ROAD PROJECT** aims to develop knowledge and innovative technologies for enhanced end of life strategies for asphalt road infrastructures. Such a strategy has an important impact on the energy efficiency and the environmental footprint of the European transport system and fits within the life-cycle thinking which is being introduced in waste policy at European level. It leads to reduction of the need for new raw materials, prevents the creation of waste and the occupation of landfills and consequently minimizes the need to transport these materials to and from the work site and hence reducing energy, pollution including $CO_2$-emissions.

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A FP7 Collaborative Project
WORK PROGRAMME Sustainable Surface Transport
SST.2007.1.2.2 End of life strategies for vehicles/vessels and infrastructures

**WORK PACKAGES**

WP 1 Sampling and Characterization of RA
*Virginie Mouillet*

WP 2 Impact of RA quality and characteristics on mix design and performance of asphalt containing RA
*Konrad Mollenhauer*

WP 3 Environmental performance of RA
*Anja Enell*

WP 4 RA processing and RA management at the mixing plant
*Erik Nielsen*

WP 5 Performance modelling of RA
*Sabine Werkmeister*

*RA = Reclaimed asphalt*