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AllBack2Pave

High-content RA asphalt mixture design

Deliverable No D2.1
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Recycling: Road construction in a post-fossil fuel society

ALLBACK2PAVE

Toward a sustainable 100% recycling of reclaimed asphalt in road pavements

Deliverable No D2.1
High-content RA warm asphalt mixture design

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List of abbreviations

AADT	Average Annual Daily Traffic
AC	Asphalt Concrete
ANAS	Azienda Nazionale Autonoma delle Strade
BBR	Bending Beam Rheometer
BK	Load category (**B**elastungs**k**lasse)
BS	British Standard
BTDC	Bitumen Test Data Chart
DCM	Dichloromethane
DP	Dust Proportion
DSR	Dynamic Shear Rheometer
EU	European Union
ESA	Equivalent Standard Axle
$G_{mm,RA}$	Theoretical maximum specific gravity of RA
HMA	Hot Mix Asphalt
HVR	High Volume Road
ITS	Indirect Tensile Strength
ITS_d	Indirect Tensile Strength (dry condition)
ITS_w	Indirect Tensile Strength (wet condition)
ITSR	Indirect Tensile Strength Ratio
MA	Mastic Asphalt
NCHRP	National Cooperative Highway Research Program
OMV	Austrian bitumen producer (**Ö**sterreichische **M**ineralöl**v**erwaltung)

PA	Porous Asphalt
PmB	Polymer Modified Bitumen
P_b	Binder content
$P_{b,RA}$	Binder content of RA
PSV	Polished Stone Value
RA	Reclaimed Asphalt
RAag	RA aggregate
RAb	RA binder
RejA	Rejuvenator A
RejB	Rejuvenator B
R&B	Ring and Ball
r.m.s.	root mean square
RTFO	Rotating Thin Film Oven Test
RVB	Replaced Virgin Binder
SHRP	Strategic Highway Research Program
SMA	Stone Mastic Asphalt
SP	Softening Point
SUPERPAVE	Superior PERforming Asphalt PAVEment
Tc	Critical Temperature
TUD	Technische Universität Dresden
UNIPA	University of Palermo
UNOTT	University of Nottingham
USA	United States of America
V_a	Void content

VB	Virgin binder
VFA	Void Filled with Asphalt
VMA	Voids in the Mineral Aggregate
WMA	Warm Mix Asphalt
WMAadd	Warm Mix additive

1 Introduction

Given today's societal concerns with environmental protection and sustainable development in a post-fossil fuel era, road authorities in Europe are working together to make the dismantling and end-of-life strategies of asphalt pavements more energy efficient. In this context, the amount of recycling of reclaimed asphalt (RA) in new asphalt pavements has grown to the point that it is no longer a simple green construction alternative but a common practice in almost all of Europe. In recent years, due to the rising cost of asphalt binder, new efforts have been made to increase the amount of RA used in asphalt pavements. Several interdisciplinary research projects related to the usage of hot mix asphalts with RA have been carried-out in Europe during the last decades (Direct-MAT, 2011), (Re-Road, 2012). The outcome of these projects showed that the durability of mixes with RA proved to be satisfactory. However, in general, the share of recycling of RA in new asphalt courses remains rather lower than it could be technically.

Highway authorities together with the asphalt paving industry worked together to develop new methods and design approaches to increase the share of recycling in pavement construction and rehabilitation. Economic and environmental benefits are the driving forces behind research in asphalt pavement recycling. Economics benefits are mainly associated with the reduction of use of virgin materials (aggregates and binder). The environmental profit include reduced emission and energy consumption in the production and transportation of virgin materials as well as reduced demand of non-removable resources.

Despite of the above mentioned benefits, the amount of RA used in surface layers in Europe is very limited. There is a common concern that the high quality material requirements for wearing courses are not met if the major volumetric component of the mix comes from a recycled material. The background of this fear is the inherit heterogeneity of the RA, which properties depend in great extent on factors such as the technique used to reclaim the asphalt, the maintenance history of the road, the storage conditions, etc., which are not considered in standard mix design procedures.

The production of asphalt mixtures for road pavements is now an entirely automatic process that implies an adequate mix design procedure carried out in laboratory.

Whatever technique is used, the mix design process is the crucial moment in order to produce the asphalt mixture having the required performance characteristics within the road pavement. Generally these performances can be identified as: workability and susceptibility to compaction during the mixing and the laying; fatigue resistance and resistance to rutting during the service in life.

Possibly the mix design process is even more crucial when we have to design asphalt mixes with relevant percentage of the Reclaimed Asphalt (RA) because of the variability of such materials. This fact involves preliminary stage analysis of the RA to determine its properties in terms of aggregates and binder (type and content). Therefore you can identify the typical parameters of the asphalt mixtures (gradation, type and content of the whole binder and air voids content).

This report summarises the first results of a research on the feasibility of going toward 100% recycling of asphalt pavements into wearing courses through an increasing percentage of RA within the mixes. The research is carried out within a two-year CEDR Transnational Road Research project, AllBack2Pave, led by the Technische Universität Dresden (Germany), together with the University of Nottingham (UK) and the University of Palermo (Italy).

To facilitate the deployment of lean concepts and lean production practices, the investigation is implemented in close collaboration with the private sector, including asphalt mixing plants, chemical additives producers and waste material managers.

The main objectives of the project are - to establish, through laboratory tests on binders and asphalt mixes, whether the use of high rates of RA is feasible in mixes with high level of durability, and - to develop an "AllBack2Pave end-user manual" on how to best produce cost-effective and high-quality asphalt mixes with high RA content. This will be complemented by a sustainability assessment of the practice of using asphalt surface mixes with high recycling rates based on chosen European case studies to identify the most cost-effective solutions, together with their environmental impact over the whole lifecycle of selected road pavements.

The mixes selected for the investigations are typical asphalt mixes for wearing courses of road pavements used in Germany (stone mastic asphalt - SMA - with polymer modified bitumen) and in Italy (asphalt concrete - AC - with paving bitumen). The percentage of RA within each mixture vary from 0% (control mix) to the closest feasible amount to 100% RA. The comparison between the mechanical characterisation results of the control mix and the mixes with increasing content of RA, will identify the most sensitive factors - either good or bad - that affect the mixture performance.

The objective of this report (output of work package 2: Mixture design) is to develop a lab mix design procedure with focused attention on better handling high shares of RA. The mix design procedure shall account for the effect of the variability of RA properties in the performance of the mix.

The report consists of three parts: start point, methodology and drawing up to describe the experience gained in the three laboratories in Germany, Italy and United Kingdom in order to define mix designs with different RA content up to the entirety of the used material. In addition, the use of rejuvenators and warm mix additives was investigated to understand whether these components are necessary to increase the RA content in asphalt mixes, but also to eventually highlight their limitations.

The innovative idea of the research is – in contrast to usual practice - the use of this kind of mixtures in wearing courses that are directly affected by thermic and traffic conditions. The mix designs of the selected bituminous mixtures, required by Italian and German specifications, have been independently carried out in the two laboratories of the universities in Dresden (Germany) and Palermo (Italy) with the support of the laboratory of the University of Nottingham in terms of binder blend designs.

2 Asphalt mixes

2.1 Italian asphalt mixes

The mix design was carried out for a typical Italian asphalt mixture for wearing courses, with a nominal grain size of 20 mm and a not-modified binder (bitumen with penetration grade 50/70). This type represents a common asphalt mixture used over the entire Italian road network.

Generally, it allows good performance in terms of durability (technical life equal to design life) and ride quality (in terms of cost).

As regard the asphalt components, the distribution of aggregates is dense graded; the used aggregates are a basaltic and limestone combination; the binder is a bitumen with a low penetration grade and following not much susceptible to low temperatures.

With the aim of analysing the impact of RA on the performance of asphalt mixtures, four mixes with different amounts of RA were designed: one control mix without RA and three mixes with an increasing amount of RA, namely RA0, RA30, RA60 and RA90. In addition, the effect of using a rejuvenator pre-blended with a warm mix additive was also investigated (Table 1). These mixes will be referred in this report as Italian mixes.

It is useful to emphasise that in Italy the use of RA is generally limited to asphalt mixtures used for base courses with a maximum amount of RA of 30% of the whole mass.

In Italy, actually, hot asphalt mixes with RA are designed based on experiences (best practices). Following, the mix design process was performed using an experimental approach according to the volumetric approach of the SUPERPAVE method.

Table 1: Description of investigated Italian asphalt mixes

Mix	Description	Binder type	% RA*	WMA
RA0	ANAS wearing course asphalt mix Type A grading band (h = 4÷6 cm)	Conventional bitumen (Pen 50/70) without renewing agents	0	No
RA30	ANAS wearing course asphalt mix Type A grading band (h = 4÷6 cm)	Conventional bitumen (Pen 50/70) with renewing agents	30	Yes
RA60	ANAS wearing course asphalt mix Type A grading band (h = 4÷6 cm)	Conventional bitumen (Pen 50/70) with renewing agents	60	Yes
RA90	ANAS wearing course asphalt mix Type A grading band (h = 4÷6 cm)	Conventional bitumen (Pen 50/70) with renewing agents	90	Yes

* By mass of the total mixture

2.2 German asphalt mixes

The mix design was performed on a common asphalt mixture used in wearing courses of high volume roads of Germany. The material is a SMA with a nominal grain size of 8 mm (SMA 8S), and a polymer-modified bitumen (PmB 25/55-55).

The use of SMA in surface layers of heavy traffic roads is a common practice not only in Germany but also in all around Europe. The SMA as a surfacing material is widely used because of its rutting resistance. SMA is characterised by a strong coarse aggregate skeleton that gives good resistance to permanent deformation and a high bitumen content (>6%) that provides enhanced resistance to fatigue. Polymer modified binders (PmB) are usually used in SMA to give greater deformation resistance and enhanced durability. The advantages in terms of longer life and improved performance make the SMA a cost effective alternative even its initial cost is around 20% higher than the costs for conventional asphalt concrete mixes.

In order to identify the effect of the RA in the performance of the mix, three variants of the SMA 8S were designed with increasing percentage of RA: one control mix without RA, one mix with high percentage of RA (30%) and one experimental mix with very high percentage of RA (60%). In addition, the effect of using a rejuvenator pre-blended with a warm mix additive (WMA) was also investigated. The description of the mixes is summarised in Table 2. These mixes will be referred in this report as German mixes.

Table 2: Description of investigated German asphalt mixes

Mix	Description	Binder type	% RA*	WMA
D-1	SMA with max. grain size of 8 mm (SMA 8)	PmB without rejuvenator	0	No
D-2	SMA with max. grain size of 8 mm (SMA 8)	PmB without rejuvenator	30	No
D-3	SMA with max. grain size of 8 mm (SMA 8)	PmB without rejuvenator	60	No
D-4	SMA with max. grain size of 8 mm (SMA 8)	PmB with rejuvenator	60	Yes

* By mass of the total mixture

All German mixes, except the control mix, contain RA with polymer modified bitumen. Although this is a common practice, the EU standards EN 13108-4 have the following restriction in the amount of RA in mixtures with Pmb:

> *"when using reclaimed asphalt from mixtures in which a modified bitumen and/or a modifier additive has been used, and/or the mixture itself contains a modified bitumen and/or a modifier additive, the amount of reclaimed asphalt shall not exceed, (unless otherwise agreed between client and manufacturer), 10% of the surface courses by mass of the total mixture and 20% for the others".*

It means that an agreement is needed between road authorities and road manufacturers in order to produce mixes such as the ones described herein.

The German mixes were designed and produced according to the German technical guidelines for hot asphalt mixes with RA. There are three regulatory documents containing specifications at national level regarding the use of RA in Germany. The first, Technical Delivery Specification TL-Asphalt StB 07 (TL Asphalt-StB 07, 2013), is a document that contains general technical specifications for asphalt. It allows the use of RA in all types of asphalt mixes with the exception of porous asphalt. It also regulates the mix composition and the quality requirements for each type of mix. TL Asphalt-StB 07 is a general specification harmonised with the European norms. The second document Additional Technical Terms of Contract and Guidelines (ZTV Asphalt-StB 07, 2007), is a contractual specification. In this document, the use of RA is excluded also from SMA mixes unless the bidder specifies otherwise. ZTV Asphalt-StB 07 deals with contractual issues applicable in Germany and addresses the local concerns regarding the use of RA in SMA. Finally, the third document (TL AG-StB 09, 2009) regulates specifications concerning the quality of RA itself.

3 Sampling and collection of mix constituents

The heterogeneity of reclaimed asphalt due to the type of the source (i.e. type of pavement and dismantled layer, utilised milling machine and so on) is against the need of the mix designer who has to reach technical goals on the basis of regulatory framework. Although it cannot be erased every kind of uncertainty, an appropriate characterisation of the RA, can reduce the potential of errors to a minimum.

In this part of the report the authors describe the process of the RA characterisation in accordance with a shared experimental protocol and the preliminary sampling of the RA in plant.

3.1 Italian procedure

The considered procedure is “sampling from stockpile”. Among different types of sampling this one has been selected because the storage in stockpiles is the most common routine in plant. Sampling for at least one set of tests per 500 tons of RA is considered to be the best practice, in accordance with the EN 13108-8.

Under the assumption of reaching a high level of the RA homogeneity within the stockpile, EN 932-1 was followed for sampling.

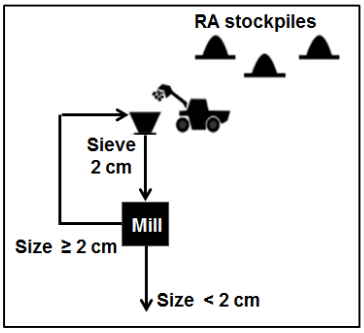

Figure 1: Milling of RA from stockpiles

Finally, the following sampling procedure has been established:

- use a front end loader to dig into to the ready to use RA stockpile;
- through a mill (Figure 1) reduce the RA extracted from stockpile at a certain maximum dimension;
- discharge RA on a clean surface to form miniature sampling stockpile;
- use the loader to back blade across the top of the mini stockpile to create a flat surface;
- mini stockpile ready to be sampled;
- use a square-end shovel to obtain samples from the surface of the mini stockpile;
- sample from three locations over the surface of the mini stockpile;
- combine samples taken from the same mini stockpile until reaching about 30 kg. This sample will later be divided into test portions;
- repeat this process to obtain samples at other locations around the RA stockpile;
- do not combine samples from different locations.

3.2 German procedure

The constituent materials were sampled from the mixing plant where the industrially produced mixes were prepared.

For mixes with high percentage of RA it is necessary to ensure that the binder of the RA is fully melted for blending with the newly added binder. It is known that blending is a function of mixing time, however, for mixes with high amount of RA (>30%) increasing the mixing time is not sufficient to ensure proper commingling between virgin and RA binder. Therefore, mixing plants with special equipment such as batch plants with parallel drums, twin dryer drums or double barrel drums are a prerequisite in order to produce asphalt mixes with high shares of RA without impairing the material quality or exceeding the legal limits of emissions.

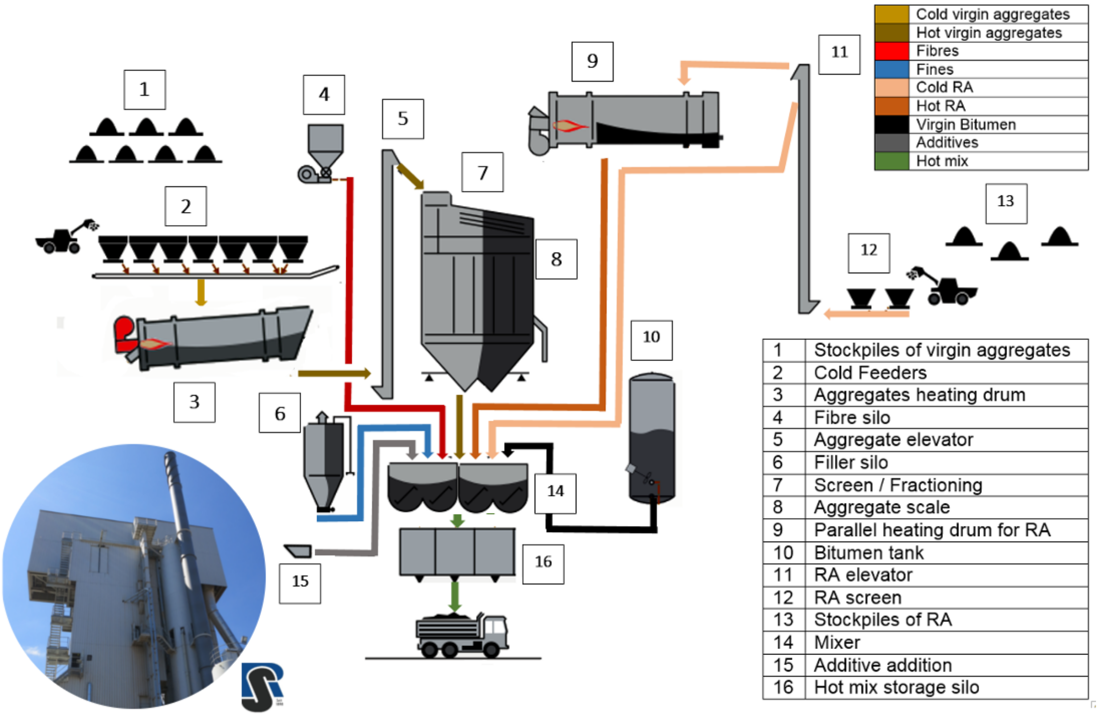

Figure 2: Scheme of German mixing plant

The plant used to produce the German mixes is located in Gilching, near Munich (Germany). It is a batch type plant with a parallel drum (item 9 in Figure 2) to preheat the RA. As said before, without the parallel drum the maximum RA that can be used in batch plants finds its limits at approx. 30% due to the very high temperature needed to transfer heat from the virgin aggregates to the RA. Even if temperature and the associated emissions are not a problem, there are issues with excessive ageing of the binder from the RA due to contact with superheated aggregate particles.

From the feedstock of the mixing plant, the raw materials were sampled for further characterisation at the laboratories of the universities of Dresden and Nottingham. A description of the mix constituents and sampling quantities is given in Table 2.

Table 3: Constituents of German mixes

	Material	*Source / Producer*	*Sampling*
Coarse Aggregates	Crushed stone 8/11	Quarry in Gilching	2 buckets of 15kg each for each aggregate.
	Crushed stone 8/11	Quarry in Treidling	
	Crushed stone 5.6/8	Quarry in Gilching	
	Crushed stone 5.6/8	Quarry in Treidling	
	Crushed stone 2/5.6	Quarry in Gilching	
	Crushed stone 2/5.6	Quarry in Treidling	
Sand	Sand 0/2	Quarry in Gilching	2 buckets of 15 kg each
Fines	FrendFuller	Quarry in Lauterhofen	1 bucket of 15 kg
Fibres	Fibres	Viatop premium	1 bucket of 5 kg
Virgin Bitumen	Bitumen (PmB 25/55-55)	OMV	1 bucket of 15 kg
Additives	Blend of rejuvenator and WMA	Storimpex	1 sample of 5 kg was obtained from the producer
RA	Reclaimed asphalt SMA 11S	Rehabilitation of A8 highway near Munich	10 buckets of 15 kg each. The buckets were filled with RA from 5 random locations of the stockpile

It was ensured that the materials used in the laboratory design were the same as those that were used in the industrial production. Special care was taken to avoid using bitumen of different producers and sources. The authors experience indicates that PmB of the same type but from different manufacturers may show significant performance variations.

The RA was stockpiled in open-air piles without fractionation. This may lead to an accelerated binder ageing due to air exposure and oxidation. Furthermore, exposure to the environmental conditions will increase the moisture content in the RA resulting in high heat consumption and low thermal efficiency during mixing. The material records at the mixing plant showed that the RA was made up of a bituminous surface originally designed as a SMA with a nominal grain size of 11mm (SMA 11S) and a Polymer modified bitumen (PmB 25/55-55). The original mix design formulas and maintenance history of the RA were not available.

The RA was milled from the surface layer of a high volume road near Munich (highway A8), afterwards it was crushed and screened in the mixing plant to a nominal maximum aggregate size of 22 mm.

4 Laboratory characterisation of mix constituents

4.1 Italian mix constituents

The bituminous mix design process is addressed to a typical mix for wearing courses of motorway pavements in Italy. It was decided to use an AC with paving bitumen for the investigations.

4.1.1 Virgin aggregates

Following the design process (Figure 28) the evaluation of the material properties during the preliminary stage consists of two steps. The first, namely virgin aggregates characterisation, implies the choice of the grading band, the determination of the aggregates grading and the evaluation of all physical and mechanical parameters.

According to the ANAS (Azienda Nazionale Autonoma delle Strade - Italian road authority) grading band the grading limits shown in Figure 3 were used by the associated mixing plant Ferrara-Accardi.

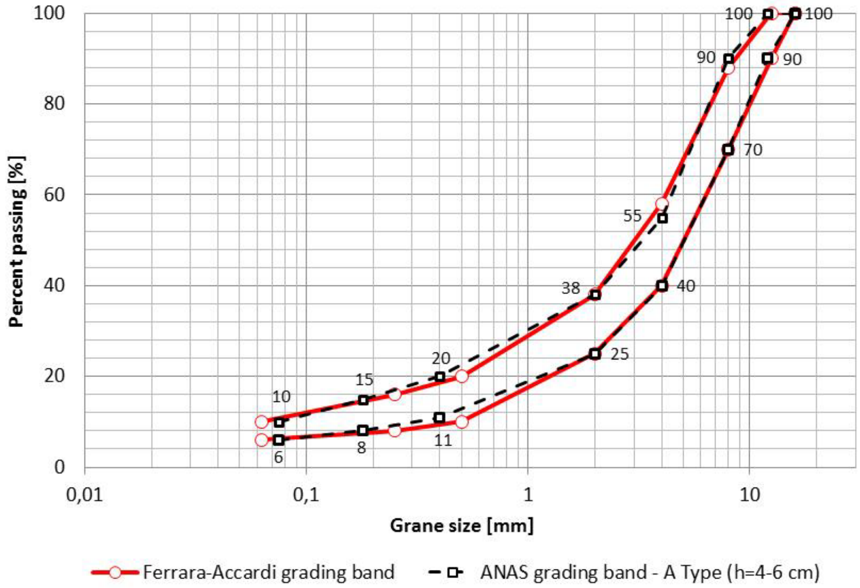

Figure 3: Minimum and maximum requirement of Italian regulation for grading limits for wearing course asphalt mixes

The grading of the designed asphalt mixture, also known as target grading, defined as RA0, is within the ANAS grading limits and commonly used in the pavements of the Sicilian highway network (Figure 4).

In Figure 5 to Figure 7 the grading curves of the asphalt mixes with RA are compared to the target grading. It can be seen that the RA30 and RA60 grading curve have exactly been reproduced while the RA90 grading curve is slightly different, but it keeps within the ANAS grading band. This difference is arisen because of the very high amount of RA together with the notable difference between the RAag grading curve (white condition) and the target grading curve.

The aggregates supplied by Ferrara-Accardi plant are composed of 3 fraction classes based on the “minimum-maximum sieve sizes” (F1_10-15; F2_4-8; F3_0-4 [mm]) and the filler. The F1 and F3 class are composed half from basaltic aggregates and half from volcanic ones. The F2 class is composed by only volcanic aggregates.

The outcomes of the sampling from over 6 different sources are reported in Table 4. The last column of Table 4 reports the value of the selected aggregate mix that represents the designed RA0 grading.

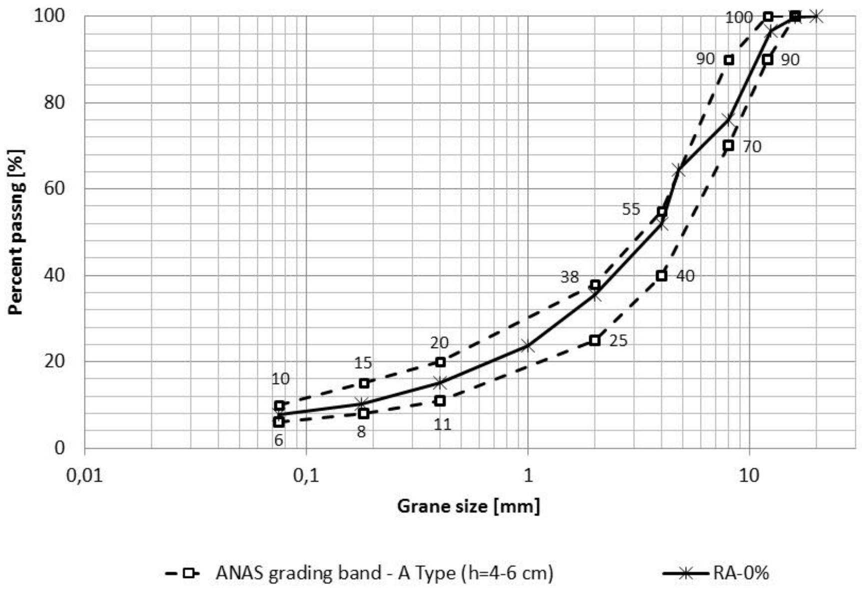

Figure 4: Minimum and maximum requirement of Italian regulation for grading limits for wearing course asphalt mixes and designed grading curve for Italian asphalt mixture with 0% RA + Additive (mix RA0)

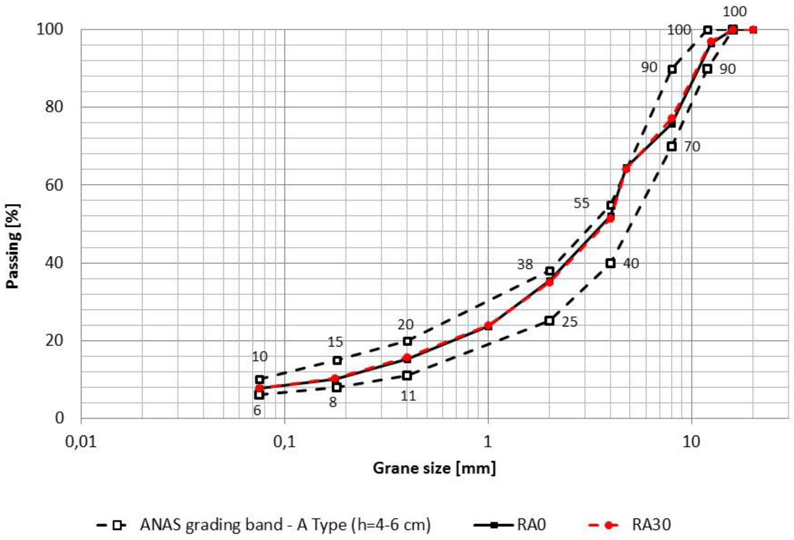

Figure 5: Minimum and maximum requirement of Italian regulation for grading limits for wearing course asphalt mixes and designed grading curve for Italian asphalt mixture with 30% RA + Additive (mix RA30)

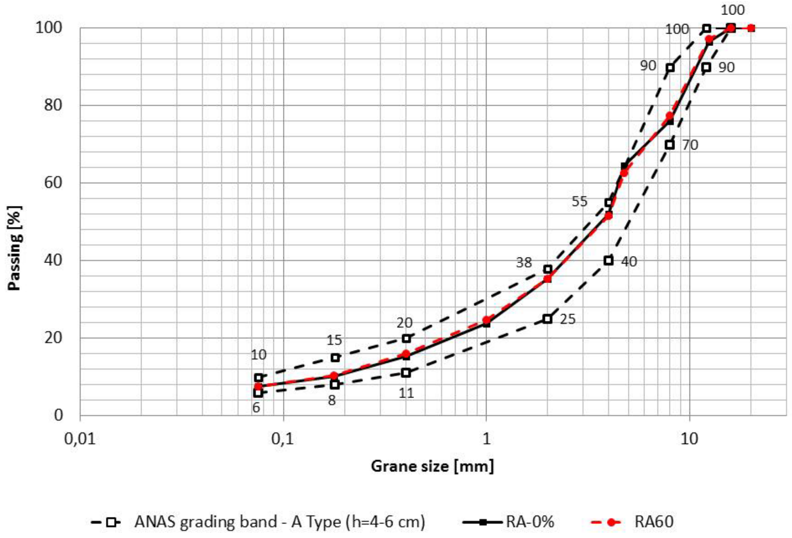

Figure 6: Minimum and maximum requirement of Italian regulation for grading limits for wearing course asphalt mixes and designed grading curve for Italian asphalt mixture with 60% RA + Additive (mix RA60)

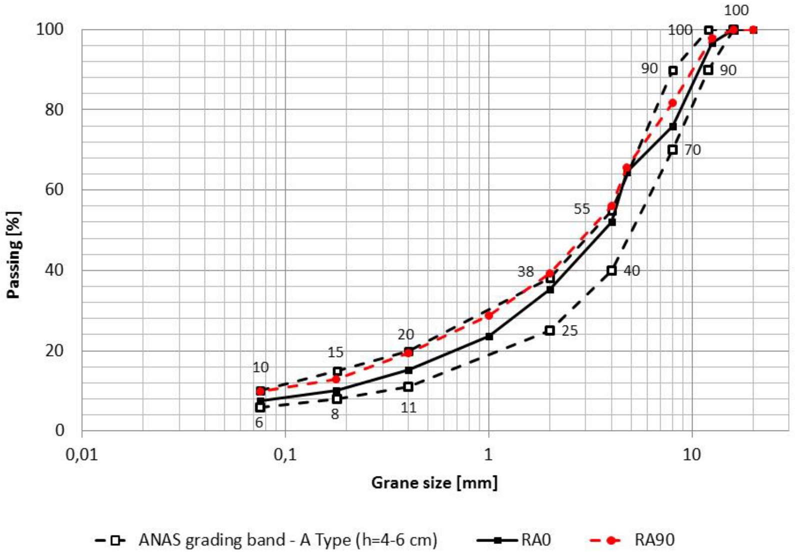

Figure 7: Minimum and maximum requirement of Italian regulation for grading limits for wearing course asphalt mixes and designed grading curve for Italian asphalt mixture with 90% RA + Additive (mix RA90)

Table 4: Grain size distribution for each granulometric class and target grading (average values)

Size [mm]	F1_10-15	F2_4-8	F3_0-4	Filler	Aggregate Mix
	Passing [%]	Passing [%]	Passing [%]	Passing [%]	Passing [%]
20	100.00	100.00	100.00	100.00	100.00
16	99.78	100.00	100.00	100.00	99.93
12.5	88.54	99.89	99.90	100.00	96.58
8	18.38	99.23	99.83	100.00	75.91
4.76	3.59	70.36	99.60	100.00	64.47
4	1.54	22.06	99.34	100.00	52.01
2	0.11	2.52	70.71	99.90	35.40
1	0.07	0.69	42.52	99.76	23.69
0.4	0.06	0.20	21.72	99.31	15.23
0.177	0.04	0.11	9.18	98.30	10.13
0.075	0.03	0.06	3.82	93.17	7.64

The granulometric classes and masses of each class are calculated through an analytical recursive process with the aim to obtain four identical grading curves. The results are reported in Table 5.

Table 5: Distribution of aggregate masses

Fraction	RA0 [%]	RA30 [%]	RA60 [%]	RA90 [%]
F1_10-15	29.21	23.36	18.93	9.43
F2_4-8	24.34	17.77	8.51	0.00
F3_0-4	39.91	25.04	11.58	0.00
Filler	6.54	3.64	0.60	0.00
RAag	0.00	30.19	60.38	90.57

In addition, the aggregate gradation control for the mix RA0 (0% RA + Additive), according to the SUPERPAVE method, was successful, as shown in Figure 8.

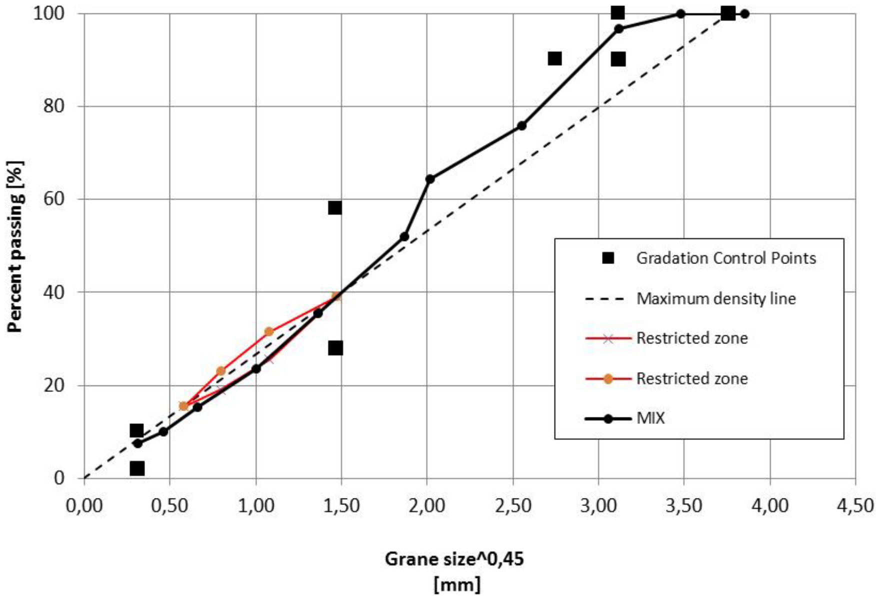

Figure 8: Aggregate Gradation Control for Italian asphalt mixture with 0% RA + Additive (mix RA0)

According to specific tests physical, geometrical and mechanical parameters of the aggregates are included in Table 6 and Table 7.

Table 6: Apparent specific gravity (Gsa), bulk specific gravity (Gsb) and effective specific gravity (Gsb) for mix aggregate

Physical parameters			
Classes	**G_{sa} [g/cm^3]**	**G_{sb} [g/cm^3]**	**G_{se}[g/cm^3] (*)**
F1_10-15	3.067	2.772	-
F2_4-8	3.013	2.790	-
F3_0-4	3.000	2.839	-
Filler	2.795	2.795	-
Mix Aggregates Target	3.008	2.805	2.968

(*) Estimated value

Table 7: Physical, geometrical and mechanical parameters for type of aggregate

Other parameters				
Parameter	**Fraction**	**Basaltic Aggregates**	**Volcanic Aggregates**	**Standard**
Sand equivalent test [%]	F3_0-4	89	81	EN 933-8
Coarse aggregate angularity [%]	F1_10-15	$C_{100/0}$	$C_{100/0}$	EN 933-5
	F2_4-8	$C_{100/0}$	$C_{100/0}$	
Resistance to fragmentation (LA) [%]	F1_10-15	16	25	EN 1097-2
	F2_4-8	16	25	
Polished Stone Value	F1_10-15	55	49	EN 1097-8
Resistance to wear (Micro Deval) [%]	F1_10-15	18.6	15	EN 1097-1

4.1.2 Virgin binder

The virgin binder, also supplied by Ferrara-Accardi, is a bitumen 50/70 with the characteristic properties reported in Table 8.

Table 8: Characteristic properties of bitumen 50/70

Type of Bitumen	Pene-tration [1/10 mm]	Softening Point [°C]	Fraass [°C]	Viscosity (135°C) [mPa s]	Viscosity (60°C) [mPa s]	Density [g/cm^3]
Virgin Binder (50/70, target)	68	47.6	< -8	303.0	205700	1.02

The viscosity at different temperatures has been measured by means of Brookfield viscometer (Figure 29).

4.1.3 Additives

A general definition of additives can be find in paragraph 4.2.4. A description of the performance of the used additive follows in chapter 5.

4.1.4 RA material

The RA material needs to be evaluated before the actual mix design. This is because with ageing and oxidation some changes may occur in the mix. For the binder, this includes hardening (increase in viscosity) and loss of ductility. For the aggregates, the gradation may change due to degradation caused by traffic loads and environmental conditions.

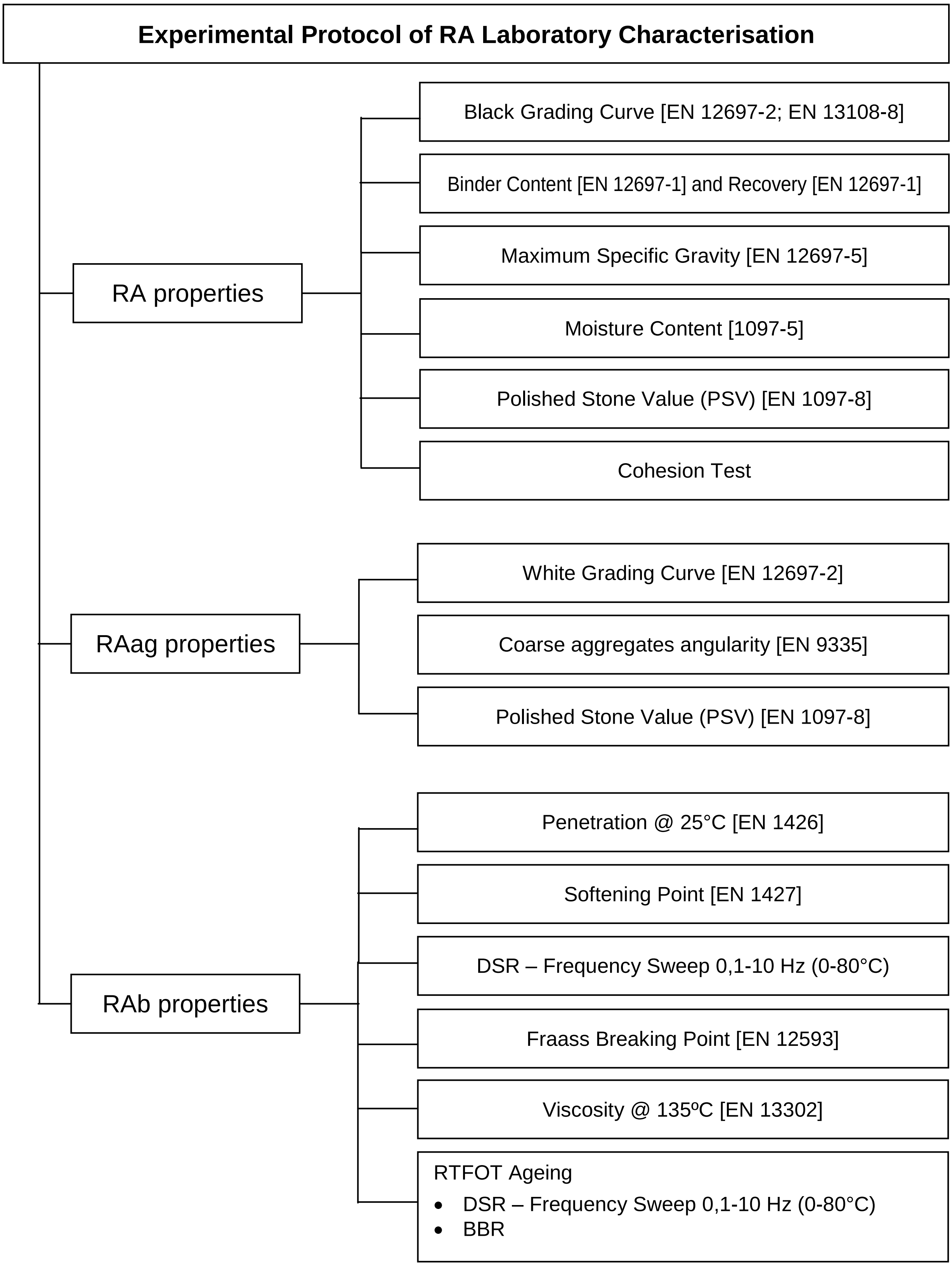

Figure 9: Structure of the experimental protocol for the RA laboratory characterisation

This part includes all relevant preliminary tests for the characterisation of the Italian RA. For the characterisation of the reclaimed asphalt an experimental protocol has been established. It has been defined with the aim to obtain the relevant properties of the RA by conducting only a small number of necessary tests. In Figure 9 the structure of the experimental protocol is shown.

The concept behind the protocol is to evaluate the properties of RA in terms of physical, geometrical and mechanical parameters. In addition every single component of RA, namely RA aggregate (RAag) and RA binder (RAb) after recovery, have been analysed according to specific tests.

Most of all tests have been selected in order to obtain all parameters involved in the mix design process; just a few tests such as PSV and Cohesion test have been carried out to assess respectively the friction parameter and the mechanical resistance because the RA material is previewed as part of bituminous mixtures for wearing courses.

This part contains all results from the test protocol referring to the RA material and its components supplied by the associated partner Ferrara-Accardi. The RA material comes from a milled pavement of an urban street.

4.1.4.1 RA aggregates properties

Black grading curve

Figure 10 shows the so called black curve representing the grading distribution of the RA before binder extraction. The result has been obtained by averageing 16 grading curves coming from the RA samples.

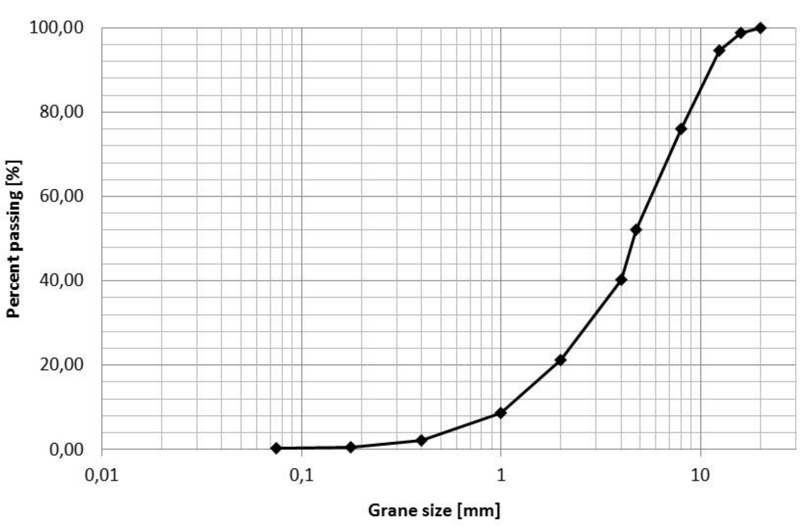

Figure 10: Average black curve of Italian RA

In Table 9 the mean value of each passing mass, the root mean square (r.m.s.) at each grain size and the coefficient of variation of each size are presented. It can be noticed that a quite significant dispersion regards the intermediate fraction.

Table 9: Grain size distribution of Italian RA aggregates

Size [mm]	Passing mean value [%]	r.m.s.	Coefficient of variation
20	100.00	0.00	0.00
16	98.87	1.21	0.01
12.5	94.50	2.96	0.03
8	75.97	9.31	0.12
4.76	52.16	13.30	0.25
4	40.25	13.17	0.33
2	21.18	8.52	0.40
1	8.70	3.54	0.41
0.4	2.20	0.82	0.37
0.177	0.50	0.28	0.55
0.075	0.22	0.20	0.90

Binder content and recovery

The binder content was obtained by the Soxhelete method in accordance with the standard EN 12697-1 over 16 samples.

The mean values of the binder content of RA, respectively for the course fraction and the fine fraction, are reported in Table 10. As expected, the percentage of the fine fraction is higher than the percentage of the course fraction.

Table 10: Average binder content for each granulometric class

Granulometric classes	**M.-%**	**$P_{b,RA}$ [%]**
RA Course aggregates (size ≥ 4.76 mm)	47.84	4.76
RA Fine aggregates (size <4.76 mm)	52.16	6.83
Average value of total grade		5.83

In order to recover the RAag, the binder has been extracted by the centrifuge extractor method [EN 12697-1].

RAb was first recovered and then together with the virgin binder subjected to conventional and rheological tests listed in Figure 9.

The binder recovery was carried out by the laboratory of the University of Nottingham through the standard method EN 12694-4:2005 - binder recovery: Fractionating column by using DCM as solvent.

In order to carry out the performance-related binder blend designs, binders were also subjected to the short-term ageing procedure RTFOT (BS EN 12607-1:2007) that simulates the ageing that the binder suffers during the manufacture process of the asphalt mixtures, as more fully described in chapter 6.

Maximum specific gravity

The theoretical maximum specific gravity $G_{mm,RA}$, equal to 2.659 g/cm^3 in average, has been measured by the pycnometer method with vacuum pump [EN 12697-5].

Moisture content

The moisture content is equal to 0.43% as mean value over 16 samples. This value is typical for a material milled and kept in storage in dry climate.

Polished Stone Value (PSV)

In accordance with the EN 1097-8:2009 the Polished Stone Value Test (PSV), has been applied both to the RA (black condition) and to the RAag, (white condition). The PSV is equal to 50% in average over 6 samples (Table 13).

Cohesion test

Recently, the Cohesion test (Testing and characterisation of sustainable innovative bituminous materials and systems TG-6- Cold Recycling-coded by RILEM Technical Committe 237-SIB) was considered as a representative possibility to analyse the mechanical resistance of RA mixtures.

The cohesion test consists of:

- Preparing RA material of aggregates with a maximum grain size of 20 mm, dried at 30°C for 24 hours;
- Manufacturing Marshall samples at three compaction temperatures (20°C, 70°C, 140°C) by 50 blows (Figure 11). The samples are tempered to the test temperature for 4 hours.
- After tempering at 25°C for 2 hours, conducting of ITS tests - dry and wet condition, according to UNI EN 12697-23 and UNI EN 12697-12.

Figure 11: Marshall samples compacted at 70°C (left) and 20°C (right)

An additional sample has been used to measure the air void content according to EN 12697-8. In addition, the air voids were measured at samples not determined for laboratory tests.

Table 11: Cohesion test values

	ITS 140°C [N/cm^2]	ITS 70°C [N/cm^2]	ITS 20°C [N/cm^2]
Dry	16.40	3.40	*
Wet	13.38	2.06	*
Air voids [%]	14.95	19.94	*
ITSR [%]	81.57	60.66	*

*at 20°C the compaction was unsuccessful

The results are given in Table 11. Here the ITSR value stay for the ratio between the results obtained under wet and dry condition.

White grading curve

In order to carry out an effective mix design process it is necessary to determine the grading curve of a RA after extraction (white curve). The grading of the final mixture strictly depends on the grading curve of the RA that is chosen (white or black curve). Using the white curve implies that the entire RAb merges with the virgin binder; otherwise if the black curve is selected, it means that RA is considered as a black stone (no merging with the virgin binder).

In theory, the preferred option would be to use an intermediate RAag grading because the two above mentioned curves represent extreme conditions.

Figure 12 shows the RA and RAag grading curves.

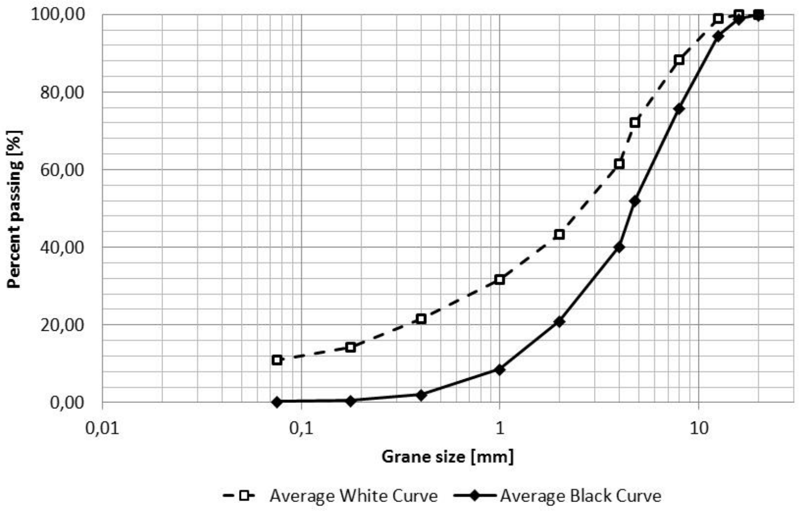

Figure 12: RA and RAag grading curves

Coarse aggregates angularity

The coarse aggregates angularity of the RAag has been determined in accordance to EN 933-5 over 6 sample. The mean values are given in Table 12.

Table 12: Coarse aggregates angularity of the RAag

Fraction	Coarse aggregate angularity [%]	Standard
4 - 20 mm	$C_{100/0}$	EN 933-5

Polished Stone Value (PSV)

The PSV results of RA and RAag are reported in Table 13.

Table 13: PSV values for RA and RAag

PSV [EN 1097-8]	**RA (black condition)**	**RAag (white condition)**
	50%	48%

Assuming that virgin aggregates and RAag have the same PSV, it can be supposed by comparing the PSV results that the use of RA could will not worse the friction coefficient of the entire asphalt mixture.

4.1.4.2 RA binder properties

In the following bullet point the testing plan for the determination of characteristics of recovered binder is explained:

- Penetration @ 25°C [EN1426];
- Softening Point [EN1427];
- DSR – Frequency Sweep 0.1-10 Hz (0-80°C);
- Fraass Breaking Point [EN 12593];
- Viscosity @ 135ºC [EN 13302];
- RTFOT Ageing
  - DSR – Frequency Sweep 0.1-10 Hz (0-80°C);
  - BBR.

Such experimental activities were carried out by the laboratory of the University of Nottingham. The methodology, tests and results are described in chapter 5.

4.2 German mix constituents

4.2.1 Virgin aggregates

4.2.1.1 Coarse aggregates

Two sources of coarse aggregates, from two different quarries (Gilching and Treidling), were used. The physical attributes of the aggregates are summarised in Table 14. The grain size distribution is shown in Figure 13 together with the limits imposed by the German specification for aggregates in asphalt mixes (TL Gestein-StB 04, 2004).

Table 14: Physical attributes of coarse aggregates

			Aggregate angularity (DIN EN 933-5)		
	Material	**Dry density (DIN EN 1097-6) [Mg/m^3]**	**Aggregates with fractured faces [M.-%]**	**Aggregates without fractured faces [M.-%]**	**PSV (DIN EN 1097-8) [-]**
Coarse Aggregates	Crushed stone 8/11 (Gilching)	2.705	100	0	48
	Crushed stone 8/11 (Treidling)	2.749	100	0	53
	Crushed stone 5.6/8 (Gilching)	2.705	100	0	48
	Crushed stone 5.6/8 (Treidling)	2.749	100	0	53
	Crushed stone 2/5,6 (Gilching)	2.705	100	0	48
	Crushed stone 2/5,6 (Treidling)	2.749	100	0	53

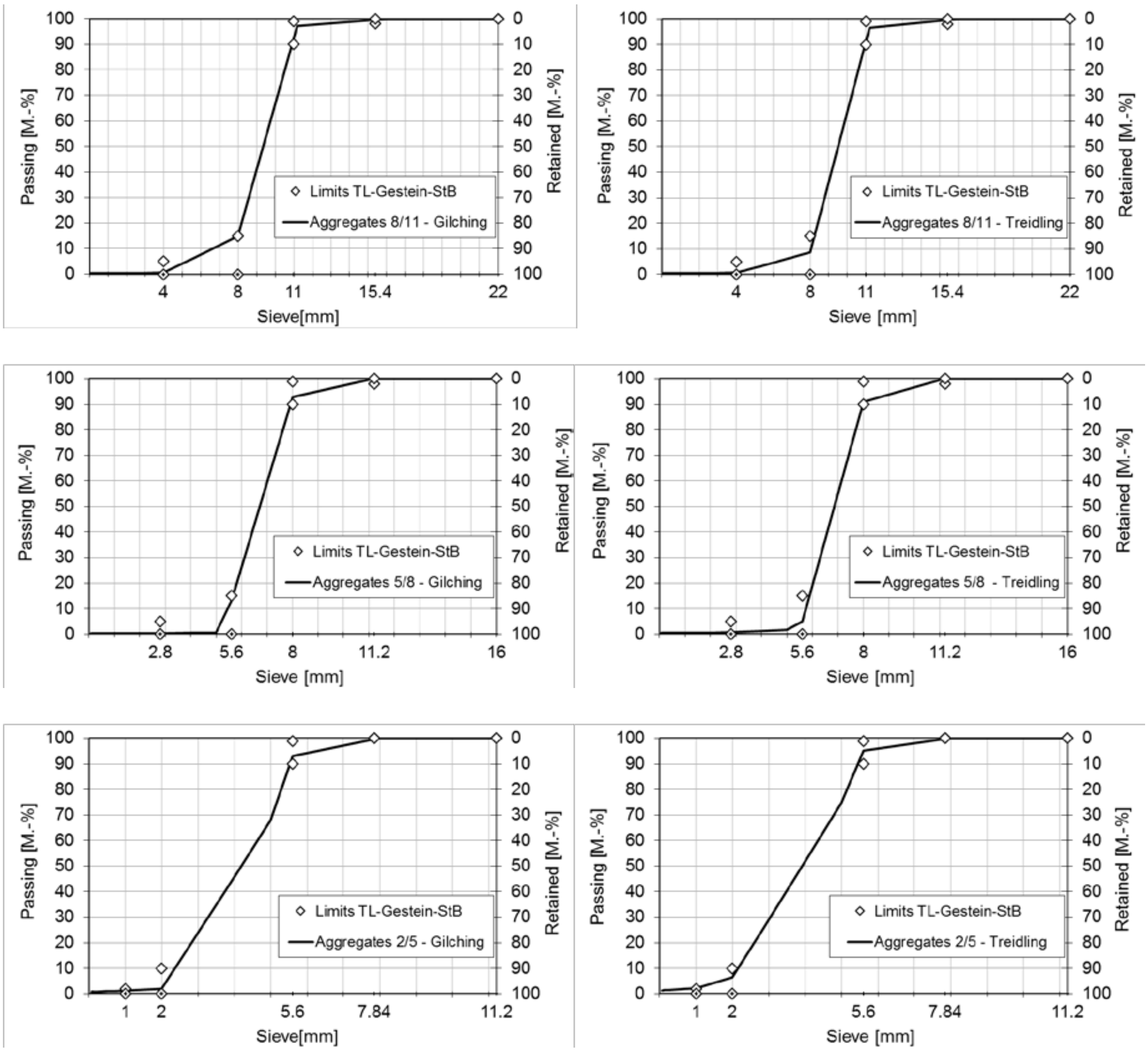

Figure 13: Gradation of coarse aggregates

4.2.1.2 *Fine aggregates*

One source of crushed fine aggregates (0.063-2), with the grain size distribution shown in Figure 14, were used for the design and production of the German mixes.

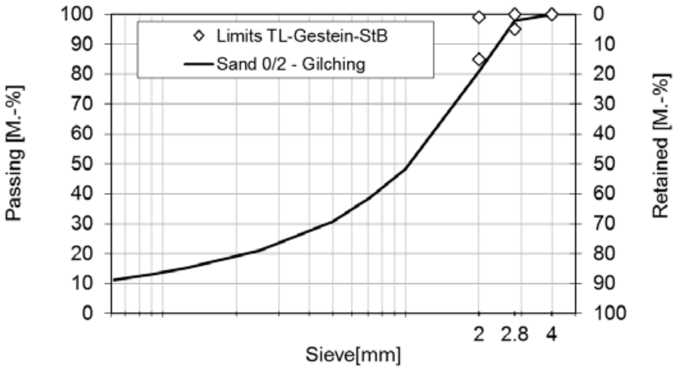

Figure 14: Gradation of fine aggregates

4.2.1.3 Filler

The physical attributes of the filler are shown in Table 15.

Table 15: Physical attributes of filler

Attribute	**Units**	**Results**	**Requirements (TL Gestein-StB)**
Petrography	[-]	Limestone	-
Dry density	[Mg/m^3]	2.738	-
Grain size distribution	[M.-%]		
Passing sieve ≤ 2mm		100	100
Passing sieve ≤ 0.125mm		96.2	85-100
Passing sieve ≤ 0.09mm		90.4	0
Passing sieve ≤ 0.063mm		78.4	70-100

4.2.2 Fibres

Pelletized cellulose fibres were used in all mixes. The function of the fibres is to avoid bitumen drain-down due to the high binder content and coarse aggregate skeleton of the mixes.

4.2.3 Virgin binder

The type of virgin bitumen depends on the properties of the bitumen in the RA and on the properties of the target binder. The target binder is the bitumen resulted from the mix between virgin and RA bitumen. In other words, the bitumen of the final mix.

The target binder selection was done based on traffic and loading requirements expected in wearing courses of high volume roads in Germany. Table 16 shows that for a federal high volume road with a surface layer made of a SMA material, it is required to use a modified bitumen of the type 25/55-55. The contract specifications of this type of bitumen are presented in Table 17.

The German specifications only allow an adjustment of the RA bitumen properties by using a softer virgin bitumen of one grade above the target. The degree of adjustment depends on the ageing of the bitumen in the RA. This ageing manifests itself as a hardening that decreases the needle penetration value and increases the R&B softening point.

In order to determine a suitable virgin bitumen, a comprehensive blend study was performed at the laboratory of the University of Nottingham (see chapter 5). The results showed that the properties of the bitumen from the RA do not differ much from the properties of the target binder. Therefore, it was decided to use as virgin binder a PmB 25/55-55 (i.e. the same type and grade as the target).

Table 16: Recommended bitumen types and grades (ZTV Asphalt-StB 07, 2007)

	Load class	Pavement layer					
		Base course	Binder course	Wearing course			
				AC	SMA	MA	PA
HVR	**Bk 100 and Bk 3.2**	50/70	25/55-55 30/45	-	**25/55-55**	20/30 30/45	40/100-65
	Bk 10			25/55-55			
	Bk 3.2						
	Bk 1.8	50/70	50/70	50/70	50/70	30/45	-
	Bk 1.0	70/100	-				
	Bk 0.3				70/100		

Table 17: Contractual requirements for a PmB 25/55-55 (TL Bitumen-StB 07, 2007)

Attribute	Units	Spec.	Requirements (PmB 25/55-55)
Needle penetration at 25°C	0.1mm	EN-1426	25 to 55
Ring and ball softening point	°C	EN-1427	≥55
Tensile ductility	J/cm2	EN 13589, EN 13703	≥2 (at 10°C)
Flammable point	°C	EN ISO 2592	≥235
Breaking point by Fraass	°C	EN 12593	≤-10
Elastic recovery @ 25°C	%	EN 13398	≥50

Table 18: Empirical properties of virgin bitumen

Lab	Pen [1/10 mm]	R&B Temp. [°C]	Fraass Temp. [°C]	Viscosity at 135°C [mPa.s]
UNOTT	43	60.4	-16	1195
Manufacturer	46	57.2	-	-

Table 19: Critical temperatures of virgin bitumen

Lab	High Tc [°C]	Intermediate Tc [°C]	Low Tc [°C]
UNOTT	79.3	19.2	-16.0

A sample of the virgin bitumen was obtained from the bitumen tank of the mixing plant for further characterisation at the laboratory of the University of Nottingham. The results of the lab tests are presented in Table 18 and Table 19.

4.2.4 Additives

4.2.4.1 Rejuvenators

Asphalt mixtures, especially bituminous binders, are like all materials more or less influenced by different ageing factors and processes. Asphalt mixtures are ageing in an irreversible process during manufacturing, transportation, laying and service life. Over the years, bituminous binders become stiffer and more brittle and lose their visco-elastic behaviour. This is evident, among others, by the increase in the softening point in the ring and ball test. Rejuvenators can be added to asphalt mixes to compensate the properties of aged binders by lowering the softening point.

4.2.4.2 Warm mix additive

The use of high recycling rates in asphalt mixes combined with the use of a parallel drum requires a great amount of energy. Virgin aggregates and reclaimed asphalt must be heated separately. The installation temperature of a SMA, regulated in the German technical specification for asphalt TL-Asphalt StB 07 (TL Asphalt-StB 07, 2013), is given within a range of 150°C to 190°C. Taking into account the temperature losses between production and installation a minimum mixing temperature for at least 170°C has to be envisaged.

To effect resource-efficient and sustainable production processes and to avoid unnecessary material damage due to excessive heating of the reclaimed material warm mix additives can be added. Generally, the use of warm mix additives allows a reduction of the mixing temperature up to 20°C, still ensuring a constant workability.

To take into account both effects, binder rejuvenation and temperature reduction, the additive ‘Storbit +’ from *StorimpexAsphaltec GmbH* has been added to the asphalt mix with 60% reclaimed asphalt with a rate of 0.6%. That quantity must be considered for the calculation of the binder content. ‘Storbit +’ is a mixture of rejuvenator and warm mix additives.

4.2.5 RA material

The RA material needs to be evaluated before the actual mix design. This is because with ageing and oxidation some changes may occur in the mix. For the binder, this includes hardening (increase in viscosity) and loss of ductility. For the aggregates, the gradation may change due to degradation caused by traffic loads and environmental conditions.

4.2.5.1 Binder content

An automatic solvent extraction using trichloroethylene as solvent (per EN 12697-1) was used when determining the binder content in the RA. In the solvent extraction, the binder is extracted from the RA using a solvent in a centrifuge. The amount of bitumen in the RA is determined as the difference in mass before and after extraction.

The binder recovery was performed at the laboratory of the Technische Universität Dresden on two different samples of the feedstock. The results (Table 20) showed that the RA had a relatively low binder content of 4.8%. Since the RA was made of a SMA, it was expected a binder content of at least 6%.

Table 20: Binder content in the reclaimed asphalt

Laboratory	Binder content [%]	Average binder content [%]
TUD	4.8	4.8
	4.8	
Mixing plant	4.7	

4.2.5.2 RA binder properties

The recovering of binder for further characterisation was carried out separately at the laboratories of the universities of Dresden (TUD) and Nottingham (UNOTT). The method for separation and extraction was different at each lab:

- TUD: automatic solvent extraction using trichloroethylene as solvent per EN12697-1 and 12697-3.
- UNOTT: Fractionating column by using DCM as solvent per EN 12694-4:2005

Table 21: Experimental programme on RA binder

Lab	Test	Applicable standard
TUD	R&B Softening point	EN 1427
UNOTT	Needle Penetration at 25°C R&B Softening point Fraass breaking point Viscosity at 135°C Critical temperatures by DSR and BBR	EN 1426 EN 1427 EN 12593 EN 13302

After recovering, a representative set of laboratory tests were performed in order to characterize the physico-chemical state of the bitumen from the RA. Both, empirical and performance related properties were determined as per Table 21. In order to ensure reproductivility, the tests were peformed on binders recoveded from different random samples of RA (three at UNOTT and two at TUD).

Empirical properties

The results of the empirical tests are reproduced in Table 22.

Table 22: Results of empirical tests on RA binder

Lab (replicate)	Pen [1/10 mm]	R&B Temp. [°C]	Fraass Temp. [°C]	Viscosity at 135°C [mPa.s]
UNOTT (1)	21	66.2	-8	1518
UNOTT (2)	21	65.8	-8	1518
UNOTT (3)	21	65.0	-8	1434
TUD (1)	-	66.8	-	-
TUD (2)	-	63.8	-	-
Mean	21	65.5	-8	1490

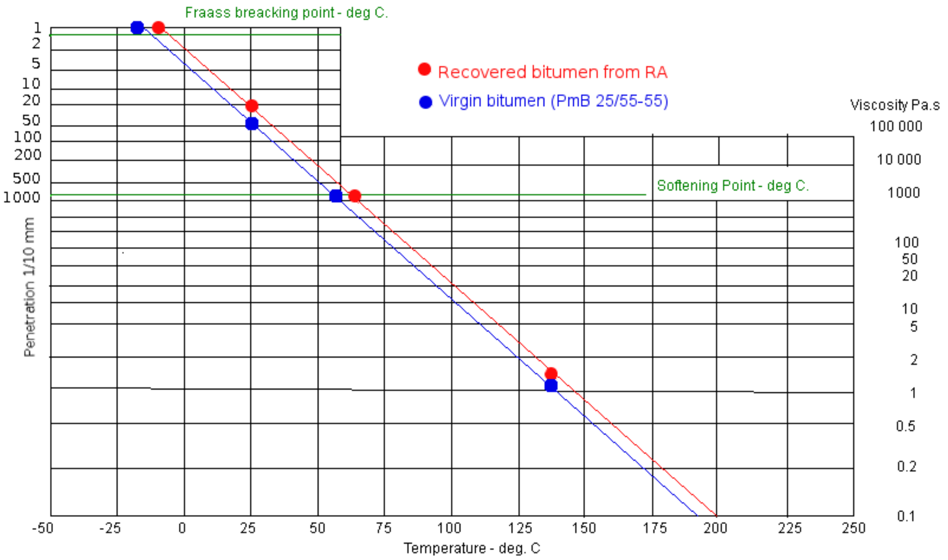

Figure 15: Bitumen test data chart of virgin and RA binder.

For comparison, the empirical properties of the recovered bitumen are plotted in the bitumen test data chart (BTDC) of Figure 15 together with the properties of the virgin bitumen (Table 18). The BTDC is a useful system to visualise the temperature dependence of penetration, softening point, Fraass breaking point and viscosity on one chart.

From the results in the chart it is deduced that the characteristics of both bitumens are very similar: the two regression lines are parallel and the line of the recovered bitumen is slighly shifted to the right, representating a relatively low hardening due to ageing.

The two regression lines in the BTDC represents the two extreme cases of a blend between virgin and RA bitumens (i.e. 100% virgin bitumen for the blue line and 100% recovered bitumen for the red line). Since both bitumens are similar, the properties of the blend could be obtained by linear interpolation between both extremes. The results of this interpolation are the so called “blending design charts” of empirical properies (for more details see chapter 5).

Performance related properties

The critical temperatures of the recovered binder were determined at the laboratory of the University of Nottingham using the data from DSR and BBR tests on unaged and aged binder samples. Three represenative temperatures, related to the three major damage phenomenons of asphalt: rutting, fatigue cracking and low-temperature cracking, were calculated following the procedure described in Appendix 1. The results are shown in Table 23.

Table 23: Critical temperatures of RA binder

Laboratory	High Tc [°C]	Intermediate Tc [°C]	Low Tc [°C]
UNOTT	80.1	22.5	-13.5

4.2.5.3 RA aggregates properties

Gradation

The gradation of the RA aggregates is one of the most important factors associated with the control of asphalt mixes with high RA content. At very high recycling rate, the gradation of the RA affects the overall performance of the final mix including stiffness, fatigue resistance, rutting and moisture damage.

A sieve analysis (per DIN EN 12697-2) was conducted on two random samples of recovered aggregates to obtain the gradation (white-curve) of the RA. The resulted grain size distribution is given in Table 24.

Figure 16 shows the mean gradation line of the RA together with the grading limits of a German SMA 11S. It is observed that the white-curve falls outside the original grading band and that the aggregates of the processed RA are finer and denser than the original ones. This is attributed to a strong mechanical degradation by milling and crushing.

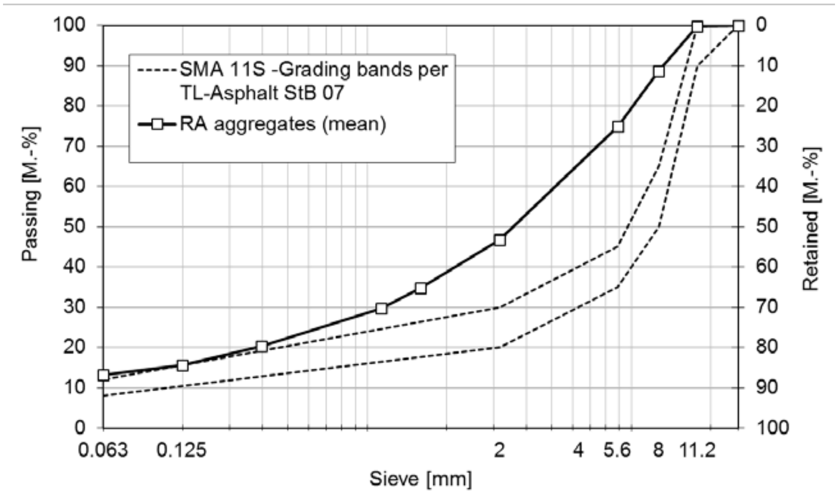

Figure 16: Grading of RA aggregates (white-curve)

Table 24: Grain size distribution of RA aggregates

	Laboratory (replicate)			
	TUD (1)	**TUD (2)**	**Mixing Plant (1)**	**Mean**
Sieve [mm]	**Passing [M.-%]**	**Passing [M.-%]**	**Passing [M.-%]**	**Passing [M.-%]**
16	100.0	100.0	100.0	100.0
11.2	99.2	99.9	100.0	99.7
8	88.3	88.7	89.0	88.7
5.6	73.2	74.6	77.0	74.9
2	45.2	45.5	49.6	46.8
1	33.6	33.6	36.7	34.6
0.71	29.6	29.6	-	29.6
0.25	19.8	19.8	21.4	20.3
0.125	15.2	15.3	16.3	15.6
0.063	12.4	13.2	13.8	13.1

Let us recall that the particle size distribution of a recycled asphalt material may vary to some extent depending on the technique and equipment used to produce the asphalt, and in this case, the RA was processed twice: initially it was milled from the road and afterwards it was crushed at the mixing plant.

Dry density

The maximum density of the RA aggregates, needed for the volumetric mix design, was determined from two samples of the coarse fraction 8/11. The test results are presented in Table 25.

Table 25: Maximum dry density of RA aggregates

	Laboratory (replicate)		**Mean**
	TUD (1)	**TUD (2)**	
Dry density [Mg/m^3] (DIN EN 1097-6)	2.690	2.767	2.728

Skid resistance

The aggregates ability to resist skidding is crucial when designing wearing course mixes. The polished stone value (PSV) is the evaluation method used for measuring skid resistance in Germany. Two skid test were performed to determine the PSV of the RA aggregates. Table 26 gives the results of the tests.

Table 26: PSV of RA aggregates

	Laboratory (replicate)		**Mean**
	TUD (1)	**TUD (2)**	
PSV [-] (DIN EN 1097-8)	50	52	51

From the test results it is concluded that the RA aggregates have enough good polishing characteristics to be used in SMA mixes for wearing courses of federal high volume roads (min. required PSV=51, according to TL Asphalt-StB 07)

Coarse aggregate angularity

The angularity of the RA aggregates was determined by visually inspecting a sample of coarse aggregates (fraction 8/11) and separating the sample into the aggregates with fractured faces and those without fractured faces. The results are given in .

Table 27: Coarse aggregate angularity of RA aggregates

	Aggregate angularity (DIN EN 933-5)	
Lab	**Aggregates with fractured faces [M.-%]**	**Aggregates without fractured faces [M.-%]**
TUD	95	5

5 Binder grade selection by blending design

5.1 International state of practice

5.1.1 Blending models based on conventional properties (EU)

Most countries have developed their own blending models for the use of RA binder and rejuvenators in new asphalt mixtures. Thereby, European countries use conventional properties to design blends, while USA use performance-related properties.

5.1.1.1 EU specifications

European Standard BS EN 13108-8:2005 for reclaimed asphalt sets some specifications about RA binders:

- reclaimed asphalt shall be categorised as P15 if the penetration of the binder of each of the samples is at least 10 d mm and the mean penetration of all of the samples is at least 15 d mm, or
- reclaimed asphalt shall be categorised as S70 if softening point of the binder of each of the samples is not greater than 77°C and the mean softening point of all of the samples is no greater than 70°C
- for other reclaimed asphalt, either the mean penetration values or the mean softening points shall be declared as category P_{dec} or S_{dec}
- for reclaimed asphalt to be used in soft asphalt, the mean viscosity at 60°C shall be declared as V_{dec}.

5.1.1.2 EU blending models

European blending models are based on penetration and softening point properties of the RA recovered binder and the virgin binder.

The binder class of the virgin binder may be used unaltered if the mix design includes less than 10% RA for surfacing layers and less than 20% RA for base layers and binder courses. If higher proportions of RA are used, the penetration and softening point values of the binder blend are to be determined using the equations in BS EN 13108-1:2006 Annex A, shown here as Equation 1 and Equation 2 respectively. The calculated penetration and softening point have to satisfy the relevant criteria set for the mix design.

$$a \log pen_1 + b \log pen_2 = (a + b) \log pen_{mix} \qquad (1)$$

where

pen_1 = penetration of the binder recovered from the RA

pen_2 = penetration of the added virgin binder

pen_{mix} = calculated penetration value of the binder in the mixture containing RA

a, b = ratios by mass of the binder from the RA and of the virgin binder respectively ($a+b=1.0$)

$$\mathrm{T}_{\mathrm{R\&}B\ mix} = a\ \mathrm{T}_{\mathrm{R\&}B\ 1} + b\ \mathrm{T}_{\mathrm{R\&}B\ 2} \tag{2}$$

where

$\mathrm{T}_{\mathrm{R\&}B\ 1}$ = softening point of the binder recovered from the RA

$\mathrm{T}_{\mathrm{R\&}B\ 2}$ = softening point of the added virgin binder

$\mathrm{T}_{\mathrm{R\&}B\ mix}$ = softening point of the binder in the mixture containing RA

a, b = ratios by mass of the binder from the RA and of the virgin binder respectively ($a+b=1.0$)

5.1.2 Blending models based on performance-related properties (USA)

5.1.2.1 USA specifications

NCHRP Report 452 (2001) specifies that for low RA contents (10 – 20%), it is not necessary to do tests because there is not enough of the old, hardened RA binder present in the mix to change the total binder properties. At higher RA contents, however, the RA binder will have a notice able effect, and it must be accounted for by using a softer grade of binder. For intermediate ranges of RA, the virgin binder grade can simply be dropped one grade. Thereby, for higher percentages of RA, a binder blend design exercise through blending charts is necessary. In fact several studies have shown how the final blend properties and the RA% are in linear relation (McDaniel et al. 2001). Figure 17 shows an example of this kind of chart.

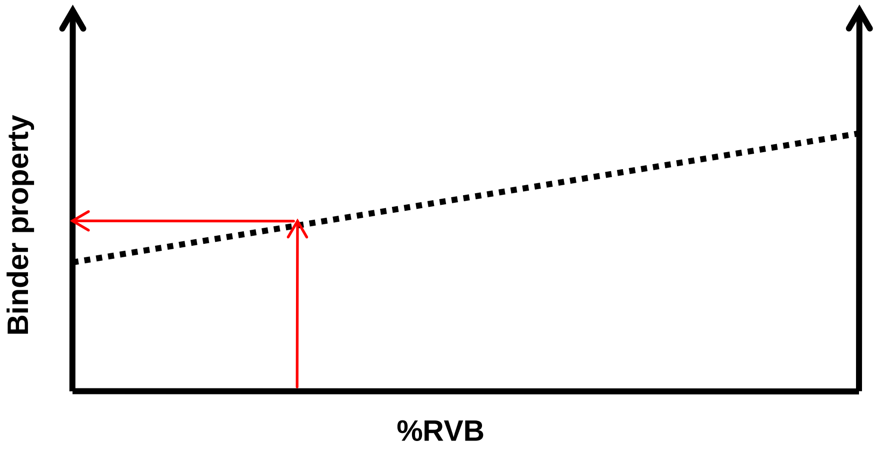

Figure 17: Example of blending chart

From these blending charts, the properties of the binder that will be used in the final mixture can be obtained depending on the percentage of RA that the mix will have.

However, the input in blending charts is not the percentage in weight of RA but the percentage of Replaced Virgin Binder (%RVB) that will be provided by the RA. This can be estimated by knowing the RA binder content, targeting the asphalt mix binder content and making an assumption on the extent of binder released from the RA during the asphalt mixing. With regards to the latter, literature confirms that a realistic situation is closer to the “100% blending” rather than “black rock” effect (Shirodkaret al., 2013).

5.1.2.2 USA blending models

NCHRP Report 452 (2001) describes the procedure to obtain blending charts based on performance-related properties. This procedure is based on performance-related critical temperatures of asphalt materials and follows the prediction law (Equation 3):

$$T_{blend} = T_{RA}*\%RA + T_{VB}*\%VB \qquad (3)$$

where,

T_{blend} = critical temperature of the final blend of binders

T_{RA} = critical temperature of the RA binder

T_{VB} = critical temperature of the virgin binder used as rejuvenator

$\%RA$ = percentage of RA in the blend

$\%VB$ = percentage of virgin binder in the blend

Table 28: Experimental program to build USA blending charts (NCHRP Report 452, 2001)

Binder	Property	Temperature Range
Original (not aged)	DSR G*/Sin δ	High
RTFO aged	DSR G*/Sin δ	High
	DSR G* Sin δ	Int
	BBR Stiffness (S)	Low
	BBR Δm-value (M)	Low

Therefore, in order to construct blending charts, critical temperatures of the RA recovered binder and the virgin binder would need to be measured. Usually three temperatures are considered for the design, and they are related to three major damage phenomenons of asphalt: rutting, fatigue cracking and low-temperature cracking. In order to determine these critical temperatures, DSR and BBR tests have to be carried out as follows: Firstly, RA binder has to be tested on the DSR at high temperatures. Then, RA binder has to be aged through the RTFOT and tested on the DSR at high and intermediate temperatures and on the BBR at low temperatures. Table 28 shows a scheme of the experimental programme needed for the performance-related characterisation of the binders.

With the results of those tests, critical temperatures can be determined as follows:

High critical temperature ($T_c(High)$). Determine the slope of the stiffness-temperature curve of the unaged RA binder as $\Delta Log\ (G^*/\sin\delta)/\Delta T$ and use Equation 4:

$$\mathrm{T_C(High)_1} = \left(\frac{\mathrm{Log(1.00) - Log(G_1)}}{\mathrm{a}}\right) + \mathrm{T_1} \tag{4}$$

where,

G_1= the G*/sinδ value in kPa at a specific temperature T_1

a= the slope of the stiffness-temperature curve described above

Determine the slope of the stiffness-temperature curve of the RTFOT RA binder as $\Delta\mathrm{Log}\ (\mathrm{G^*/sin\delta})/\Delta\mathrm{T}$ and use Equation 5:

$$\mathrm{T_C(High)_2} = \left(\frac{\mathrm{Log(2.2) - Log(G_1)}}{\mathrm{a}}\right) + \mathrm{T_1} \tag{5}$$

where,

$\mathrm{G_1}$= the G*/sinδ value in kPa at a specific temperature T_1

a= the slope of the stiffness-temperature curve described above

Choose $\mathrm{T_C(High)}$ between $\mathrm{T_C(High)_1}$ and $\mathrm{T_C(High)_2}$ as the most restrictive one (the lower one).

Intermediate critical temperature ($\mathrm{T_c(Int)}$). Determine the slope of the stiffness-temperature curve of the RTFOT RA binder as $\Delta\mathrm{Log}\ (\mathrm{G^*/sin\delta})/\Delta\mathrm{T}$ and use Equation 6:

$$\mathrm{T_C(Int)} = \left(\frac{\mathrm{Log(5000) - Log(G_1)}}{\mathrm{a}}\right) + \mathrm{T_1} \tag{6}$$

where,

$\mathrm{G_1}$= the $\mathrm{G^*/sin\delta}$ value in kPa at a specific temperature $\mathrm{T_1}$

a= the slope of the stiffness-temperature curve described above.

Low critical temperature ($\mathrm{T_C(Low)}$). Determine the slope of the stiffness-temperature curve of the RTFOT RA binder as $\Delta\mathrm{Log}\ (\mathrm{S})/\Delta\mathrm{T}$ and use Equation 7:

$$\mathrm{T_C(Low)(S)} = \left(\frac{\mathrm{Log(300) - Log(S_1)}}{\mathrm{a}}\right) + \mathrm{T_1} \tag{7}$$

where,

S_1= the S value in MPa at a specific temperature $\mathrm{T_1}$

a= the slope of the stiffness-temperature curve described above

Determine the slope of the stiffness-temperature curve of the RTFOT RA binder as $\Delta(\mathrm{m})/\Delta\mathrm{T}$ and use Equation 8:

$$\mathrm{T_C(Low)(m)} = \left(\frac{0.300 - \mathrm{m_1}}{\mathrm{a}}\right) + \mathrm{T_1} \tag{8}$$

where,

$\mathrm{m_1}$= the m value at a specific temperature $\mathrm{T_1}$

a= the slope of the stiffness-temperature curve described above

Choose $\mathrm{T_C(Low)}$ between $\mathrm{T_C(Low)(S)}$ and $\mathrm{T_C(Low)(m)}$ as the most restrictive one (the higher one).

At this point, depending on the available data for the mix design, there are two methods to proceed with the design of the blends.

Method 1**:** the RA content is known, an adequate virgin binder can be chosen in order to get a particular grade of the blend of the RA binder and the new one by using Equation 9:

$$\mathrm{T_{VB}} = \frac{\mathrm{T_{Blend}} - (\%\mathrm{RA} \times \mathrm{T_{RA}})}{(1 - \%\mathrm{RA})} \tag{9}$$

where,

$\mathrm{T_{blend}}$ = critical temperature of the final blend of binders

$\mathrm{T_{RA}}$ = critical temperature of the RA binder

$\mathrm{T_{VB}}$ = critical temperature of the virgin binder used as rejuvenator

$\%\mathrm{RA}$ = percentage of RA expressed as a decimal

Method 2**:** the virgin binder properties are known and the maximum percentage of allowable RA could be determined as follows (Equation 10)

$$\%\mathrm{RA} = \frac{\mathrm{T_{blend}} - \mathrm{T_{VB}}}{\mathrm{T_{RA}} - \mathrm{T_{VB}}} \tag{10}$$

where each term represents the same as above.

5.2 Binders blend design for the Italian mixes

The aim of this phase is to predict the properties of the future Rejuvenated RAb and virgin binder blends in order to assess whether they could be used to produce WMA and HMA.

The first step in carrying out the blend design was to define the ratio between the rejuvenators and the RAb to obtain the Rejuvenated RAb based on the indications of additives' supplier STORIMPEX. Once Rej/RAb ratio was determined, binder's blend design was performed by using both EU and USA methodology by undertaking the tests shown in Figure 18 and producing recommendations based on the variability of the optimum binder content and level of blending of RAb in the final mixture.

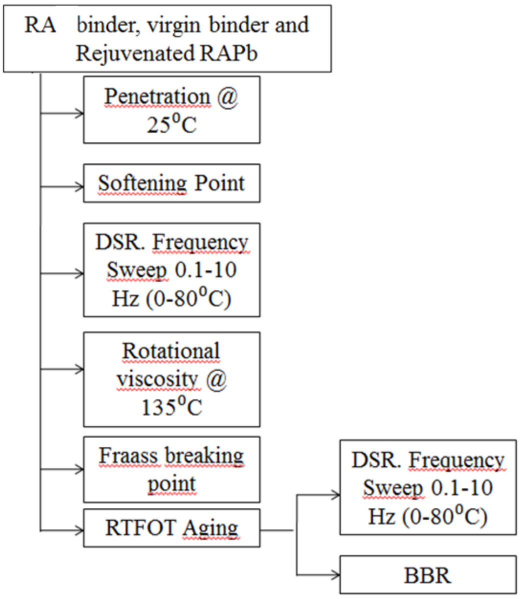

Figure 18: Testing plan for blend design

5.2.1 Characterisation of blend constituents

In order to obtain blending charts and inputs for the design of AllBack2Pave asphalt mixtures with different percentages of RA, a preliminary characterisation of the components of the final blend is necessary. For the Italian mixes, due to the RA binder properties, the blend design was carried out taking into account rejuvenated RA binder, made of RAb and rejuvenating oils, and virgin binder. In fact, the results of the RA binder's characterisation suggested that very soft rejuvenators are needed to obtain a final blend with properties comparable to the target Virgin binder using. The tested materials have been identified as follows:

RAb	Binder recovered from the Italian RA
VB	Virgin Bitumen: target binder to be used in Italy (Pen 50/70)
Rejuvenated RAb - RejA	RAb with Rejuvenator A
Rejuvenated RAb - RejB	RAb with Rejuvenator B

RAb were first recovered and then together with the target binders (VB), they were subjected to conventional tests and advanced rheological investigation. In addition, in order to carry out the performance-related blend design, binders were also subjected to the short-term ageing procedure RTFOT (BS EN 12607-1:2007) that simulates the ageing that the binder suffers during the manufacture of the mixture.

Both rejuvenator oils were supplied by *StorimpexAsphaltec GmbH*: RejA is an additive which consists of special regenerated oil and a Fischer-Tropsch wax. The oil rejuvenates the bitumen of the reclaimed asphalt to a predetermined degree of softness, while the Fischer-Tropsch wax improves the mixability and workability of the asphalt in order to obtain a WMA. RejB is an additive characterised by having high viscosity and free of polycyclic aromatic hydrocarbons. Two rejuvenators were considered because of the significant difference in price. In fact RejA is almost three times more expensive than RejB.

5.2.1.1 Rejuvenator dosage

Rejuvenators/RAb ratios were selected following the instructions of the products supplier:

RejA/RAb=0.2 and RejB/RAb=0.3. So the Rejuvanated RA binders are composed as follows

- RejuvanatedRAb - RejA = 0.2 RejA + 0.8 RAb
- RejuvanatedRAb - RejB = 0.3 RejB + 0.7 RAb

These ratios are based on the softening point of the RAb. The provider’s rule suggests that 1% of rejuvenator (over the weight of RAb) decreases 1ºC of RAb softening point. On one hand, the calculation of RejB dosage aims to rejuvenate RAb binder by decreasing its softening point to be closer to the virgin binder softening point. On the other hand, the addition of RejA would not change the softening point of the RAb due to combined effect of waxes and oil, so the recommendation of its dosage was based on conventional experiences.

N.B. *In orders to assess the amount of rejuvenator’s oil to be used as an input for the mix design, the partners have decided to follow the suggestions of the products supplier. Nevertheless, the University of Nottingham is still performing research on this very important topic and the consortium forecasts to provide some more details and possibly a tailored methodology at later stage of the project.*

5.2.1.2 Conventional properties

The following properties were obtained for all the binders (without ageing):

• Penetration (d-mm) at 25ºC	(EN 1426:2007)
• Softening Point (ºC)	(EN 1427:2007)
• Fraass Breaking Point ºC)	(EN 12593:2007)
• Viscosity at 135ºC (mPa-s)	(EN 13302:2010)

Table 29: Reproducibility of the RA binder recovery procedure, Italian mixes, EN 12694-4:2005

	Penetration at 25ºC [1/10 mm]	**Softening point [ºC]**	**Fraass breaking point [ºC]**
RAb 1	8	72	+ 8
RAb 2	9	71.4	+ 9
RAb 3	8	70.8	+ 9

Table 29 shows results to check the reproducibility of the RA binder recovery procedure, while Table 30 shows the average values of the conventional properties of RAb, VB and Rejuvenated RAb. These results reflect the differences between materials. RAb is a harder and more brittle binder, as it has been exposed to oxidation during his service life in a pavement, while the VB is a softer one.

Table 30: Average value of conventional properties of Italian binders

	Penetration at 25ºC [1/10 mm]	Softening point [ºC]	Fraass breaking point [ºC]	Viscosity at 135ºC [mPa.s]
RAb	8.3	71.4	+ 9	1827
VB	68	47.6	- 8	273
Rejuvenated RAb - RejA	92	68.4	-13	372.5
Rejuvenated RAb - RejB	120	65.7	-27	1094

5.2.1.3 Performance-related properties

In order to characterise the rheological behavior of the binders at asphalt service temperatures, frequency/temperature sweeps were performed using a DSR from 0ºC to 80ºC. For low temperature characterisation, BBR tests were conducted at different temperatures based on DSR results. High and intermediate temperature characterisation was carried out for original and RTFOT binders. Low temperature characterisation was performed with RTFOT binders. Table 31 shows critical temperatures obtained for the RAb, VB and rejuvenated RA binders.

Table 31: Critical temperatures of binders

	High Tc [^{0}C]	Intermediate Tc [^{0}C]	Low Tc [^{0}C]
RAb	87	33	-6
VB	66	19	-16
Rejuvenated RAb - RejA	71	11	-21
Rejuvenated RAb - RejB	71	9.5	-13

5.2.2 Blending charts

Blending charts allow predicting the properties of the binder of the final mixture in relation to the percentage of RA. However, the input in blending charts is not the percentage in weight of RA but the percentage of Replaced Virgin Binder (%RVB) that will be provided by the RA. In order to calculate the %RVB, the following considerations were taken into account:

1. Binder content in the RA. It was determined through laboratory tests (EN 12697-1 Part 1) and equal to 5.8%.
2. Percentage of blending. As the real percentage of blending that will occur on the mix is unknown, 100, 80 and 60% of blending were studied.
3. Final content of binder in the mixture. As the optimum binder content is not fixed, assumption of 6.0, 6.5 and 7.0% of binder content in the mix were used.

With these considerations, different %RVBs were obtained as shown in Table 32. Once blending charts were produced, using %RVB as inputs, we will be able to obtain the desired properties for the final binder in the mixture as outputs of the blending charts.

Table 32: Percentages of replaced virgin binder for blending charts – Italian mixes

%RA	**Blending**	**%Binder**	**%RVB**
30% RA	White 100%	6.0	29.20
		6.5	27.08
		7.0	25.26
	Grey 80%	6.0	23.28
		6.5	21.59
		7.0	20.14
	Grey 60%	6.0	17.46
		6.5	16.19
		7.0	15.11
60% RA	White 100%	6.0	58.39
		6.5	54.16
		7.0	50.52
	Grey 80%	6.0	46.56
		6.5	43.18
		7.0	40.28
	Grey 60%	6.0	34.92
		6.5	32.38
		7.0	30.21
90% RA	White 100%	6.0	87.59
		6.5	81.23
		7.0	75.79
	Grey 80%	6.0	69.83
		6.5	64.77
		7.0	60.42
	Grey 60%	6.0	52.38
		6.5	48.57
		7.0	45.32

5.2.2.1 Blending charts based on conventional properties (EU)

Penetration and softening point blending charts and prediction laws were produced according to Equations 1 and 2 of this document. Figure 19 and Figure 20 show these results.

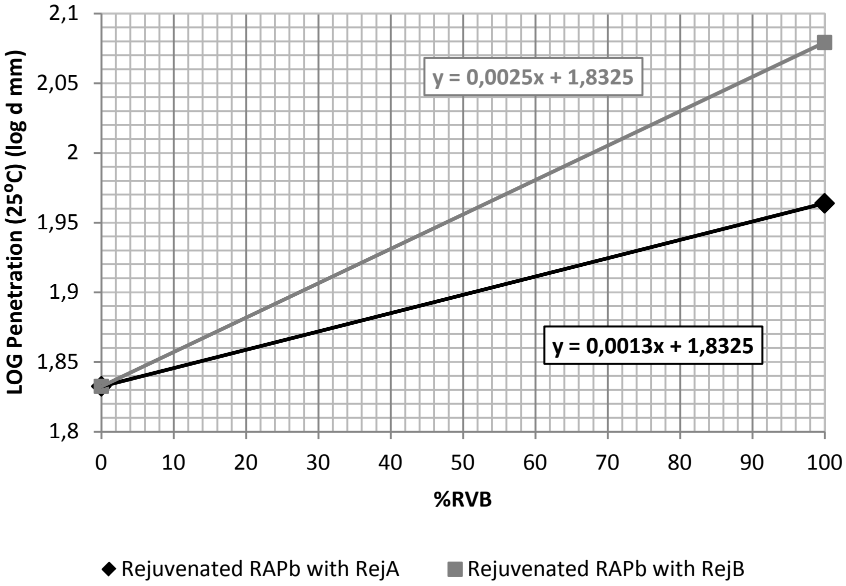

Figure 19: Blending chart and prediction law for Penetration (25^{0}C) [1/10 mm]

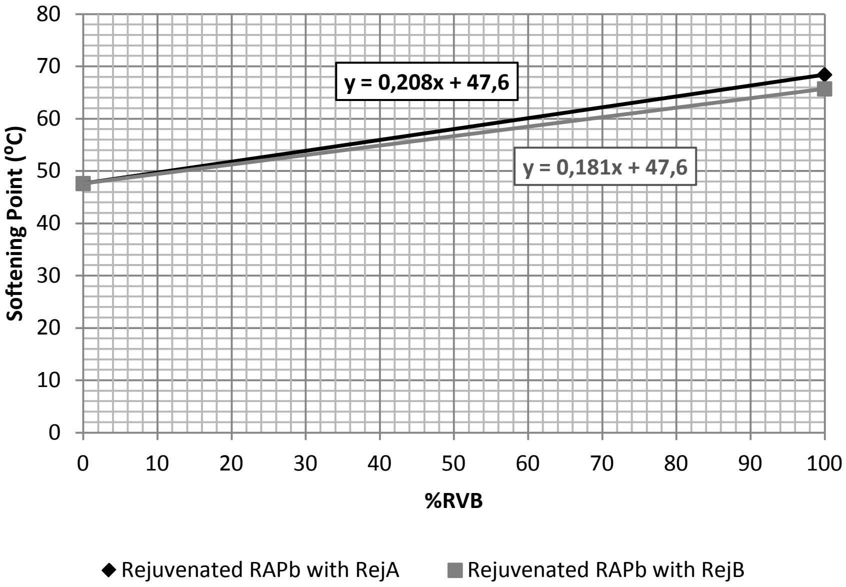

Figure 20: Blending chart and prediction law for Softening Point (^{0}C)

5.2.2.2 Blending charts based on performance-related properties (USA)

Given critical temperatures showed in Table 31, the blending chart and prediction laws depending on the %RVB were produced as displayed in Figure 21 and Figure 22.

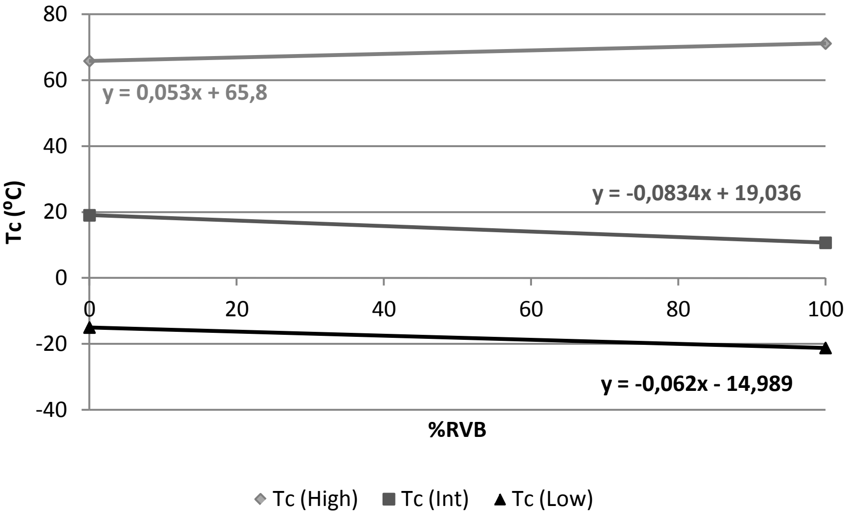

Figure 21: Blending chart and prediction laws for critical temperatures for virgin binder and rejuvenated RAb with RejA

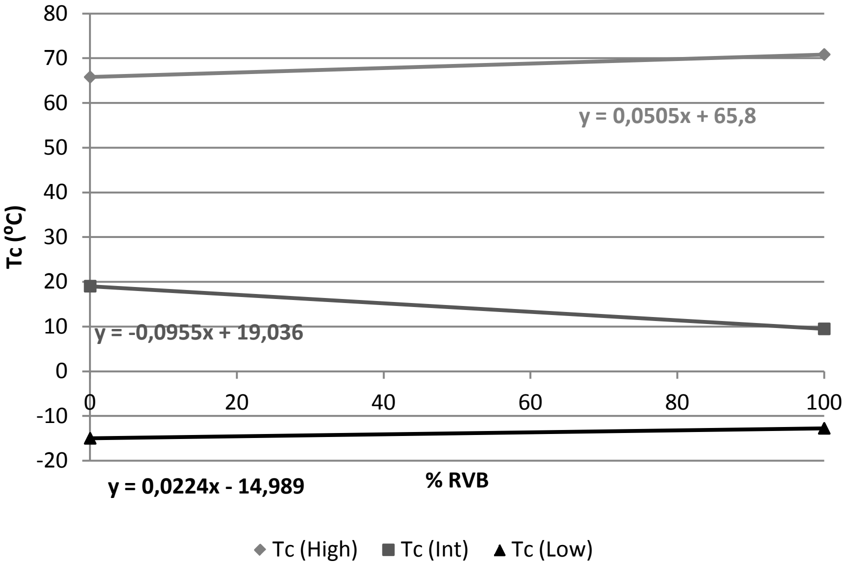

Figure 22: Blending chart and prediction laws for critical temperatures for virgin binder and rejuvenated RAb with RejB

5.2.3 Input for mix designs

5.2.3.1 Results of Blend design

Once blending charts have been built, based on the assumptions regarding %RVB, the ranges of properties of the binders with both rejuvenators to be used for mix design were obtained. Table 31 and Table 32 show these ranges for design based on conventional or rheological properties. For example, from Table 33 and Table 34 we could know that if the final mix has a 90% RA and RejA, the High critical temperature of the binder of that mix would be between 75.4 and 83.4°C.

Table 33: Final properties of blend with RejA at different blending ratio

RA [%]		Penetration 25^{0}C (1/10 mm)	SP (^{0}C)	Tc (High)	Tc (Int)	Tc (Low)
30%	Min.	71.0	50.5	69.7	16.7	-16.7
	Max.	73.9	53.3	72.4	17.9	-15.9
60%	Min.	70.4	53.4	72.5	14.4	-18.4
	Max.	80.3	59.0	77.9	16.7	-16.7
90%	Min.	77.3	56.4	75.4	12.1	-20.1
	Max.	87.2	64.7	83.4	15.5	-17.6

Table 34: Final properties of blend with RejB at different blending ratio

RA [%]		Penetration 25^{0}C (1/10 mm)	SP (^{0}C)	Tc (High)	Tc (Int)	Tc (Low)
30%	Min.	75.9	51.1	66.8	15.4	-14.6
	Max.	84.2	54.4	67.7	17.2	-14.1
60%	Min.	84.8	54.6	67.8	11.8	-14.1
	Max.	104.4	61.2	69.6	15.3	-13.3
90%	Min.	94.6	58.1	68.7	9.8	-13.7
	Max.	117.9	65.1	70.7	13.5	-12.8

5.2.3.2 Italian requirements

The Italian case study will target the design of a hot mix (reference mix) commonly used in Italy as asphalt wearing course. The mix will require a binder with the characteristics in Table 35:

Table 35: Binder properties for the Italian mixture

Bitumen type:		Conventional bitumen	
Bitumen Type and grade:		Pen 50/70	
Bitumen content		Min 6.5%	
Attribute	**Units**	**Test method**	**Requirements**
Needle penetration at 25°C	0.1 mm	EN-1426	50 to 70
Ring and ball softening point	°C	EN-1427	46-54
Rotational Viscosity	mPAs	EN 295	
Breaking point by Fraass	°C	EN 12593	≤-8

5.2.3.3 Conclusions

Comparing results from the blend design with the requirements for the binder to be used in the Italian mix and considering the following assumptions:

- With a RA binder content equal to 5.8%
- With a final binder content of 6.0% – 7.0%
- With a partial blending effect of 100% to 60%

it is possible to conclude that:

1. Binder's blend design based on conventional properties shows that by using the selected binder Pen 50/70 as a virgin binder and RejA and RejB for the selected RA-mixes (30%, 60% and 90%), both Pen and SP values struggle to achieve the target. SP resulted to be lower in most of the cases, especially at 30% and 60% RA. Penetration results are always much higher indicating a too high dose of rejuvanatours. Nevertheless, laboratory tests proved that these results are due to a visible phase separation of rejuvenators during conditioning of the sample at 25^{0}C in a water bath for 1 hour. In fact the difference in density of the materials leads the aged recovered bitumen to sink and the rejuvenator oil to float, making the Penetration test not suitable for these materials.

2. Blend design based on performance-related properties shows that by using the selected binder Pen 50/70 as a virgin binder and RejA and RejB for the selected RA-mixes (30%, 60%, and 90%), it is possible to obtain a final blend with comparable properties to the

target binder VB. The only issue could be represented by the proportions indicated by the supplier which result to be ideal for RejA, while are improvable for RejB (RejB/RAb should be higher) because results show some issues with Low critical temperatures.

Table 36: Conventional properties blend design results for binder with RejA and RejB with limits indicating 100% and 60% blending

%RA in mixture	**Final properties of blend with RejA**		**Final properties of blend with RejB**	
	Penetration at 25^{0}C [1/10 mm]	Softening Point [^{0}C]	Penetration at 25^{0}C [d mm]	Softening Point [^{0}C]
30% RA	71.8	51.3	75.9	51.1
	75.5	54.8	84.2	54.4
60% RA	75.8	55.0	84.8	54.6
	83.9	62.1	104.4	61.2
90% RA	80.0	58.8	94.6	58.1
	91.0	67.6	117.9	65.1
target	**50-70**	**≥54**	**50-70**	**≥54**

Table 37: Performance-related blend design results, for a target binder content of 6.5% and with the assumption of 100% blending

	Final properties of blend with RejA			**Final properties of blend with RejB**		
Binder	High Tc [^{0}C]	Int Tc [^{0}C]	Low Tc [^{0}C]	High Tc [^{0}C]	Int Tc [^{0}C]	Low Tc [^{0}C]
RAb	87	33	-6	87	33	-6
Final Blend (30% RA – white100)	66.7	16.1	-17.1	66.8	15.4	-14.6
Final Blend (60% RA – white100)	67.7	13.2	-19.3	67.8	11.8	-14.1
Final Blend (90% RA – white100)	68.6	11.0	-21.0	68.7	9.8	-13.7
target (VB)	**≥66**	**≤19**	**≤-16**	**≥66**	**≤19**	**≤-16**

3. As final remark, when rejuvenator oils are used, binder’s blend design based only on penetration and softening point could be misleading. Instead, looking at the critical temperatures (rheological properties) it is possible to affirm that both products RejA and RejB can be used to manufacture the RA asphalt mixes of this case study, namely 30%, 60% and 90% RA.

4. Mix design of 90%RA mixes should consider an optimum binder content over 6%. In fact, the selected rejuvenators would need at least 6.5% of total binder content to provide the desired level of modification.

5. From this follows that with these inputs, potentially the RA mixes obtained in the Italian case study will be at least comparable to the control asphalt mix manufactured with only virgin materials. However, tests on the mixes are needed to confirm these findings.

5.3 Binder blend design for German mixes

The aim of this phase is to produce a design of the binder resulting from incorporating different amount of RA within asphalt mixes for German wearing courses. This design will consist in predicting the properties of the final blend to provide inputs for performing the mix design. Binder's blend design was performed by using both EU and USA methodology by undertaking the tests shown in Figure 23 and producing recommendations based on the variability of the optimum binder content and level of blending of RA binder in the final mixture.

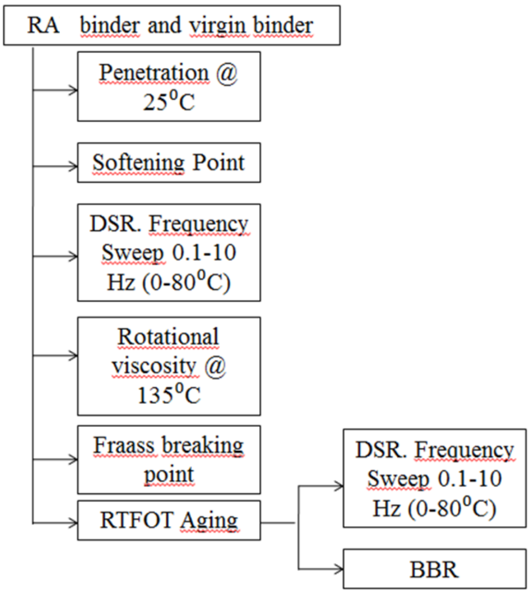

Figure 23: Testing plan for blend design

5.3.1 Characterisation of blend constituents

In order to obtain blending charts and inputs for the design of AllBack2Pave asphalt mixtures with different percentages of RA, a previous characterisation of materials is necessary for recovered binders from the RA (which will be called "RAb-D" in the German case study), eventual rejuvenating additives and virgin binders. For the German case study, due to the RA binder properties, the blend design was carried out taking into account RAb-D and the target virgin binder. The tested materials have been identified as follows:

- RAb-D Binder recovered from the German RA
- VB – DVirgin binder to be used in Germany (PMB 25/55)

RAb-D was first recovered and then together with virgin binders, they were subjected to conventional and rheological tests. In addition, in order to carry out the performance-related binder blend design, binders were also subjected to the short-term ageing procedure RTFOT (BS EN 12607-1:2007) that simulates the ageing that the binder suffers during the manufacture of the mixture.

5.3.1.1 RA binder recovery

In order to ensure reproducibility, RAb-D was obtained by selecting three random samples of RA and performing binder recovery for each of them. The binder recovery was carried out through the standard method EN 12694-4:2005 Binder recovery: Fractionating column by using DCM as solvent.

5.3.1.2 Conventional properties

The following properties were obtained for all the binders (without ageing):

- Penetration (d-mm) at 25ºC	(EN 1426:2007)
- Softening Point (ºC)	(EN 1427:2007)
- Fraass Breaking Point ºC)	(EN 12593:2007)
- Viscosity at 135ºC (mPa-s)	(EN 13302:2010)

Table 38 shows results to check the reproducibility of the RA binder recovery procedure, while Table 39 shows the average values of the conventional properties of RAb-D and VB-D. These results reflect the differences between both materials. RAb-D is a harder and more brittle binder, as it has been exposed to oxidation during his service life in a pavement, while the VB-D is a softer one.

Table 38: Reproducibility of RA binder recovery procedure EN 12694-4:2005

	Penetration at 25ºC [1/10 mm]	**Softening point [ºC]**	**Fraass breaking point [ºC]**	**Viscosity at 135ºC [mPa.s]**
RAb-D 1	21	66.2	-8	1518
RAb-D 2	21	65.8	-8	1518
RAb-D 3	23	65	-8	1434

Table 39: Average value of conventional properties of German binders

	Penetration at 25ºC [1/10 mm]	**Softening point [ºC]**	**Fraass breaking point [ºC]**	**Viscosity at 135ºC [mPa.s]**
RAb-D	21.67	65.7	-8	1518
VB-D	43	60.4	-16	1195

5.3.1.3 Performance-related properties

In order to characterize the rheological behavior of the binders at asphalt service temperatures, frequency/temperature sweeps were performed using a DSR from 0ºC to 80ºC. For low temperature characterisation, BBR tests were conducted at -12ºC and -18ºC.

High and intermediate temperature characterisation was carried out for original and RTFOT binders. Low temperature characterisation was performed with RTFOT binders.

5.3.2 Blending charts

Blending charts allow predicting the properties of the binder of the final mixture in relation to the percentage of RA. However, the input in blending charts is not the percentage in weight of RA but the percentage of Replaced Virgin Binder (%RVB) that will be provided by the RA.

Table 40: Percentages of replaced virgin binder for blending charts – German mixes

%RA	Blending	%Binder	%RVB
70%	White 100%	7%	**49.59**
		7.20%	**48.30**
		7.40%	**47.09**
	Grey 80%	7%	**39.67**
		7.20%	**38.64**
		7.40%	**37.67**
	Grey 60%	7%	**29.76**
		7.20%	**28.98**
		7.40%	**28.25**
60%	White 100%	7%	**42.51**
		7.20%	**41.40**
		7.40%	**40.36**
	Grey 80%	7%	**34.01**
		7.20%	**33.12**
		7.40%	**32.29**
	Grey 60%	7%	**25.50**
		7.20%	**24.84**
		7.40%	**24.22**
30%	White 100%	7%	**21.25**
		7.20%	**20,70**
		7.40%	**20.18**
	Grey 80%	7%	**17.00**
		7.20%	**16.56**
		7.40%	**16.14**
	Grey 60%	7%	**12.75**
		7.20%	**12.42**
		7.40%	**12.11**

In order to calculate the %RVB, the following considerations were taken into account:

1. Binder content in the RA. It was determined through laboratory tests (EN 12697-1 Part 1) and equal to 4.8%
2. Percentage of blending. As the real percentage of blending that will occur on the mix is unknown, 100, 80 and 60% of blending were studied.
3. Final content of binder in the mixture. As the optimum binder content is not fixed, assumption of 7, 7.2 and 7.4% of binder content in the mix were used.

With these considerations, different %RVBs were obtained as shown in Table 40. Once, blending charts were produced, using %RVB as inputs, we will be able to obtain the desired properties for the final binder in the mixture as outputs of the blending charts.

5.3.2.1 Blending charts based on conventional properties (EU)

Penetration and softening point blending charts and prediction laws were produced according to Equations 1 and 2 of this document. Figure 24 and Figure 25 show the results.

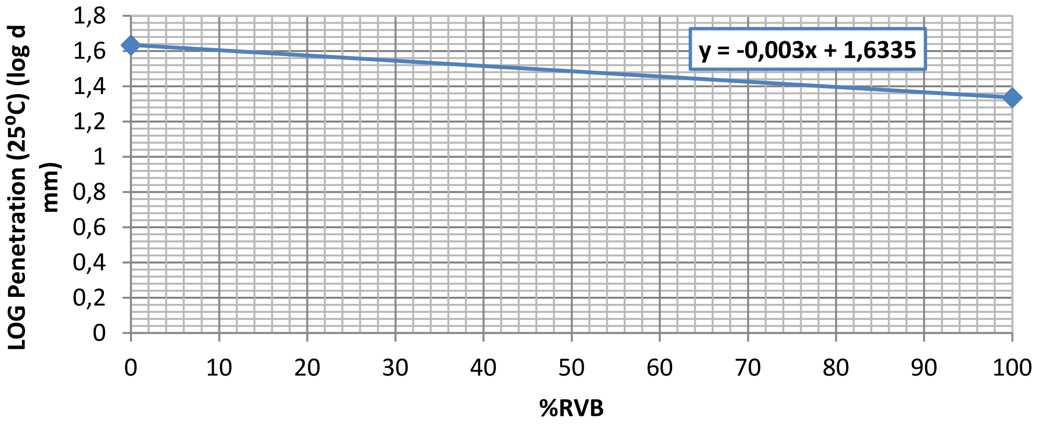

Figure 24: Blending chart and prediction law for Penetration (25^{0}C) [1/10 mm]

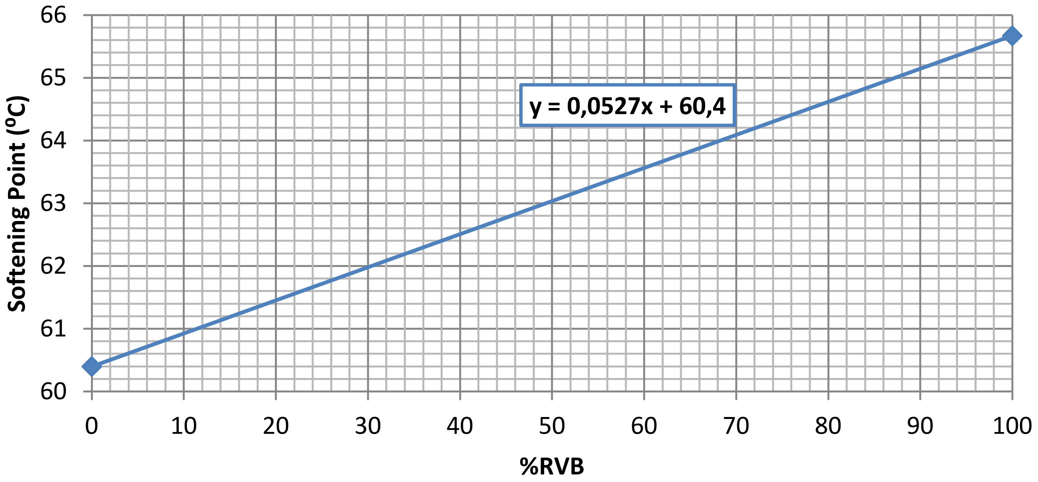

Figure 25: Blending chart and prediction law for Softening Point [^{0}C]

5.3.2.2 *Blending charts based on performance-related properties (USA)*

High, intermediate and low temperatures were calculated from the DSR and BBR tests according to the procedure described above. Table 41 shows critical temperatures obtained for the RAb-D and VB-D. Given these temperatures, the blending chart and prediction laws depending on the %RVB were produced as displayed in Figure 26.

Table 41. Critical temperatures of binders

	High Tc [^{0}C]	Intermediate Tc [^{0}C]	Low Tc [^{0}C]
RAb-D	80.1	22.5	-13.5
VB-D	79.3	19.2	-16

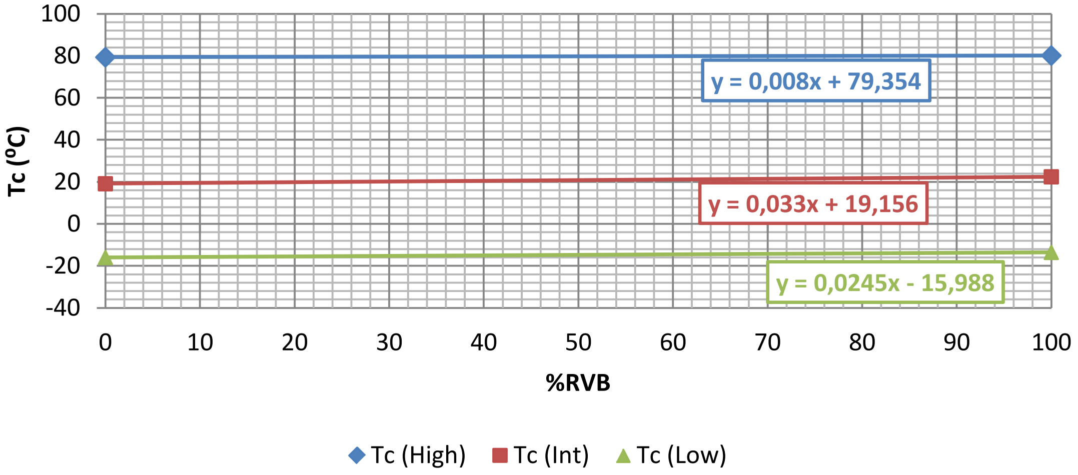

Figure 26: Blending chart and prediction laws for critical temperatures

5.3.3 Input for mix designs

5.3.3.1 Results of binder blend design

Once blending charts have been built, based on the assumptions regarding %RVB (Table 40), the ranges of properties of the binders to be used for mix design were obtained. Table 42 shows these ranges for design based on conventional or rheological properties.

For example, from Table 42 we could know that if the final mix has a 70% of RA, the Penetration of the binder of that mix would be between 37.3 and 39.7 1/10 mm at 25^{0}C.

Table 42: Binder properties for mixture design

	Conventional properties (EU design)		Rheological properties (USA design)		
%RA in the mixture	Penetration at 25^{0}C [1/10 mm]	Softening Point [^{0}C]	Tc (High) [^{0}C]	Tc (Int) [^{0}C]	Tc (Low) [^{0}C]
30	37.3	61.5	79.5	19.8	-15.5
	39.7	61.0	79.4	19.5	-15.7
60	32.3	62.6	79.7	20.5	-15.0
	36.6	61.6	79.5	19.9	-15.4
70	30.8	63.0	79.7	20.8	-14.8
	35.7	61.8	79.6	20.1	-15.3

5.3.3.2 German requirements

The German case study will target the design of a Stone Mastic Asphalt which will require a binder with the characteristics in Table 43:

Table 43: Binder properties for German mixture

Bitumen type:		Elastomeric Polymer modified bitumen	
Bitumen Type and grade:		PmB 25/55-55	
Bitumen content		Min 7.2%	
Nomenclature per German Standard:		PmB 25/55-55 A	
Governing spec:		TL-Bitumen-StB 2007	
Attribute	**Units**	**Test method**	**Requirements**
Needle penetration at 25°C	0.1 mm	EN-1426	25 to 55
Ring and ball softening point	°C	EN-1427	≥55
Tensile ductility	J/cm2	EN 13589, EN 13703	≥2 (at 10°C)
Flammable point	°C	EN ISO 2592	≥235
Breaking point by Fraass	°C	EN 12593	≤-10
Elastic recovery @ 25°C	%	EN 13398	≥50

5.3.3.3 Conclusions

Comparing results from the binder blend design with the requirements for the binder to be used in the German mix and considering the following assumptions:

- With a RA binder content equal to 4.86%
- With a final binder content of 7.0% – 7.4%

With a partial blending effect of 100% to 60%

It is possible to conclude that:

1. Binder blend design based on conventional properties shows that by using the selected binder PMB 25/55 (VB-D) as a virgin binder for the selected RA-mixes (30%, 60%, and 70%), it is possible to obtain a final blend whom properties are still within the limits of Penetration grade, Softening Point Ring and Ball (Table 44).

Table 44: Conventional properties binder blend design results

%RA in the mixture	**Penetration at 25^{0}C [1/10 mm]**	**Softening Point [^{0}C]**
Final Blend (30% RA)	37.3	61.5
	39.7	61.0
Final Blend (60% RA)	32.3	62.6
	36.6	61.6
Final Blend (70% RA)	30.8	63.0
	35.7	61.8
target	**25-55**	**≥55**

Table 45: Performance-related binder blend design results

%RA in the mixture	**High Tc [^{0}C]**	**Intermediate Tc [^{0}C]**	**Low Tc [^{0}C]**
Final Blend (30% RA)	79.5	19.9	-15.5
	79.5	19.6	-15.7
Final Blend (60% RA)	79.7	20.6	-14.9
	79.6	20.2	-15.4
Final Blend (70% RA)	79.8	20.8	-14.8
	79.6	20.1	-15.3
Target (VB-D)	**>79.3**	**<19.2**	**<-16.0**

2. Binder blend design based on performance-related properties shows that by using the selected binder PMB 25/55 (VB-D) as a virgin binder for the selected RA-mixes (30%, 60%, and 70%), it is possible to obtain a final blend whom properties do not differ too much from the selected VB (Table 45). Taking the VB as a reference for the properties of the final blend, it is possible to affirm that

   - VB-D can be used for the mix with 30% RA, but tests on the mixes should provide a confirmation. In fact being VB-D a PMB, and by including more than 10% RA, asphalt mixes for surface courses may be jeopardizing some of their good performance properties if adjustments to the virgin binder are not made.

   - For the 60% RA and 70% RA, another type of virgin binder (softer), rather than the selected PMB 25/55 is advisable to enhance intermediate and low temperature properties of the final blend. VB-D can also be used but tests on the mixes should provide a confirmation.

5.3.4 German mix with warm mix additive

Given the results and conclusions in the previous section, a warm mix additive (WMadd) was selected to be used for the 60% RA mix. The WMadd was supplied by *StorimpexAsphaltec GmbH* and it is an additive which consists of special regenerated oil and a Fischer-Tropsch wax. In this sense, the waxes allow decreasing the manufacture temperature of the mix.

To study the additive behavior, RA-D and WMadd were mixed following the supplier recommendations in order to obtain the adequate warm mix effect, using a 0.6% of additive over the total weight of the mix. DSR, Brookfield, RTFOT and BBR tests were undertaken in order to check the critical temperatures of the RA-D+WMadd.

Results are shown in Table 46 and Figure 27.

Table 46: Performance related properties of RA-D with WMadd

	High Tc [^{0}C]	Intermediate Tc [^{0}C]	Low Tc [^{0}C]
RA-D+WMadd	78.8	18	-14.7

According to results in Table 46, and applying the same design procedure using %RVB from Table 40, the blending chart for critical temperatures is displayed in Figure 27 and final results in Table 47.

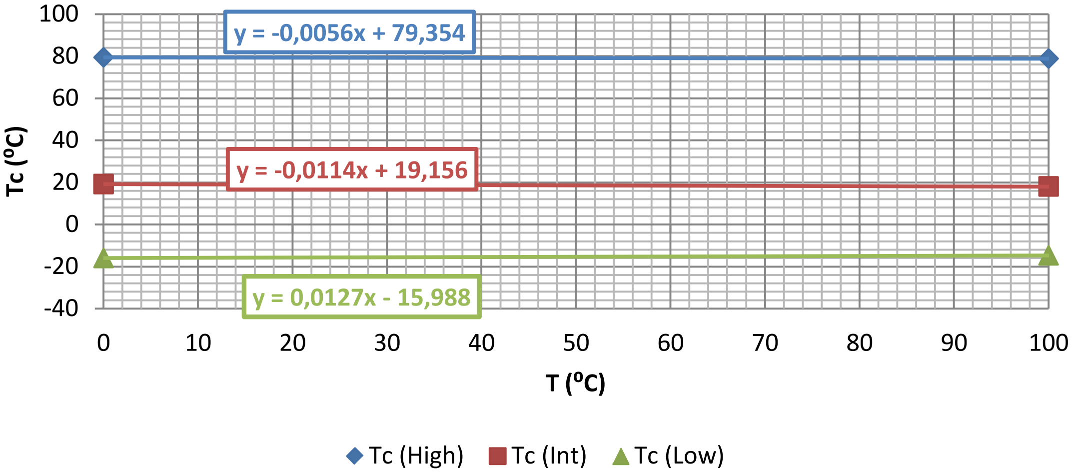

Figure 27. Blending chart and prediction laws for critical temperatures using WMadd

Table 47. Performance-related binder blend design results for 60% RA with WMadd

%RA in the mixture	**High Tc [ºC]**	**Intermediate Tc [ºC]**	**Low Tc [ºC]**
Final Blend 60% RA with WMadd	79.1	18.7	-15.5
	79.2	18.9	-15.7
Target (VB-D)	**>79.3**	**<19.2**	**<-16.0**

From results in Figure 27 and Table 47 it can be said that the WMadd has improved low and intermediate temperatures without excessively compromising high temperatures behaviour and would allow a decrease in the manufacture temperature of the mix.

6 Mix Design

The aim of the entire project is to reach a maximum amount of recycling of asphalt materials coming from dismantled pavements. Technically and economically speaking this aim is feasible if an additive, such as renewing agent, is incorporated within the mixture. In fact the use of the renewing agent is needed, most of all, to decrease the mixing temperature or to keep it equal to that for mixtures without RA. In other words, through a rejuvenator additive we obtain a high workability because the viscosity of the binder is kept low. By this way economic and environmental advantages can be reached during the production in plant.

This chapter describes two different methods for mix design procedures of asphalt mixes, by analysing two different types of bituminous mixtures with RA: the first mixture type - an asphalt concrete with paving bitumen with three different contents of RA and a constant percentage of additive (mix of rejuvenator and warm mix additive) in relation to the envisaged binder content, has been designed and analysed in the laboratory of the University of Palermo; the second one, a stone mastic asphalt with PmB with two different contents of RA and the alternate presence of additives was designed and analysed in the laboratory of the Technische Universität Dresden.

6.1 Italian methodology

The bituminous mix design process is addressed to a mix for wearing courses of motorway pavements. The applied mix design procedure is similar to the SUPERPAVE method (level 1) but modified in few steps. The process shown in the flow chart below (Figure 28) describes step by step the differences between the SUPERPAVE method and the used one.

Knowing that the aim of the research is to design a bituminous mixture with the highest possible amount of RA (towards 100% RA) and with high durability and remarkable mechanical performances three asphalt mixes with different amounts of RA (RA30, RA60 and RA90; all as WMA) have been designed and compared to the reference material (RA0, designed as HMA).

In order to obtain asphalt mixtures with RA with a suitable level of workability and to decrease or, at least, to keep the mixing temperature for all near to typical values for HMA, Storbit+ additive (RejA, supplied by *StorimpexAsphaltec GmbH*) has been used as additive.

The additive quantity used for each mixture with RA is equal to 20% of the RA binder mass.

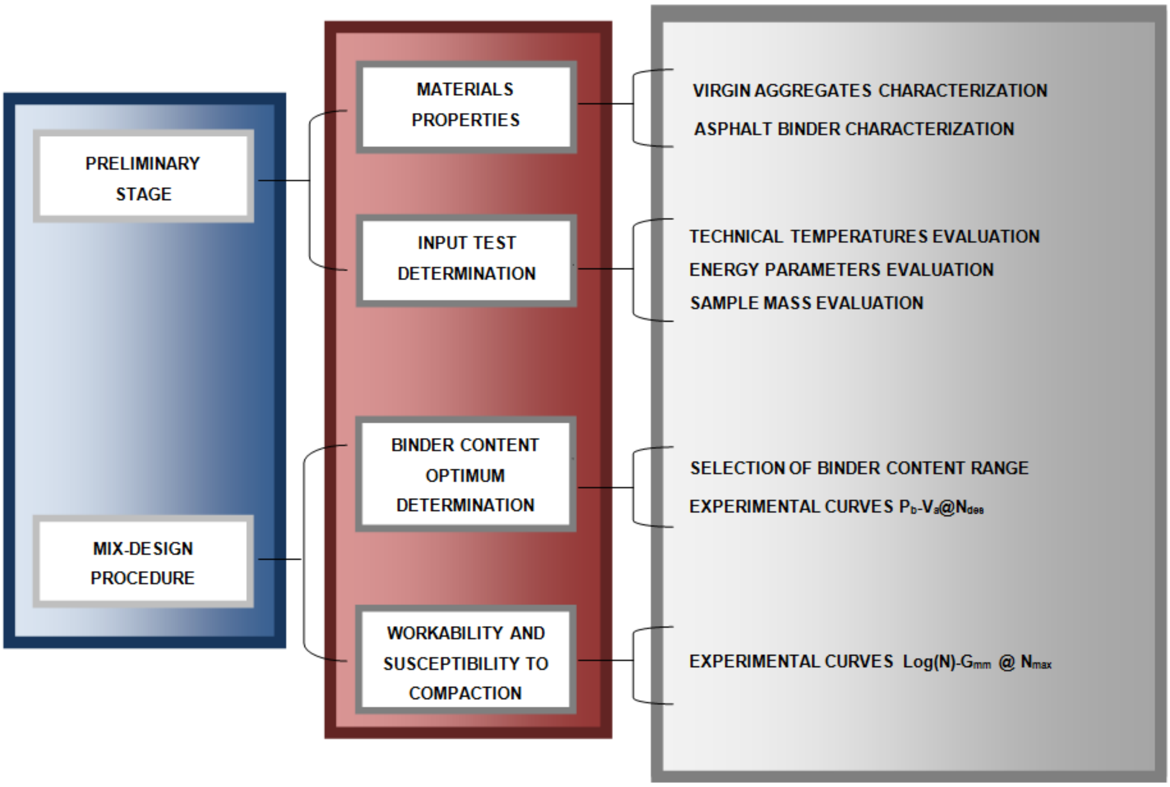

Figure 28: Flow chart of asphalt mixture design process

6.1.1 Preliminary stage

The preliminary stage consists of all activities which are needed to identify each mix constituent (i.e. aggregates and binder) and as well as to determine every test parameter such as technological temperatures and number of gyrations needed for the design process. For the mix design of asphalt mixtures with RA some additional specific issues such as aggregates structure design, viscosity of the renewing agent and the final blend have to be respected.

6.1.1.1 Material properties

Following the design process (Figure 28) the evaluation of the material properties during the preliminary stage consists of two steps. The first, namely virgin aggregates characterisation, implies the choice of the grading band, the determination of the aggregates grading and the evaluation of all physical and mechanical parameters (see paragraph 4.1).

6.1.1.2 Input test determination

As it is known, the determination of the input data for the gyratory compaction strictly depends on the type of binder, the climate of the site where the bituminous mixture will be placed and the foreseen heavy traffic (in terms of Equivalent Standard Axle - ESA).
The mixing and compaction temperatures are determined by Brookfield viscometer according to the equiviscosity criterion, 0.10Pa*s and 0.15Pa*s respectively. These values are less than the usual ones equal to 0.17 Pa s and 0.28 Pa s. By this way the industrial process of

the plant during the mixing time has been reproduced knowing that the workability of an asphalt mixture is considered as the first goal to reach.

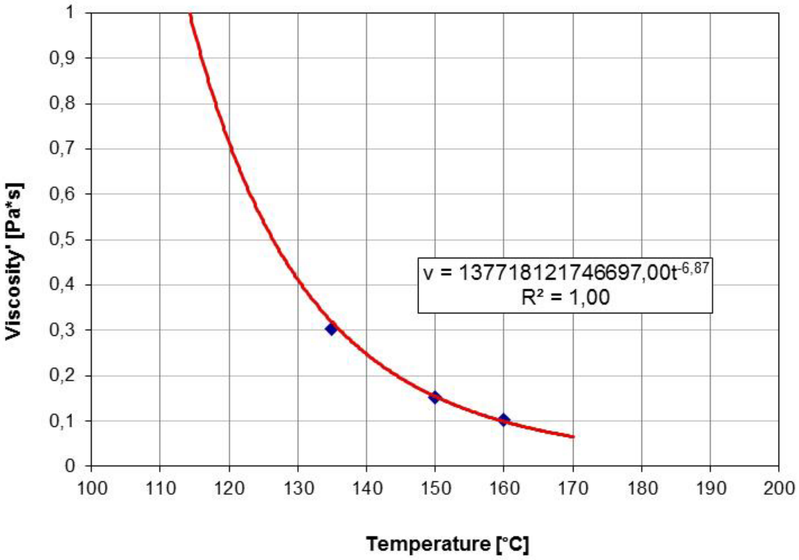

Figure 29: Viscosity-temperature curve by means of Brookfield viscometer

To consider climate and traffic conditions as well as long-term performances a motorway section on A19-E392 Palermo-Catania has been considered as test track.

The climate has to be investigated in terms of maximum air temperature of the area by analysing the historical trend, reported in Figure 30.

According to the available traffic data in terms of Average Annual Daily Traffic (AADT) of heavy vehicles (Figure 31), the total amount of ESA was calculated over a design life equal to 10 years with an annual rate of increasing heavy traffic equal to 2%.

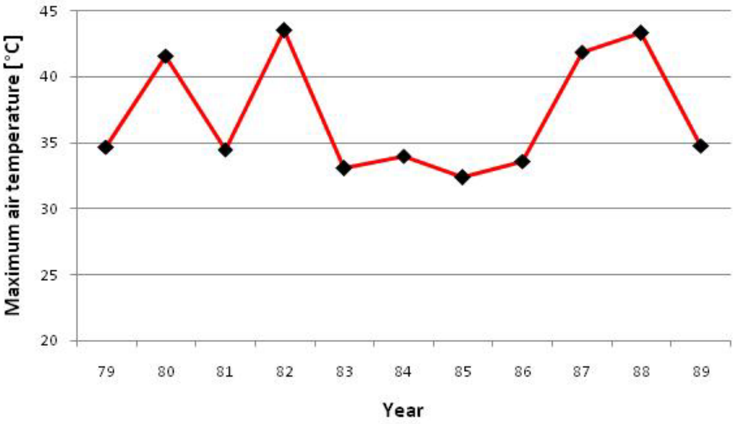

Figure 30: Historical trend of maximum air temperature

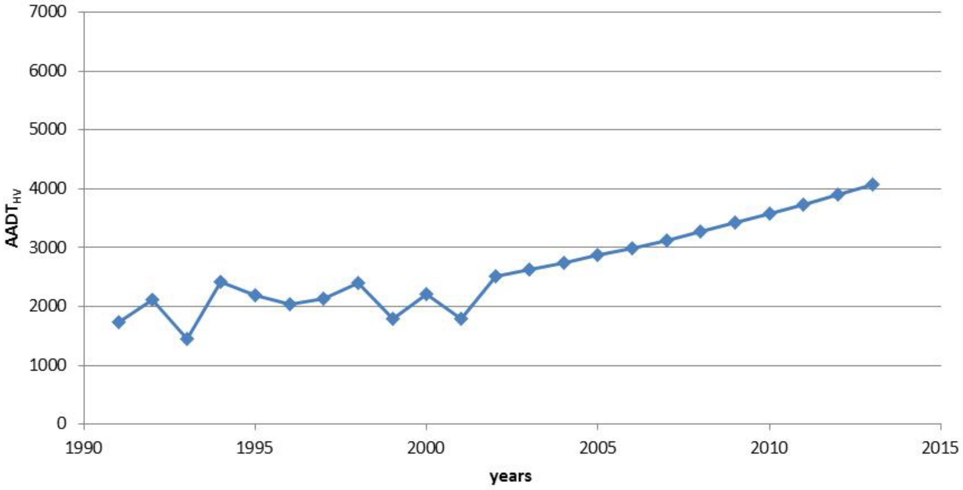

Figure 31: Historical trend of heavy vehicles AADT

Based on the SUPERPAVE matrix on Tmax, ESA and Ndes and applying the known formulas for N_{init} and N_{max}

$$Log\ (Ninit)\ =\ 0.45\ \times\ Log\ (Ndesign) \tag{11}$$

$$Log\ (Nmax)\ =\ 1.10\ \times\ Log\ (Ndesign) \tag{12}$$

the results are listed in Table 48:

Table 48: Energy parameters – number of gyrations

T_{max} = 44 °C - ESA = 70 10^6	
N_{des}	153
N_{init}	10
N_{max}	253

The mass of an asphalt sample has been determined by using a gyratory compactor test at N_{des} gyrations in order to reach the maximum conformity between laboratory activitys and laying and compaction in field. In fact, the desired thickness of the wearing course is 6 cm; according to that thickness the thickness of the sample should also be 6 cm. Because the experimental law coming from previous surveys is linear, two experimental points are sufficient to determine the material-specific function (Figure 32).

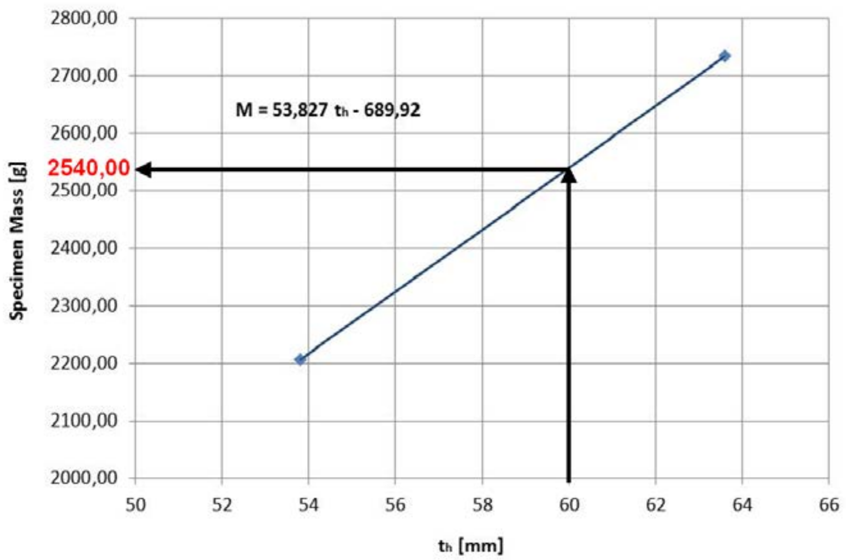

Figure 32: Specimen mass vs specimen thickness @ Ndes

In accordance with the criterion declared above the mixing temperatures have been determined on the basis of the equiviscosity of VB and rejuvenated RAb (Table 49).

Table 49: Equiviscosity temperature of final binder component

	RAb	**Rejuvenated RAb**	**VB**
Temperature [°C] @ viscosity = 0.10 Pa s	189	168	160
Temperature [°C] @ viscosity = 0.15 Pa s	181	157	150

As a consequence the mixing temperature for each WMA was evaluated by taking into account the increasing quantity of RAb. In addition, a compaction temperature equal to 10°C less than the mixing temperature was assumed. The results are summarised in Table 50.

Table 50: Technological temperatures

Asphalt Mixture	**Type**	**Mixing temp. [°C]**	**Compaction temp. [°C]**
RA0	HMA	160	150
RA30	WMA	163	153
RA60	WMA	165	155
RA90	WMA	170	160

As it can be seen the presence of RejA enable a mixing temperature close to that for virgin binder, even for the highest content of RA. On the other hand the “no reduction” of the temperature has been expected because the used reclaimed asphalt is very aged, as reported in paragraph 4.1.

6.1.2 Mix design procedure

The mix design procedure consists, on the one hand, of determining the designed binder content (P_b) on the basis of several volumetric parameters such as the air Void content (V_a) [EN 12697-8], Voids Filled with Asphalt (VFA), Voids in the Mineral Aggregate (VMA) and Dust Proportion (DP); and, on the other hand, of evaluating the properties such as workability and susceptibility to compaction of the designed asphalt.

Generally the procedure implies the comparison among different asphalt mixtures from which the designed mixture must be selected according to the above mentioned properties.

The mix design procedure has been conducted for mixture RA0, the reference material, and the three mixtures with RA RA30, RA60 and RA90, all designed as WMA.

The here described procedure shows exemplary the design of one mixture and follows substantially the method described in the NCHRP report N°452 that refers to the SUPERPAVE method.

6.1.2.1 Optimum binder content

The determination of the optimum binder content or design binder content has been determined by testing four bituminous mixes with different binder content equal to 5.5%, 6.0%, 6.5% and 7.0%. For each binder content five samples have been manufactured and tested under N_{des} gyrations with the objective of measuring the percentage of air voids V_a that, as it is known, is the target (Figure 33). According to the SUPERPAVE method the value of the target has to be equal to 4%. In this case we have followed the ANAS standard that implies a V_a value within the range of 4.0% - 8.0%. In this way the P_b equal to 6.5% has been selected because this allows to reach a V_a value close to the maximum of the range; in other words this follows the economic criterion of the minimum binder content.

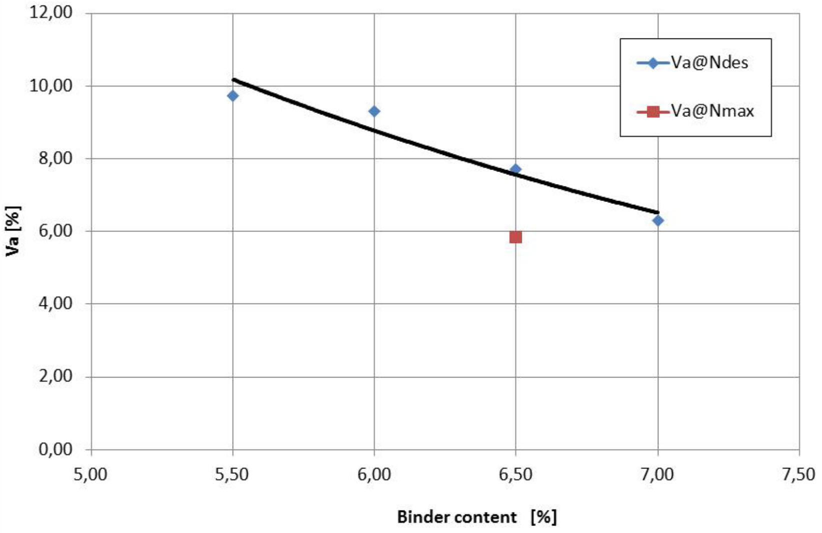

Figure 33: Experimental law of binder content vs air voids – asphalt mixture with 0% RA + additive

In addition, the other volumetric parameters have been calculated (Table 51). For the sake of clarity all parameters are reported below with their respective equations:

$$VMA = 100 - \frac{G_{mb}\,P_s}{P_s} \tag{12}$$

$$VFA = \frac{VMA - V_a}{VMA} 100 \tag{13}$$

$$DP = \frac{P_{0.075}}{P_{be}} \tag{14}$$

$$P_{be} = P_b - 100\left(\frac{G_{se} - G_{sb}}{G_{se} G_{sb}}\right) \tag{15}$$

where:

P_b = asphalt content, percent by mass of aggregate;

G_{sb} = bulk specific gravity of total aggregate;

G_{se} = effective specific gravity of aggregate;

G_b = specific gravity of asphalt;

$P_{0.075}$ = aggregate content passing the 0.075mm (75μm) sieve, percent by mass of aggregate;

P_{be} = effective asphalt binder content, percent by mass of aggregate, to the nearest.

Table 51: Volumetric parameters vs Pb@Ndes

P_b [%]	V_a@N_{des} [%]	VMA [%]	VFA [%]	DP
5.5	9.72	18.89	48.54	1.39
6	9.30	19.59	52.49	1.27
6.5	7.70	19.23	59.95	1.18
7	6.30	19.07	66.93	1.09
Specs	4 - 8	> 18	65 - 75	0.6 - 1.2

With the designed binder content 10 samples have been manufactured and tested: 5 samples with N_{des} = 153 gyrations reached an average V_a equal to 7.85%; the remaining 5 with N_{max} = 253 reached an average V_a equal to 5.85% (Figure 33).

As is known and stated by the SUPERPAVE method, the designed binder content of V_a=4% is the volumetric target at N_{des} and V_a≥2% at N_{max}.

About the first correspondence we have already spoken; regarding the second one it must be highlighted that the experimental value and the limiting one are in accordance.

On the other hand we consider V_a=4% to be a very strict limit that can provoke easily and accelerate the permanent deformation of the asphalt mixture.

Furthermore the graphs of the other volumetric mixture properties versus binder content are shown in Figure 34 and Figure 35.

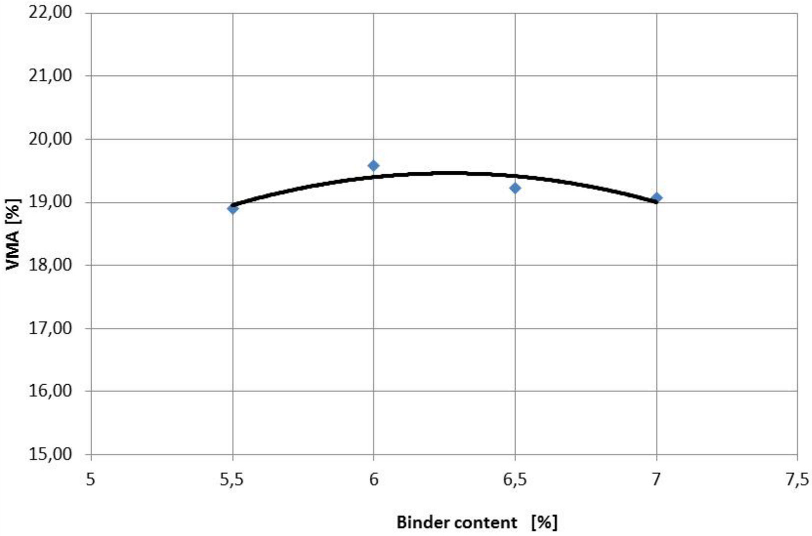

Figure 34: Experimental law of binder content vs Voids Mineral Aggregates @ Ndes – asphalt mixture with 0% RA + additive

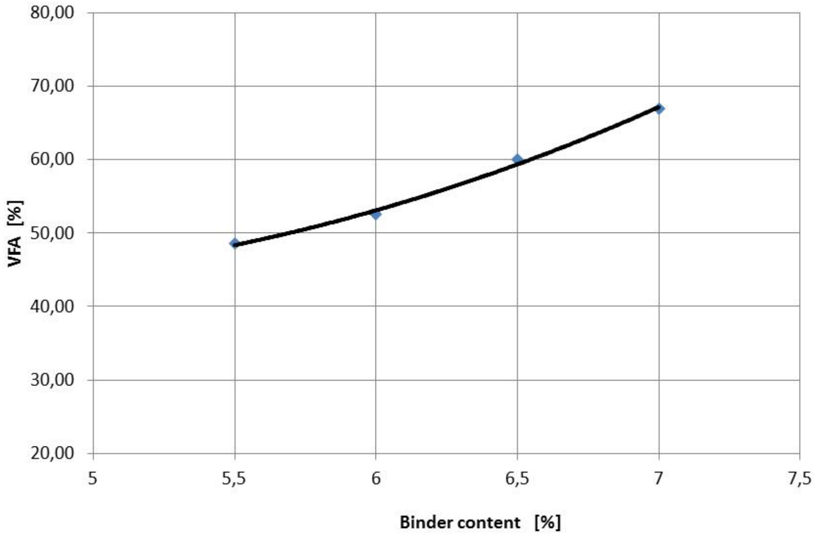

Figure 35: Experimental law of binder content vs Voids Filled with Asphalt @ Ndes – asphalt mixture with 0% RA + additive

Regarding the asphalt mixtures RA30 and RA60, the investigated binder content range has been established by analysing the experimental curve V_a-P_b @ N_{des} of the reference mix RA0 (Figure 33).

Since the V_a value was too high for P_b equal to 5.5%, the minimum value of the range was defined as 6.0%.

The maximum value has been chosen equal to 7.5% because this value represents a suitable balance between the economic and technical requirements. In fact, by assuming that the rejuvenating additive costs about three times as much as the virgin binder and the RA does not cost anything for the plant (except for dismantling and milling) a substantial saving can be noticed.

The following example illustrates this fact. For a mixture with 60% RA and a P_b equal to 7.5% the percentage of the virgin binder mass, RA_b and RejA, with respect to the aggregate mass, are respectively 3.24, 3.55 and 0.71%. Consequently, the final cost of the binder is about 30% less than the cost of the virgin binder needed for a conventional asphalt mixture with the same P_b.

Regarding the fourth asphalt mixtures RA90 the grading of the mix RA90 is different compared to the other asphalt mixes. The determined minimum binder content was equal to 6.5% and the maximum equal to 8.0%.

For each asphalt mixture with RA and each binder content, five samples have been manufactured and tested under N_{des} gyrations with the objective to measure the air void content V_a (%).

With respect to the ANAS standard a target value within the range of 4.0% to 8.0% had to be envisaged.

Asphalt mixture RA30

Since the P_b value (the P_b content at which V_a is close to 4%) was too high, according to the general criterion, the range 6.0%-7.5% has been selected. The mixture RA30 actually has a similar grain size distribution and P_b content as the RA0 mix.

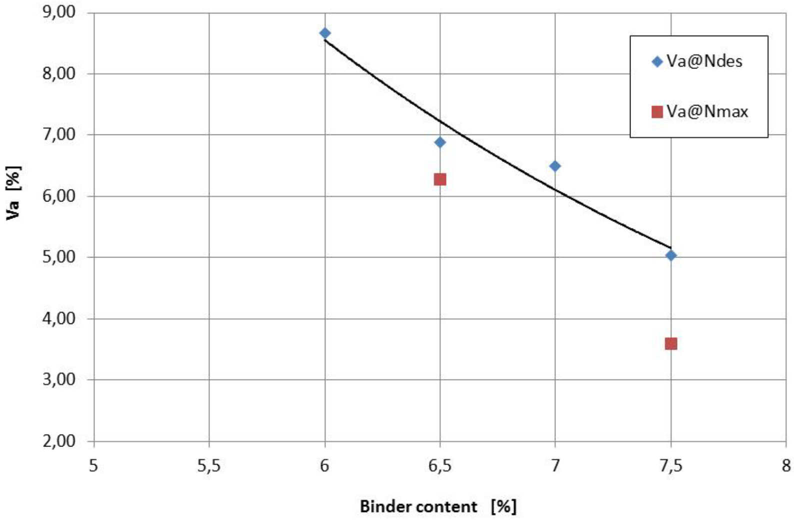

Figure 36: Experimental law of binder content vs air voids – asphalt mixture with 30% RA + additive

In addition, the asphalt mixtures with different binder contents (7.5% and 6.5%) have been tested at N_{max} gyrations.

In Figure 36 the experimental curve P_b – V_a is reported together with the 2 above mentioned experimental points.

The volumetric parameters are given in Table 52. It can be noticed that all specifications have been respected.

Table 52: Volumetric parameters vs Pb@Ndes – asphalt mixture with 30% RA + additive

Pb [%]	**Va@Ndes [%]**	**VMA [%]**	**VFA [%]**	**DP**
6	8.66	17.10	49.32	1.28
6.5	6.88	16.60	58.57	1.18
7	6.49	17.36	62.61	1.10
7.5	5.03	17.17	70.68	1.02
Specs	4 - 8	> 15	65 - 75	0.6 – 1.2

Asphalt mixture RA60

An analogous procedure has been conducted for the mix RA60. The results are given in Figure 37 and Table 53. It can be noticed that all specification have been respected.

The mixtures with different binder contents (7.5% and 6.5%) have been tested at N_{max} gyrations.

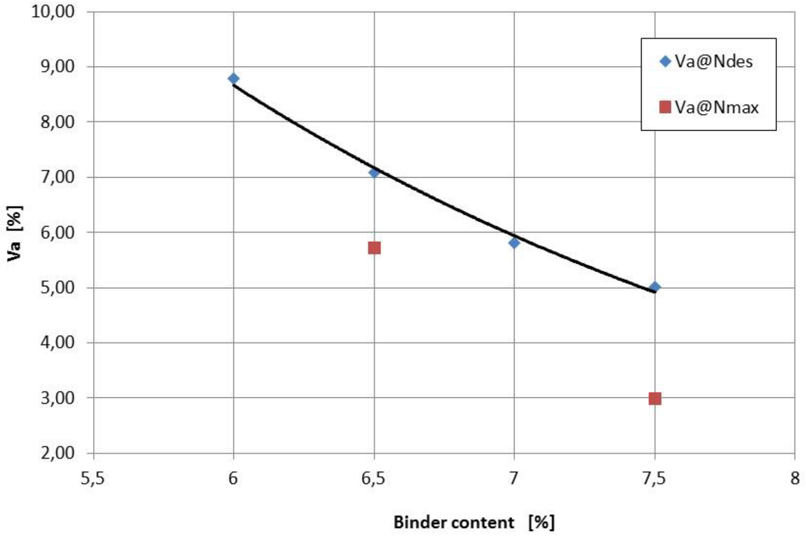

Figure 37: Experimental law of binder content vs air voids – asphalt mixture with 60% RA + additive

Table 53: Volumetric parameters vs Pb@Ndes – asphalt mixture with 60% RA + additive

Pb [%]	Va@Ndes [%]	VMA [%]	VFA [%]	DP
6	8,79	17,03	48,38	1,27
6,5	7,09	16,61	57,32	1,18
7	5,81	16,58	64,94	1,09
7,5	5,00	16,97	70,51	1,02
Specs	4 – 8	> 15	65 - 75	0,6 - 1,2

<u>Asphalt mixture RA90</u>

Since this mixture differs from the previous ones in terms of grading only the first design criterion has been followed.

The results are given in Figure 38 and Table 54. It can be noticed that all specifications have been respected except the DP. However, it can be considered, technically is the mixture acceptable because of the Va @ Nmax is largely higher than 2%.

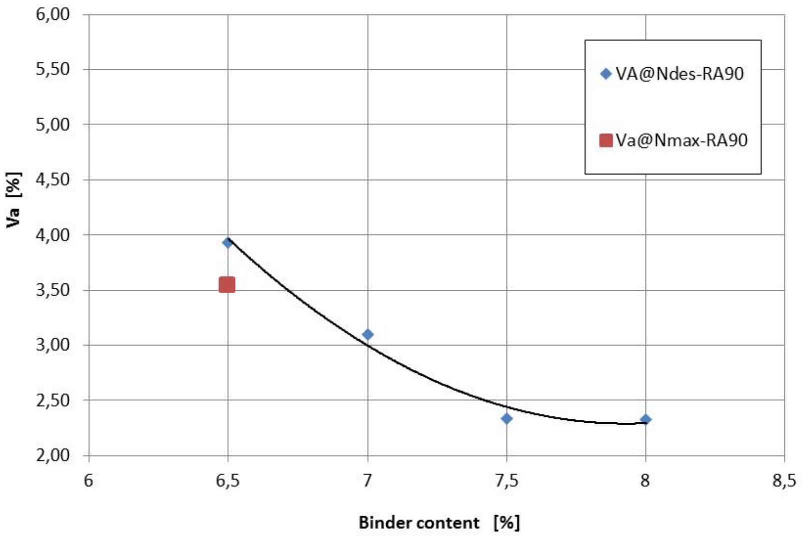

Figure 38: Experimental law of binder content vs air voids – asphalt mixture with 90% RA + additive

Table 54: Volumetric parameters vs Pb@Ndes – asphalt mixture with 90% RA + additive

Pb [%]	Va@Ndes[%]	VMA [%]	VFA [%]	DP
6,5	3,93	13,85	71,62	1,53
7	3,10	14,25	78,25	1,42
7,5	2,34	14,71	84,11	1,33
8	2,33	15,81	85,27	1,24
Specs	4 - 8	> 12	65 - 75	0,6-1,2

6.1.3 *Workability study of WMA*

The last step of the mix design process consist of the evaluation of all designed mixtures through the comparison of the volumetric properties such as the workability, the susceptibility to compaction and the residual air voids equal to 100-G_{mm} (N_{max}). Figure 39 shows the compaction curves of all WMAs together with RA0. The experimental points, that represent the average value over 5 tested samples, have been interpolated by a linear logarithmic regression (namely the experimental law N-G_{mm}).

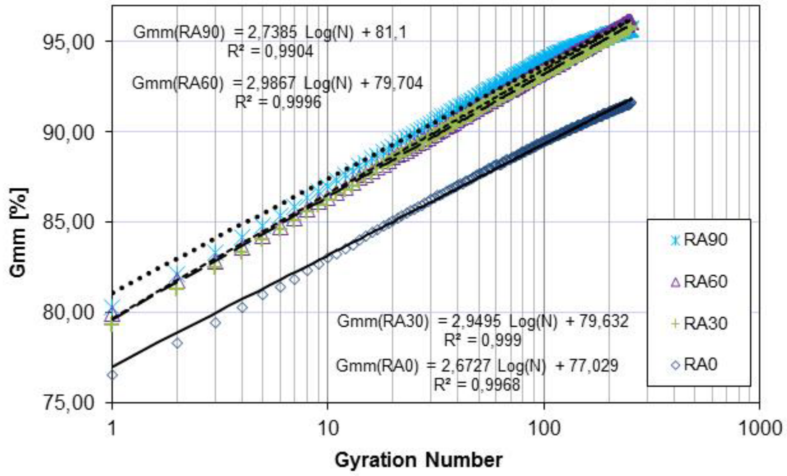

Figure 39: Mixes compaction curve @ Nmax

The regression functions are:

$$\text{RA0} \quad \rightarrow G_{mm} = 2.6727\, Log(N) + 77.029$$

$$\text{RA30} \quad \rightarrow G_{mm} = 2.9459\, Log(N) + 79.632$$

$$\text{RA60} \quad \rightarrow G_{mm} = 2.9867\, Log(N) + 79.704$$

$$\text{RA90} \quad \rightarrow G_{mm} = 2.7358\, Log(N) + 81.100.$$

As is common knowledge, the coefficient for Log(N) (slope of the curve) represents the workability of the mix (the higher coefficient the more workable) while the G_{mm}(10) means the susceptibility to compaction of an asphalt mixture. This value must be lower than 89% (Table 62) because this value (meaning very low value of Va before compaction) implies the bad quality of aggregates in terms of shape and/or grading and/or a wrong binder content.

Table 55: Workability, susceptibility to compaction and Gmm@Nmax (parameter of resistance to rutting) of designed asphalt and SUPERPAVE specifications value – asphalt mixture with 0% RA + additive.

P_b [%]	Workability	$G_{mm}@N_{init}$ [%]	$G_{mm}@N_{max}$ [%]
6.5	2.6727	83.00	94.15
Specs	-	< 89	< 98

The volumetric properties of all designed mixes are summarised in Table 56. It can be noticed that all specifications have been respected.

Generally, the workability is defined by primary material characteristics. It strongly weighs on technical and economic issues while the other ones are related to laying and resistance to rutting.

Table 56: Workability, susceptibility to compaction and Gmm@Nmax (parameter of resistance to rutting) of all designed and SUPERPAVE specifications value

Mix	P_b [%]	Workability	$G_{mm}@N_{init}$ [%]	$G_{mm}@N_{max}$ [%]
RA0	6.5	2.673	83.00	94.15
RA30	7.5	2.946	84.78	93.72
RA60	7.5	2.987	86.91	94.28
RA90	6.5	2.736	87.02	96.46
Specs		-	< 89	< 98

After comparing the test results of all investigated asphalt mixes the following conclusions can be drawn:

- The workability seems to increase with an increase of RA amount up to 60% also because of the higher binder content compared to RA0; nevertheless the workability of RA90 is slightly higher than the one of RA0 (mixtures with the same binder content).
- Although, the susceptibility to compaction does not decrease significantly with the increase of the RA amount.
- The residual air voids at the end of design life are pretty much the same up to 60% of the RA amount. As expected, by the light of the $G_{mm}(N_{init})$, just the RA90 demonstrates the lowest resistance to rutting among the designed mixtures.

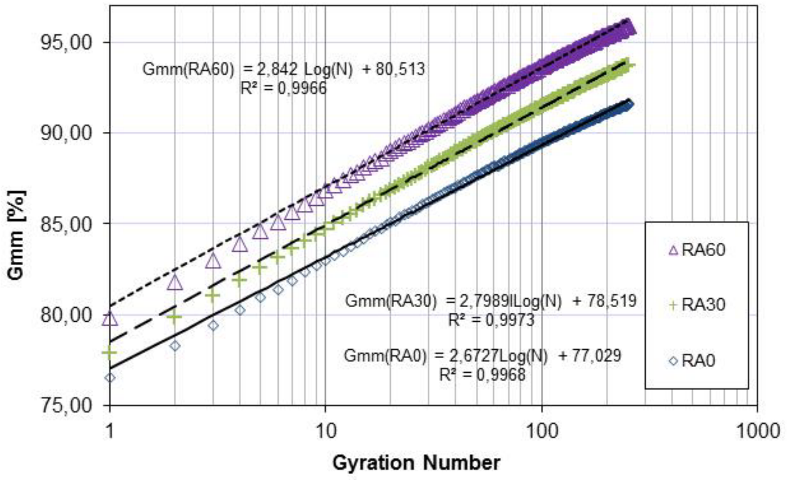

Figure 40: Mixes compaction curve @ Nmax for the mix with Pb=6.5%

With the purpose to carry out a sensitivity analysis of the RA amount on the volumetric properties, three asphalt mixtures with the same binder content and gradation were tested by gyratory compactor.

Figure 40 shows the compaction curves of the three mixtures. The experimental points, that represent the average value over 5 tested samples, have been interpolated by a linear logarithmic regression

The regression functions of the mixes with P_b = 6.5% are:

RA0 $\rightarrow G_{mm} = 2.6727\, Log(N) + 77.029$

RA30 $\rightarrow G_{mm} = 2.7989\, Log(N) + 78.519$

RA60 $\rightarrow G_{mm} = 2.8420\, Log(N) + 80.513$

The volumetric properties of mixes with P_b=6.5% are summarised in Table 57.

Table 57: Workability, susceptibility to compaction and Gmm@Nmax (parameter of resistance to rutting) and SUPERPAVE specifications value

Mix	P_b [%]	Workability	G_{mm}@N_{init} [%]	G_{mm}@N_{max} [%]
RA0	6.5	2.673	83.00	94.15
RA30	6.5	2.799	86.30	96.40
RA60	6.5	2.842	86.43	97.01
Specs		-	< 89	< 98

In this case, the properties are also consistent with the specifications.

The sensitivity analysis has substantially matched the identified trends of the designed mixtures.

The workability seems to increase with an increase of the RA amount. Instead of this the susceptibility to compaction and the residual air voids decrease with an increasing amount of RA.

In addition, the four asphalt mixtures were also tested by Marshall Hammer in order to compare their properties with the ANAS specifications.

The results are given in Table 58. It can be noticed that all specifications have been respected, except the air void content for the mixtures RA30 and RA60.

However, it can be affirmed that the mechanical performance, in terms of Marshall Stiffness, is largely consistent with the specifications.

Table 58: Marshall parameters vs Italian specifications

Mix	Binder content [%]	Air voids [%]	Stability [daN]	Flow [mm]	Stiffness [daN/mm]
RA0	6.5	3.93	1564	4.4	354
RA30	6.5	6.41	1683	4.5	375
RA60	6.5	6.50	1764	4.5	391
RA90	6.5	5.69	1989	5.7	351
ANAS Specification	-	3 ÷ 6	≥ 1000	-	≥ 300

6.1.3.1 Summary

Some issues arise from the experimental survey: The first regards the evaluation of the granulometric characteristics of the RA from which depends on the achievement of the lowest variability of the final outcome.

This concern increases with the increase of the amount of RA.

Therefore it seems necessary to define a kind of guideline document to standardise the stockpile method in order to minimise the variability of RA properties.

However, regarding the mix design process conducted in the laboratory of the University of Palermo, the good performance of all asphalt mixtures with RA (designed as WMAs) arised in terms of volumetric properties such as workability, susceptibility to compaction and as residual air voids at the end of the design life. Among these points, the workability seems to improve with an increasing RA amount.

Additionally, the positive influence of the rejuvenating agents on the volumetric properties of the asphalt mixtures with RA must be pointed out. At first glance, the use of rejuvenators implies additional costs compared to the production of conventional asphalt mixtures. For example, actually the used rejuvenating additive plus binder costs about three times of the virgin binder. However, the use of rejuvenators usually allows a considerably reduction of the virgin binder combined with the use of an elevated quantity of RA. Hence, analysing the economic factor of the production of asphalt mixtures with RA and additives, the use of renewing agents effects savings in terms of material costs, assumed that RA is without charge.

6.2 German methodology

6.2.1 Maximum possible RA content

The maximum allowable percentage of RA that can be used is determined by adjusting the mix between recycled and virgin materials to the contractual specifications of the target binder (PmB 25/55-55) and to the grading limits of the target mix (SMA 8S). Thus, the maximum possible RA content is taken as the minimum of those determined by the here called bitumen and grading aproaches.

6.2.1.1 Bitumen approach

Very often, the recovered bitumen from the RA does not meet the requirements on the characteristics of the target bitumen due to excessive ageing or hardening. In such case, a virgin binder, usually softer than the target, is added to bring the properties of the blend to the contractual stands. The type of virgin bitumen used in the German mixes was determined in section 4.2 herein.

The virgin binder content to be added is calculated by the so-called blending design charts. Figure 41 shows the blending charts of the German mixes (for details about construction of the charts refer to paragraph 5.3). The charts correlate the replaced bitumen content (RBC) with the empirical properties of the blend. By replaced bitumen content it should be understood the percentage of bitumen from the RA in the final blend.

Table 59 summarises the maximum percentage of replaced bitumen that can be used in the final blend to comply with the minimum specification requirements of a PmB 25/55-55.

Table 59: Maximum recovered binder content

	Contractual requirement (per TL Bitumen-StB 07)		
	Frass temp. (max=-10 °C)	**SP R&B (min=55 °C)**	**Pen index (min=25 1/10 mm)**
Max. RBC [M.-%]	72	100	75

The charts in Figure 41 were developed assuming that 100% of the RA binder will be mobilised and become active part of the binder in the new mix. However, in reality it is also possible that part of the RA bitumen remain non-active resulting in a partial blending scenario.

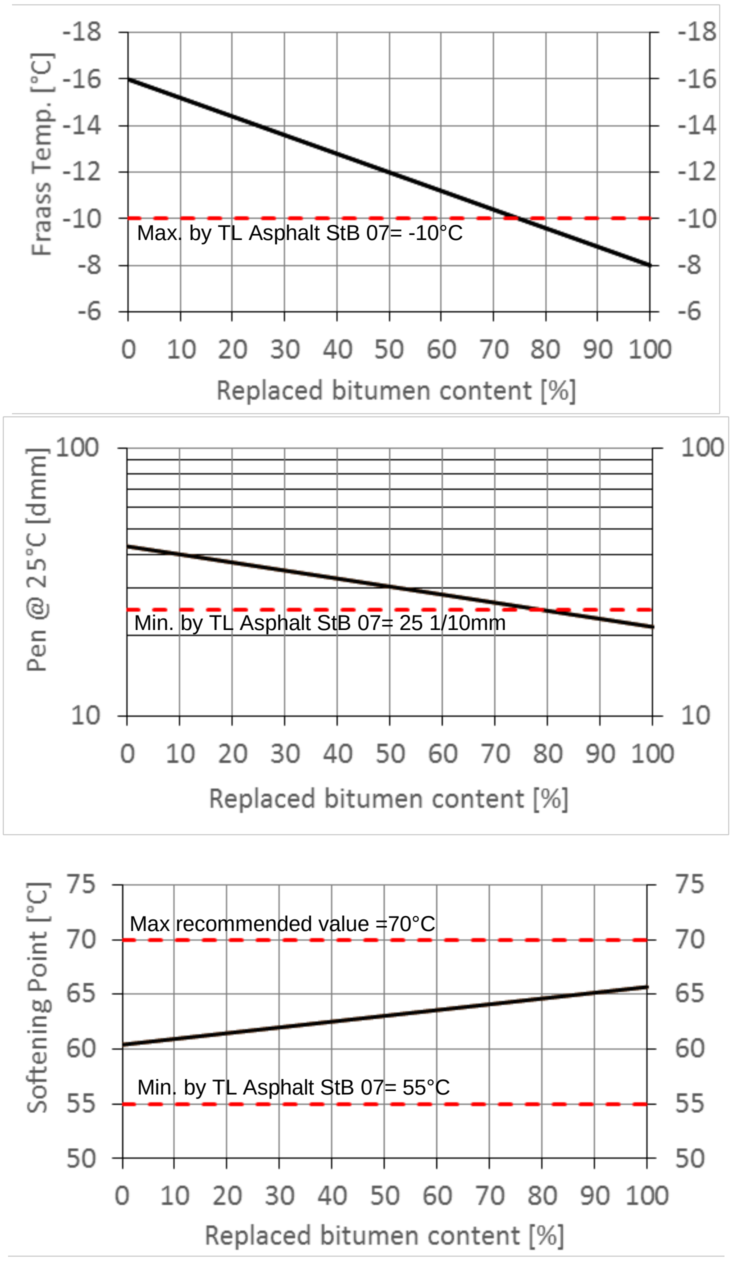

Figure 41: Blending charts of empirical properties

Considering the figure above, an extended version of the blending charts were created to account for the degree of blending between virgin and RA bitumen. The new charts, shown in Figure 42, consider the amount of RA in the mix instead of the replaced bitumen content and represent the most conservative case of the mix design, which corresponds to a mix with 7% of bitumen.

From the new charts, it is observed that there is no restriction on the amount of RA as regards contractual requirement of the bitumen (the max. RA content is capped to 97.8% by the binder content in the RA).

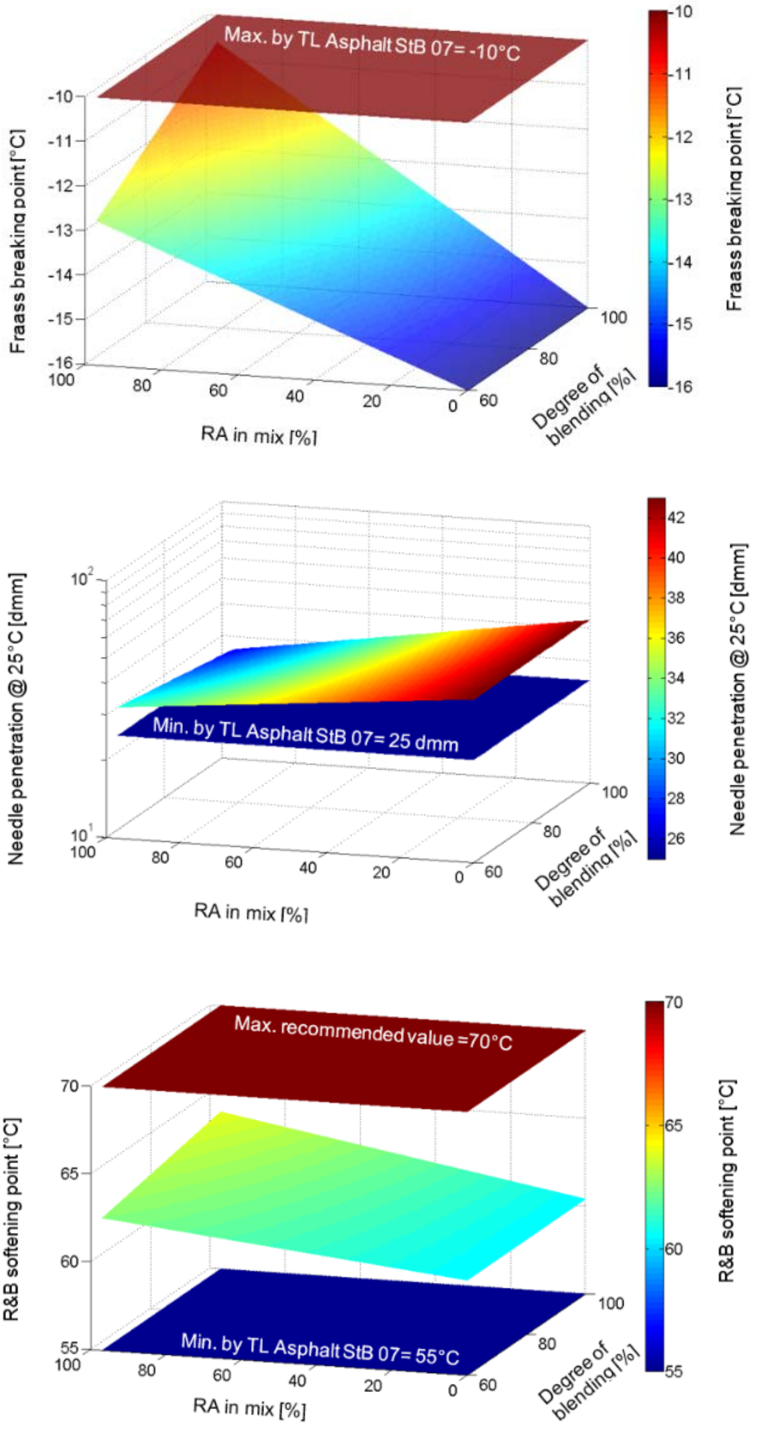

Figure 42: Extended blending charts of empirical properties

6.2.1.2 Grading approach

Since the grain size distribution of the RA does not meet the control points of the target mix (SMA 8S), it was necessary to add virgin aggregates in order to balance the grading. This was done by using an iterative algorithm that decreases the amount of RA and increases the amount of virgin aggregates.

Table 60: Composition of mix with maximum content of RA

	Material	% in Mix	% in Mix Aggregates	% in Virgin Aggregates	% in Mix Bitumen	% in RA
Virgin materials	Crushed stone 8/11 (Gilching)	0.00%	0.00%	0.00%	N/A	N/A
	Crushed stone 8/11 (Treidling)	0.00%	0.00%	0.00%	N/A	N/A
	Crushed stone 5.6/8 (Gilching)	13.05%	14.08%	50.00%	N/A	N/A
	Crushed stone 5.6/8 (Treidling)	13.05%	14.08%	50.00%	N/A	N/A
	Crushed stone 2/5.6 (Gilching)	0.00%	0.00%	0.00%	N/A	N/A
	Crushed stone 2/5.6 (Treidling)	0.00%	0.00%	0.00%	N/A	N/A
	Sand 0/2	0.00%	0.00%	0.00%	N/A	N/A
	Fines	0.00%	0.00%	0.00%	N/A	N/A
	Fibres	0.30%	N/A	N/A	N/A	N/A
	Bitumen 1	3.60%	N/A	N/A	51.40%	N/A
	Additives	0.00%	N/A	N/A	0.00%	N/A
RA	RA Aggregates	66.60%	71.84%	N/A	N/A	95.14%
	RA Bitumen	3.40%	N/A	N/A	48.60%	4.86%
	Sum	100.00%	100.00%	100.00%	100.00%	100.00%
	RA in Mix	70.00%				

*% bitumen in mix: 7.00 %

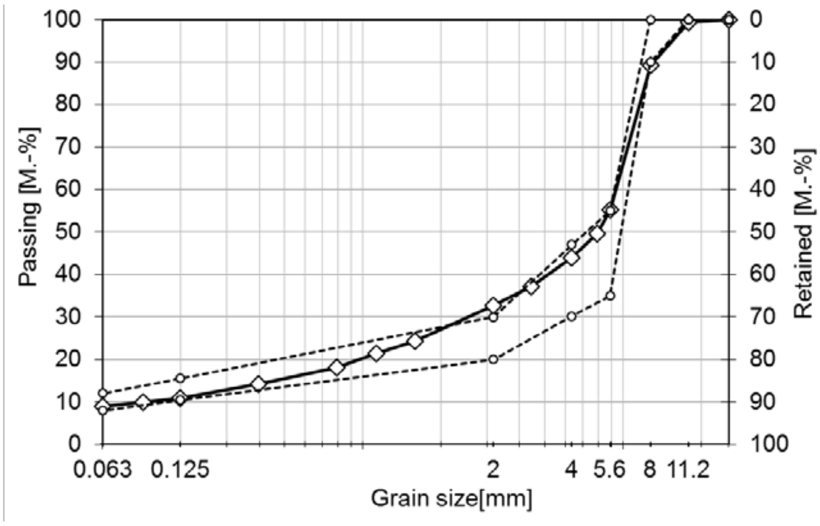

Figure 43: Grading of mix with maximum content of RA

The results, shown in Table 60 indicated that the maximum percentage of RA that can be used is 70%. Higher amounts of RA will result on mixes with grain size distribution outside the contractual limits. The grading of the mix with 70% RA is shown in Figure 43.

6.2.2 Mix design procedure

6.2.2.1 Reclaimed asphalt

In close cooperation with the responsible of the mixing plant all available relevant reclaimed asphalt mixes were selected and following in the laboratory of the Technische Universität Dresden analysed. The main criterion that limited the maximum possible amount of reclaimed asphalt was the grain size distribution of the aggregates of the reclaimed asphalt (after extraction - white grading curve). At the same time, the grading curves of the available virgin aggregates had to be analysed so that the resulting mixture could satisfy the grading limits prescribed in TL-Asphalt StB 07 (TL Asphalt-StB 07, 2013).

To allow the production of different asphalt mixes with the same grading the final grading was defined based on the maximum possible amount of reclaimed asphalt. This means the reclaimed asphalt content was firstly fixed to 90%, 80%, 70% and 60%. After the deduction of binder content and partly fibres, the grading of the reclaimed material was theoretically completed with virgin aggregate.

The resulting particle size distributions were adjusted by varying the percentages of the respective fractions of the virgin aggregate. Finally, the maximum possible amount of reclaimed asphalt had to be limited to 60% to respect the required grading limits.

Consequently, the resulting “best” reclaimed asphalt was a mixture of a removed surface and binder course from the German motorway A8 (removed the 04.09.2014).

The binder content of the reclaimed asphalt was determined as being 4.8 M.-% by the mixing plant. Since this value was unusually small for a surface or binder course, the binder content was also determined at the Technische Universität Dresden. Although, the reclaimed material has been washed 12 times during the extraction process only a maximum binder content of 4.86 M.-% was found. This value was fixed for further considerations.

6.2.2.2 Minimum binder content

The calculation of the percentages of virgin materials, described in the chapter above, was also effected with regard to the required void content in the final SMA mixtures. The final void content depends on the final grading and binder content.

According to TL-Asphalt StB 07 (TL Asphalt-StB 07, 2013)], the minimum binder content of 7.2% for a SMA 8 S refers to an aggregate bulk density of ρ_p of 2.65 g/cm³. This minimum binder content can be reduced by multiplying the factor α according to the equation shown below.

$$\alpha = \frac{2.65}{\rho_p} \tag{15}$$

Hence, the real aggregate bulk density of 2.43 g/cm³ leads to a minimum binder content of 6.6%. Based on this result Marshall specimens were prepared with three different binder contents (Table 61) and identical grading curves. The subsequent analysis showed an optimum binder content of 7.0 M.-%.

Table 61: Optimum binder content in relation to void content

Binder content [M.%]	7.0	7.2	7.4
Void content [%]	2.7	2.0	1.6

6.2.2.3 Virgin components

The four investigated German asphalt mixes are composed of reclaimed asphalt, virgin aggregate, filler, virgin binder and fibres.

For 1t of an asphalt mixture incorporating exemplary 60% reclaimed asphalt with a binder content of 4.86% 29.16kg old binder and 570.84kg aggregates result as quantity of used components. The minimum final binder content of 7.0 M.-%, according to TL-Asphalt StB 07 (TL Asphalt-StB 07, 2013), leads to an amount of 40.84kg virgin binder. The required amount of 0.3 M.-% fibres results in a necessary mass of fibres of 3kg. This results again in a total masse of 356.16kg for virgin aggregate and filler. Considering only the grading curves of the aggregate (reclaimed and virgin aggregate) the following percentages for aggregates can be obtained: aggregate from reclaimed asphalt: 61.58 M.-% and virgin aggregate + filler: 38.42 M.-%.

According to the above mentioned calculations the commercial aggregate fractions 0/2, 2/5, 5/8 and 8/11 as well as external filler were considered. Finally, the quantities of the various material components, reported in Table 62, were obtained for the investigated asphalt mixes.

Figure 44 shows the final reference grading curve for all Asphalt mixes as well as the grading curves of the virgin aggregate fractions for the mixtures with 30% and 60% reclaimed material.

Based on the calculated quantities asphalt mixes were produced in the laboratory of the Technische Universität Dresden and following, as required, compacted with a Marshall compactor. For checking purpose, following the void content has been determined and after extraction of the binder the binder content and grading curve have been determined.

Table 62: Material composition

	0% RA	30% RA	60% RA	60% RA+ Additive
Filler	6.49%	2.57%	0.00%	0.00%
Sand 0/2	25.96%	16.04%	0.89%	0.89%
2/5	11.12%	3.85%	0.00%	0.00%
5/8	43.57%	38.82%	34.73%	34.73%
8/11	5.56%	2.89%	0.00%	0.00%
RA	0%	30%	60%	60%
Virgin binder	7.00%	5.54%	4.08%	3.48%
Fibres	0.3%	0.3%	0.3%	0.3%
Additives	0.00%	0.00%	0.00%	0.60%
	100.00%	100.00%	100.00%	100.00%

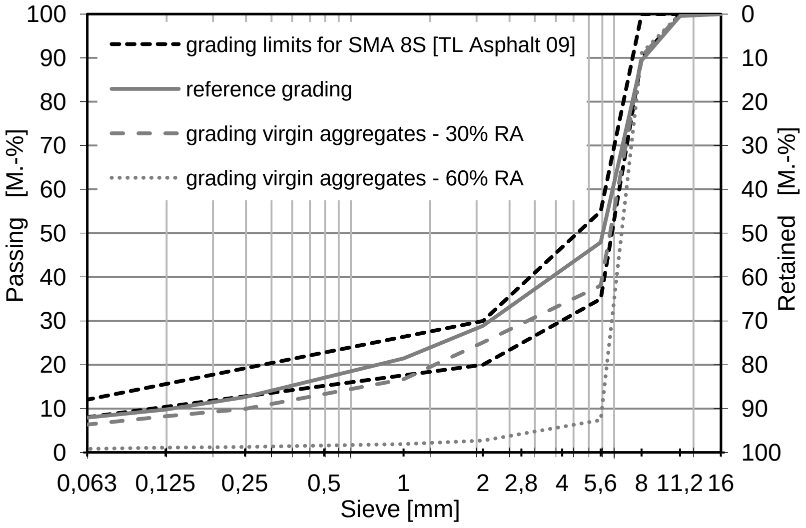

Figure 44: Grading curves of virgin aggregates for the mix designs

6.2.3 *Workability study of WMA*

6.2.3.1 Procedure

A workability study, using the Marshall test, has been carried out to study the influence of additives on the properties of asphalt mixes and on the mixing process. For this purpose, the asphalt mixes incorporating 60% RA and 60% RA + additives were included in the compaction study. Both mixes, produced at mixing plant, were reheated in laboratory to processing temperature and then divided into portions, one for each compaction temperature and mix type. Afterwards the samples were heated to the target temperature + 5°C to account the loss of temperature during placement and were finally put in the Marshall steel mold and instantly compressed with a constant compaction energy of 100 strokes per face. The compaction curve (the change in the specimen height) has been recorded simultaneously.

A realistic maximum temperature during compaction of 150°C was defined. Further investigations were carried out at a compaction temperature of 140°C and 130°C.

In a preliminary test, asphalt material with a defined mass based on internal experiences was heated to the test temperature + 5°C to account the loss of temperature and then placed in the cylindrical Marshall steel mold. The compression of the asphalt material was performed with 2x100 strokes before the final evaluation of the specimen height followed. The final specimen height has to be within the limits of 63.5 +/- 2.5 mm. If the obtained height differs significant from the expected height, the initial weight of the used asphalt mixture has to be adapted and the compression test has to be repeated.

Table 63: Compaction temperatures

Temperature	Mix
150°C	60 % RA 60 % RA + additive
140°C	60 % RA 60 % RA + additive
130°C	60 % RA 60 % RA + additive

For statistical evaluation, three specimens shall be performed per temperature and mix. Two asphalt mixes, three compaction temperatures, one preliminary test and three recorded tests result in a total number of 24 produced Marshall Specimens.

6.2.3.2 Compressibility

The evaluation of the changes in height during compression is shown in Figure 45. The influence of the material composition of the two investigated asphalt mixes on the compressibility can clearly be seen. Thus, for the mixture with 60% RA + additive already after 100 strokes a limit tendency occurred. However, after the end of the study of mixture two without additives no completed compaction can be recognized. The absolute differences of the compaction processes are also visible.

Although, the mixture with 60% RA + additives reaches the maximum compression faster than mixture two without additives, mixture two achieves greater compression, visible by a greater compression difference. However, this does not clearly imply that mixture one with 60% RA + additives has been worse compacted in comparison to the mixture two, since the results refer to the Marshall specimens and cannot be compared isolated.

6.2.3.3 *Temperature dependence*

Furthermore, a dependence of the compression on the compression temperature is recognisable for the asphalt mixture without additives. Thus, a decrease in temperature leads to a delayed and reduced compaction of the material.

In contrast, a temperature dependence of mixture one with 60% RA + additives cannot be deduced, which is undoubtedly attributable to the warm mix additives. Hence, differences in compaction temperature in the range 130°C - 150°C did not affect the compression results.

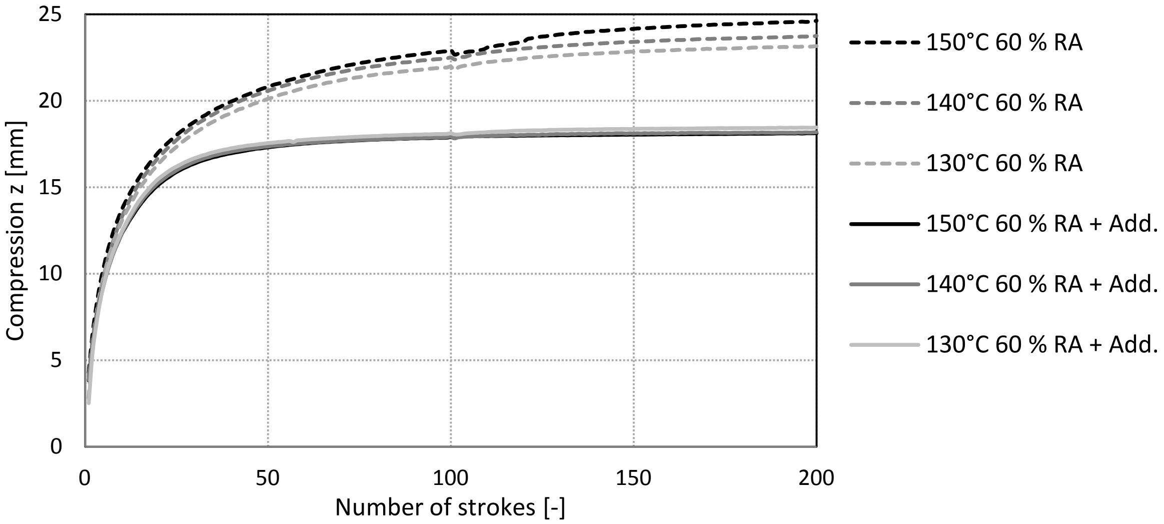

Figure 45: Evolution of compression

6.2.3.4 *Summary*

The workability study has shown that, achieving the same results and quality, the use of warm mix additives can lead to a reduction up to 20°C of the production temperature of an asphalt mixture. This allows a more energy efficient and cost reduced production. Especially in times of rising energy prices is this aspect not negligible.

Additionally, the use of warm mix additives compared with the production of mixes without additives, with an usual preparation temperature of 170 ° C, can extend the period of workability of a mix and increase the maximum distance between mixing plant and construction site. As a consequence, mixing plants can have a greater area of operation, what is particularly important for regions of low density of mixing plants, being beneficial to assurance asphalt layers of high quality.

However, due to gradual adaptation of transport vehicles with thermal isolation in Germany, the extended period of workability of the mix is not considerably important. The saving of heat energy during the production process of asphalt is of greater relevance.

7 Conclusions

The heterogeneity of the RA aggregates plays an important role in the design process of asphalt mixtures for wearing courses where high quality aggregates with high resistance to wear/abrasion (polishing) are needed. Thus, properly milled (i.e. layer by layer) and stockpilled RA is a mandatory prerequisite in order to produce durable asphalt wearing courses with high content of RA. This is a major concern because in the majority of the cases the RA is produced and stockpilled by non-selective methods in which valuable high quality aggregates of wearing courses are milled/stockpilled together with lower quality materials of deeper layers. That means that the aggregates of the RA will automatically be downgraded loosing its ihnerit economic value. One possible solution is to allow the use of high percentage of RA in wearng courses only if the RA material proceeds from the same location and layer where the new mix will be placed.

Because the major component of volume of asphalt mixes is made-up of aggregates, the performance of high RA content pavements is greatly influenced by the characteristics of the RA aggregates. Aiming towards 100% recycling, the distribution of particle sizes in the aggregates of the RA must have just the right density so that the final mix will contain the optimum amount of asphalt binder and air voids.

The asphalt mixtures, investigated within the AllBack2Pave project, were selected with the purpose to be manufactured easily in plant.

In order to achieve the main objective of the project asphalt mixtures with a maximum amount of 90% RA were designed. According to the quality of the used bituminous binders and RA as well as the desired amount of RA, the selected asphalt mixes were designed by using additives (combination of warm mix additive and rejuvenator).

To ensure adequate experiences asphalt mixtures usually produced in the mixing plants of the industrial project partners were selected as reference materials (0%RA).

The experiences gained during the experimental surveys at each partner institute are summarised in the respective chapters.

8 Acknowledgment

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