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SuPerPave[®] Mix Design Method of Recycled Asphalt Concrete Applied in the European Standards Context

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Abstract: The recycling of road and airport asphalt pavements requires greater reliability of mix design in order to ensure proper rehabilitation and effective reuse of recycled asphalt concrete. Currently, internationally, the most effective mix design procedures for recycled asphalt concrete with RAP (Reclaimed Asphalt Pavement) refer to guidelines developed by SuPerPave[®] Mixtures Expert Task Group. In this paper, according to the requirements of the European standard EN 13108, the authors investigated the reliability of the above mix design procedure. In particular, the SuPerPave[®] mix design guidelines were applied for dosing components of wearing course layer recycled asphalt mixture and for the determination of PG (Performance Grade) and critical temperatures of binder contained in RAP (RAP binder) and of binder added ex-novo (virgin binder). The experimental research program started from RAM (Reclaimed Aggregate Material) grading characterization and RAP binder content determination. Afterwards, rheological characterization of the RAP binder and selected virgin binder was carried out using the DSR (Dynamic Shear Rheometer) and BBR (Bending Beam Rheometer) devices. This step allowed us to identify the right virgin binder percentages to be added to RAP binder. Then, in compliance with European standards, the mix design study of recycled mixtures was carried out, identifying the necessary granulometric integrations and the virgin-binder-appropriate percentages to be added. In this phase, three different RAP percentages were used: 30%, 40%, and 50%. Finally, the experimental plan was completed with a preliminary mechanical characterization of the studied recycled asphalt mixtures. The results showed that the implemented rational mix design guarantees performance levels of wearing course layer recycled mixtures that are fully in compliance with European standards.

Keywords: mix design; recycled asphalt; RAP (reclaimed asphalt pavement); RAP binder; virgin binder; RAM (reclaimed aggregate material); SuPerPave[®]



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1. Introduction

In the perspective of sustainable development, the road construction field offers several solutions, among which the recycling of damaged road pavements is the most important. Obviously, the use of recycled materials in asphalt pavement works is only one of the methods to achieve sustainable development of asphalt pavements, and the damaged asphalt concrete is only one of the marginal (sustainable) materials that can be used in asphalt pavement. During their life, flexible road pavements are subject to asphalt layers degradation. To restore the structural and/or functional pavement integrity, it is necessary to perform maintenance work that, most often, involves replacing the damaged layers, with consequent accumulation of waste material commonly called RAP (Reclaimed Asphalt Pavement). In the European context, RAP is called RA (Reclaimed Asphalt) and it is defined as “the processed material in the form of milled or the ripped-up slabs from existing bituminous road layers and the asphalt mixtures from surplus, rejected or failed productions” [1–3].

In Europe in 2018, approximately 300 million tons of asphalt concrete were produced and, today, on the continent, more than 90% of the 5.5 million kilometers of roads are constructed with this material [1]. The option of landfilling RAP is generally rejected in

favor of alternatives that involve recycling it within the road pavements themselves. This issue is of extreme importance, as reflected in the considerable amount of recent studies available in the literature [4–14]. These studies investigated short and long-term mechanical performance of recycled asphalt mixtures [4,6,7,9–11], the outlook and benefits of their use [3,8], mix design issues [5,12,13], and RAP use in road embankment construction [14].

Among the most widely international recycled asphalt concrete mix design references are the guidelines developed by the SuPerPave[®] Mixtures Expert Task Group [15]. These guidelines highlight that the influence of the RAP binder on performance properties of blended binder (RAP binder + virgin binder) depends on the RAP percentage in the asphalt concrete mixture. When the RAP percentage is low, its influence is minimal and RAP is compared to a “black rock” (pure inert aggregate) that only influences volumetric properties of asphalt concrete mixture through its grading and physical/mechanical properties. As the RAP percentage increases, the RAP binder binds to the virgin binder in such a way that it significantly influences the performance properties of the blended binder [16].

The characteristics of a recycled asphalt mixture depend not only on the amount of recycled materials, but also on their nature. In the USA, RAP and RAS (Recycled Asphalt Shingles) are increasingly being recycled simultaneously [17]. More than 99% of RAP and about 1 million tons of RAS are used to make recycled asphalt concrete [18]. To take into account the simultaneous presence of different nature materials (RAP and RAS), the same NCHRP 452 report [16] has been updated several times [18–20]. Initially, the NCHRP specifications set limits for the use of RAP and RAS in asphalt mixtures, referring to their percentage by weight of total aggregate weight. However, this approach does not properly evaluate either the aged binder content in RAP and RAS or the overall performance characteristics of the blended binder [21]. To overcome these limitations, updates to NCHRP Report 452 adopted the concept of the Reclaimed Binder Ratio (RBR), which was previously introduced by AASHTO M323 [22].

Specifically, many USA agencies consider RAP and RAS Binder Ratios to be mutually equivalent and additive quantities, as shown in the following equation [18]:

$$RBR = RAPBR + RASBR = \frac{(Pb_{RAP} \times P_{RAP})}{100 \times Pb_{total}} + \frac{(Pb_{RAS} \times P_{RAS})}{100 \times Pb_{total}} \quad (1)$$

where:

- Pb_{RAP} = RAP binder content;
- P_{RAP} = RAP percentage by weight of mixture;
- Pb_{RAS} = RAS binder content;
- P_{RAS} = RAS percentage by weight of mixture;
- Pb_{total} = binder content of combined mixture.

Today, this approach is no longer considered reliable because, as already pointed out, these amounts are not additive. In fact, RAS contributes an amount of aged binder in blended binder that is about twice as much as that contributed by an equal amount of RAP [21,23]. Therefore, it can be said that there is no widely recognized method to evaluate the performance characteristics of blended binders [21]. The problem is obviously related to the correct interpretation of effects produced by shingles in recycled asphalt mixtures.

Authors believe that this problem is a “false problem” if one takes into account that the use of RAS in pavement recycling is still subject to severe limitations. For example, in the USA, although shingles are present in large quantities, their recycling has been considered only in recent years. In Europe, the use of RAS in road pavements is even more limited [17]. Based on these considerations, the authors believe that it is permissible to neglect (especially in the European context) the use of RAS and, therefore, the present study was conducted adopting as its reference the SuPerPave[®] mix design guidelines defined in NCHRP Report 452 [16,24].

In particular, SuPerPave[®] mix design guidelines were used to characterize the RAP binder performance and to identify blended binder characteristics. Experimental character-

ization of the RAP binder was conducted through rheological testing by DSR (Dynamic Shear Rheometer) and BBR (Bending Beam Rheometer).

In this study, the SuPerPave[®] mix design guidelines were used in a “hybrid” form to allow the use of pre-determined amounts of RAP (30%, 40%, and 50% by weight). This “hybrid” methodology will allow the use of a single virgin binder of known PG and, as mentioned above, predefined percentages of RAP. Finally, referring to European standards [2], mix design studies of recycled asphalt concrete mixes were developed and their mechanical characterization was carried out.

The obtained results highlight the reliability of the SuPerPave[®] rational mix design in achieving performance levels of recycled asphalt mixtures that are also fully compliant with European standards. The opportunity to produce recycled asphalt concrete for surface layers of good performance, with reuse of high RAP percentages, allows for the provision of an effective response to sustainability needs in road pavement construction. In fact, the degraded pavements reuse with the SuPerPave[®] rational mix design techniques generate economic, environmental, and social benefits, fully interpreting the sustainability paradigm. More specifically, from an economic and environmental point of view, the use of high RAP percentages in road surface layers results in significant savings due to the reduced use of virgin high-quality aggregates.

2. SuPerPave Mix Design Method

In this study, the mix design of recycled asphalt concrete mixtures was conducted according to the rational SuPerPave[®] procedure (Figure 1). With this procedure, the actual rheological performance of RAP binders contained in milled asphalt can be taken into account.

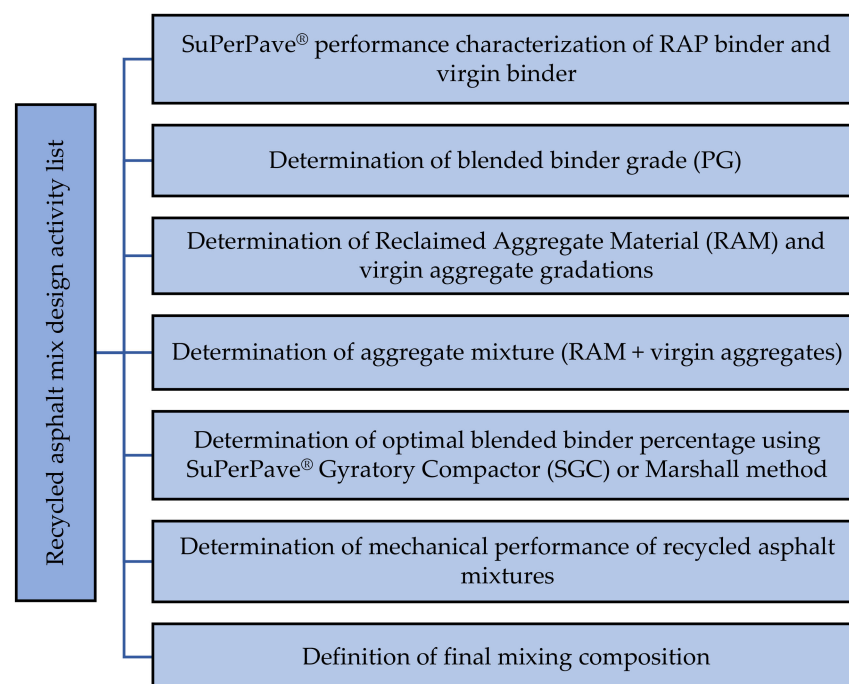


Figure 1. Recycled asphalt mix design activity list.

Referring to Figure 1, it must be pointed out that some phases are common to those provided by traditional mix design methods, while phases related to the determination of the quantities and types of binder to be used in final asphalt concrete mixture are the true innovation introduced by the SuPerPave[®] method.

2.1. SuPerPave® Performance Characterization of RAP Binder

The PG (Performance Grade) choice of the virgin binder to be added to the RAP binder is of fundamental relevance to the success of mix design and is measured by referring to rheological characterization of both binders.

However, if the RAP percentage to be used in recycled asphalt mixture is less than 15%, the PG of the virgin binder is the same, as would normally be determined based on location and environmental conditions of site where the asphalt concrete mixture is used. If, on the other hand, the amount of RAP to be used is between 15% and 25%, the PGXX-YY of the virgin binder is reduced by one class for both the XX and YY values to take into account the hardening effect of the aged bitumen. If the RAP percentage exceeds 25%, mixing nomograms or specific equations must be used to determine RAP percentages that can be used with a predetermined type of virgin binder or, conversely, determine the gradation of virgin binder to be added at a predetermined RAP percentage [16].

The performance of the RAP binder is identified by Dynamic Shear Rheometer (DSR) tests. These tests allow us to determine the critical temperature T_c (High) corresponding to a $G^*/\sin\delta$ value equal to 1.00 kPa (Figure 2):

$$T_c(High)_{RAP} = \left(\frac{\log 1.00 - \log G_1}{a} \right) + T_1 \quad (2)$$

where:

- $G_1 = G^*/\sin\delta@T_1$ temperature;
- $a = \left[\Delta \log \left(\frac{G^*}{\sin\delta} \right) \right] / \Delta T$ slope of the Rutting Factor curve (in log scale) as a function of temperature.

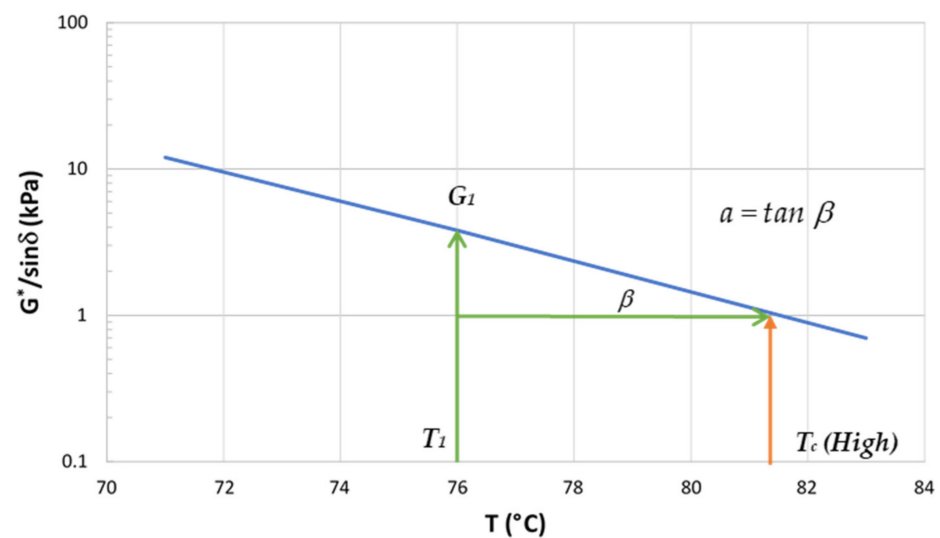


Figure 2. Example of T_c (High) determination.

Bitumen recovered from RAP was further aged using a rolling thin film oven (RTFO) and then tested by DSR in order to determine the critical temperature T_c (High) corresponding to a $G^*/\sin\delta$ value of 2.20 kPa:

$$T_c(High)_{RTFO} = \left(\frac{\log 2.20 - \log G_1}{a} \right) + T_1 \quad (3)$$

The T_c (High) to be considered for the determining class XX of PGXX-YY of the RAP binder will be the lower between T_c (High)_{RAP} and T_c (High)_{RTFO}. To determine the intermediate critical temperature T_c (Int), corresponding to a Cracking Factor ($G^* \cdot \sin\delta$) value of 5000 kPa, the RTFO-aged RAP binder is still used (the RAP binder should not

be aged by Pressure Aging Vessel). The intermediate critical temperature can then be determined as:

$$T_c(Int)_{RTFO} = \left(\frac{\log 5000 - \log G_1}{a} \right) + T_1 \quad (4)$$

where:

- $G_1 = G^* \cdot \sin \delta @ T_1$ temperature;
- $a = \Delta \log(G^* \cdot \sin \delta) / \Delta T$ slope of Cracking Factor curve (in log scale) as a function of temperature.

The RTFO-aged RAP binder was subsequently tested with a Bending Beam Rheometer (BBR) in order to determine the critical Low $T_c(S)$ and $T_c(m)$ temperatures, which correspond to a stiffness equal to 300 MPa and an m -value equal to 0.3, respectively:

$$T_c(S)_{RTFO} = \left(\frac{\log 300 - \log S_1}{a} \right) + T_1 \quad (5)$$

$$T_c(m)_{RTFO} = \left(\frac{0.3 - m_1}{a_1} \right) + T_1 \quad (6)$$

where:

- $S_1 = S\text{-value} @ T_1$ temperature;
- $m_1 = m\text{-value} @ T_1$ temperature;
- $a = \Delta \log(S) / \Delta T$ slope of stiffness curve S (in log scale) as a function of temperature.
- $a_1 = \Delta m / \Delta T$ slope of m -value curve (in log scale) as a function of temperature.

The T_c (Low) to be considered; to define the RAP binder, PGXX-YY will be the greater between $T_c(S)$ and $T_c(m)$.

Once the RAP binder has been rheologically characterized as described in this section, the rheological characterization of the virgin binder was carried out according to the usual SuPerPave[®] procedures [24]. Finally, it is possible to move on to the mix design of the recycled mixtures.

2.2. Blending Strategy

Two criteria can be used to define the mixture of binders (blended binder) [16]:

- blending at a known RAP percentage (Method 1);
- blending with an unknown RAP percentage (Method 2).

If the amount of RAP to be used is known a priori, Method 1 is applicable. The T_{blend} of binder is given by the relation:

$$T_{blend} = T_{virgin}(1 - \%RAP) + T_{RAP} \cdot \%RAP \quad (7)$$

where:

- T_{virgin} = critical temperature of the virgin binder;
- T_{blend} = critical temperature of the binder's mixture;
- $\%RAP$ = fixed RAP percentage expressed as a decimal number;
- T_{RAP} = critical temperature of recovered RAP binder.

The critical temperature T_{blend} was identified on the basis of location and environmental conditions of the site where the recycled asphalt mix is to be used (a function of the maximum and minimum temperature of the place where pavement will be built), while T_{RAP} is identified by performing rheological tests on extracted binder. It follows that the unknown parameter in Equation (7) is the virgin binder critical temperature, so Equation (7) is rewritten as follows:

$$T_{virgin} = \frac{T_{blend} - \%RAP \cdot T_{RAP}}{1 - \%RAP} \quad (8)$$

This equation allows SuPerPave[®] requirements to be met at low, intermediate, and high temperatures.

Method 2 (blending at a known binder grade) applies if the amount of RAP to be used is unknown, but the virgin binder PG is known. The RAP percentage is given by the expression:

$$\%RAP = \frac{T_{blend} - T_{virgin}}{T_{RAP} - T_{virgin}} \quad (9)$$

In this study, a “hybrid” methodology was employed because only one virgin binder of known characteristics was used and, at the same time, different RAP percentages were set (30%, 40%, and 50%), each time deriving the T_{blend} directly from Equation (7). Given the T_{blend} , it is possible to determine site characteristics where the different mixtures could be used.

3. Materials Characterization

As already pointed out, the recycling process requires a preliminary phase of study and control of aged asphalt concrete (RAP), the definition of the necessary integrations for its regeneration, and the verification of the suitability of the recycled asphalt concrete’s physical and mechanical characteristics. In this experimentation, the following operational phases were carried out:

- analysis of a representative sample of reclaimed asphalt (RAP);
- bituminous binder extraction, i.e., separation of bitumen from aggregates without altering the RAP binder’s characteristics;
- determination of the amount and PG of the RAP binder by rheological tests;
- particle size analysis of the RAP aggregates mixture (RAM) and definition of the appropriate virgin aggregate additions;
- determination of virgin binder dosage and identification of the optimal percentage of blended binder by Marshall method;
- specimens preparation and verification of recycled asphalt mixtures physical and mechanical characteristics.

The used RAP is a cold-milled material and not stockpiled, which prevents any material alteration of physical characteristics. The supply site provided RAP from milling of wearing course layers to a depth of approximately 5–6 cm, which can be reused to produce wearing course and/or binder concrete asphalt mixtures.

Two different types of RAP binder extractions were carried out: hot and cold extractions. Hot extractions [25], which have quite fast execution times, allowed us to determine binder content in milled material, equal to 4.5%, and the gradation of RAM. Cold extractions [26,27], which avoids the alteration of the binder, allowed RAP binder rheological characteristics determination.

3.1. Rheological Characterization of RAP Binder

The critical high-temperature determination, corresponding to a Rutting Factor $G^*/\sin\delta$ value of 1.00 kPa, was performed by DSR tests on the RAP binder. Since it is an aged binder, a relatively high initial test temperature of 70 °C was used, resulting in a Rutting Factor value of 11.98 kPa. Subsequently, two more determinations series were conducted at 76 and 82 °C, obtaining 3.95 and 1.05 kPa, respectively. Having assessed linear dependence between test temperature and the corresponding logarithm of $G^*/\sin\delta$, applying Equation (2) where $a = -0.0881$, $G_1 = 1.05$ kPa, and $T_1 = 82$ °C, the T_c (High)_{RAP} was determined to be 82.24 °C.

The T_c (High)_{RTFO} was then determined, where the RAP binder aged through RTFO reached the $G^*/\sin\delta$ value of 2.20 kPa. DSR tests were conducted at 70, 76, and 82 °C, obtaining the Rutting Factor values of 11.35, 6.50, and 3.01 kPa, respectively. Applying Equation (3) where $a = -0.0480$, $G_1 = 3.01$ kPa, and $T_1 = 82$ °C, the T_c (High)_{RTFO} was

determined to be 84.84 °C. Thus, the RAP binder XX class of PGXX-YY was determined to be 82 °C (lower of 82.24 and 84.84 °C).

The RAP binder $T_c (Int)_{RTFO}$ determination was conducted by DSR tests on the RTFO-aged binder. For the execution of these tests, parallel plates 8mm in diameter were used with test temperatures of 34 and 37 °C, at which $G^* \cdot \sin \delta$ values of 6754 and 4659 kPa were obtained, respectively. These values, introduced in Equation (4) where $a_1 = -0.0538$, $G_1 = 4659$ kPa, and $T_1 = 37$ °C, allowed the $T_c (int)_{RTFO}$ to be determined as 36.43 °C.

The critical Low $T_c (S)$ and $T_c (m)$ RAP binder temperatures were determined by a series of BBR tests on the RTFO-aged binder. RAP binder beams were created at a temperature of 175 °C. This temperature value was necessary because of the high viscosity of the RAP binder due to its aging degree. In fact, at the usual temperatures (about 145 °C), it is not possible to obtain a correct beams filling. In addition, to reduce thermal shock when the binder comes into contact with the mold, the metal mold was pre-heated to a temperature of approximately 90 °C. The critical Low $T_c (S)$ RAP binder temperature was determined by performing two sets of BBR tests at temperatures of −6 and −12 °C, obtaining creep stiffnesses S of 309.50 and 416.15MPa, respectively. Therefore, by using Equation (5), in which $a = -0.0214$, $S_1 = 309.50$ MPa, and $T_1 = -6$ °C, $T_c (S)_{RTFO}$ of −5.37 °C was obtained. The m -values obtained at temperatures of −6 and −12 °C were 0.305 and 0.265, respectively. By introducing these values into Equation (6) and placing $a_1 = 0.0102$, $m_1 = 0.305$ MPa, and $T_1 = -6$ °C, $T_c (m)_{RTFO}$ results in −6.70 °C. As a conclusion, the YY class of RAP binder PGXX-YY was determined to be −10 °C. This value corresponds, according to AASTHO MP1 [24], to the higher of the two determined Low temperatures (−5.37 and −6.70 °C).

According with requirements of AASTHO MP1, overall analysis of experimental results allowed us to identify a RAP binder PG equal to PG82-10 (Table 1).

Table 1. RAP binder's results.

Aging	Property	Critical Temperature (°C)	
Original	DRS $G^* / \sin \delta$	High	82.24
RTFO	DRS $G^* / \sin \delta$	High	84.84
RTFO ¹	DRS $G^* \cdot \sin \delta$	Intermediate	36.43
RTFO ¹	BBR S -value	Low	−5.37
RTFO ¹	BBR m -value	Low	−6.70
		PG (MP1)	PG82-10

¹ Test RTFO-aged recovered RAP binder as if PAV-aged.

3.2. Rheological Characterization of Virgin Binder

The virgin binder is a PMB (Polymer Modified Binder) with low radial SBS polymer modification (2.5%), with penetration at 25 °C [28] equal to 58 mm, ball and ring softening point [29] equal to 65 °C, and dynamic viscosity [30] at 160 °C equal to 0.35 Pas. The rheological characterization of the binder provided the results shown in Table 2. In particular, it allowed us to determine the virgin binder PG equal to PG64-22. On the virgin binder, further tests were conducted at 60 °C to determine the ZSV (Zero Shear Viscosity) [31,32] which provided a viscosity η_0 value of 65 Pas.

Table 2. Virgin binder's properties.

Aging	Property	Critical Temperature (°C)	
Original	DRS $G^*/\sin\delta$	High	61.15
RTFO	DRS $G^*/\sin\delta$	High	64.11
PAV	DRS $G^*\cdot\sin\delta$	Intermediate	22.35
PAV	BBR S -value	Low	−12.35
PAV	BBR m -value	Low	−12.13
	PG (MP1)	PG64-22	

3.3. Blended Binders Performances

In this study, the idea was to use fixed RAP percentages in recycled asphalt concrete mixtures. Therefore, blended binder performances were determined corresponding to fixed RAP percentages, as a function of the characteristics of the used RAP binder and virgin binder. On the basis of these performances, the PGs of the blended binders were defined, which allowed us to identify the recycled asphalt mixtures' climatic and environmental employ zones.

For each predetermined RAP percentage (30%, 40%, and 50%), equation 7 allowed us to obtain the T_{blend} temperatures of the corresponding blended binders. This allowed us to determine the blended binders' PGs based on AASTHO MP1 (Table 3).

Table 3. Blended binder's properties calculated.

Property	Critical Temperature		
	RAP 30%	RAP 40%	RAP 50%
	(°C)	(°C)	(°C)
T_c (High)	69.55	71.36	73.17
T_c (Intermediate)	26.57	27.98	29.39
T_c (Low)	−7.40	−8.07	−8.75
PG (MP1)	PG64-16	PG70-16	PG70-16

In accordance with the above determinations, it can be stated that recycled asphalt concrete mixtures, with all RAP percentages, can be effectively used in climatic zones with medium to low winter temperatures (PGXX-16).

In order to verify the reliability of binder blends critical temperatures, determined according to the SuPerPave[®] methodology, with reference to different RAP percentages, it was appropriate to prepare different mixtures of the RAP binder and virgin binder. In particular, assuming that for producing the recycled asphalt concrete the bituminous binder percentage to be used is equal to 5%, taking into account that the RAP binder content in RAP is 4.5%, with a RAP percentage of 30%, the RAP binder content in-mixture is 27% of the total bitumen, and the remaining 73% must be made up of added virgin binder. Similarly, for a RAP percentage of 40%, the RAP binder makes up 36% of the total bituminous binder to which 64% of virgin binder must be added. At the 50% RAP percentage, the RAP binder in milled material made up 45% of the total bitumen, while the virgin binder to be added was 55%.

Using these percentages, three different mixes of blended binders were prepared, on which DSR tests were conducted on both unaged blends and the corresponding aged by RTFO and PAV blends. From experimental results (Table 4), there was considerable convergence with respect to the critical temperatures calculated using Equation (7).

Table 4. Blended binder's properties verification.

Aging	Property	Critical Temperature		
		RAP 30%	RAP 40%	RAP 50%
		(°C)	(°C)	(°C)
Original	DRS $G^*/\sin\delta$	68.46	70.13	72.47
RTFO	DRS $G^*/\sin\delta$	69.12	71.59	73.61
PAV	DRS $G^*\cdot\sin\delta$	25.89	27.15	29.05
PAV	BBR S -value	−7.28	−7.05	−8.71
PAV	BBR m -value	−6.85	−7.94	−8.13
	PG (MP1)	PG64-16	PG70-16	PG70-16

4. Recycled Asphalt Concrete Mixtures

The particle size analysis of aggregate extracted from milled asphalt (RAM) was performed by drying the material in an oven and then sieving it with sieves selected in according EN 13043 [33] and EN 13108-1 [34] (Figure 3). The obtained RAM gradation is shown in Figure 4 and Table 5 and it is indicated as RAP (white curve).

Referring to EN 13108-1, the general grading requirements of the target composition (basic sieve set plus set 2) are those related to $D = 12$ (12.5 mm), which obviously refer to a wearing course layer asphalt concrete. For the grading envelope definition of the recycled asphalt concrete target composition, reference was made to the Italian ANAS specifications [35], which are fully compliant with EN 13108-1 (Figures 4 and 5, Table 5).

As shown in Figure 4, in order to obtain a target composition within the grading envelope, a granulometric integration of virgin aggregate was necessary. This integration was carried out using limestone aggregate with discrete mechanical characteristics (Los Angeles Index $LA = 24.5\%$) [36] and with substitution of 3% of natural filler ($d < 0.063\text{mm}$) with monohydrated lime.

A 6/8 gravel of category $G_c 90/15$ and a 0/2 sand of category $G_f 85$ were used for granulometric integration [33]. The gradations of virgin aggregates are shown in Figure 4 and Table 5.



Figure 3. RAP (a) before binder extraction (black); (b) after binder extraction (RAM-white).

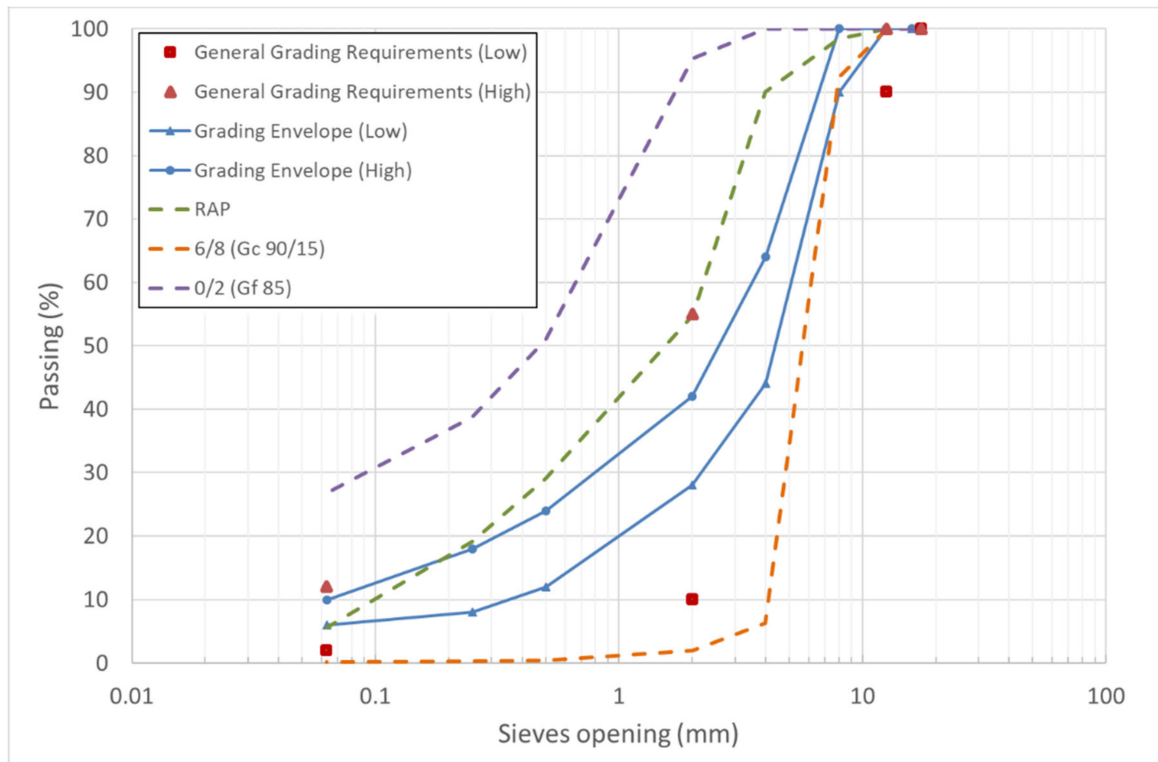


Figure 4. RAP and virgin aggregates gradations.

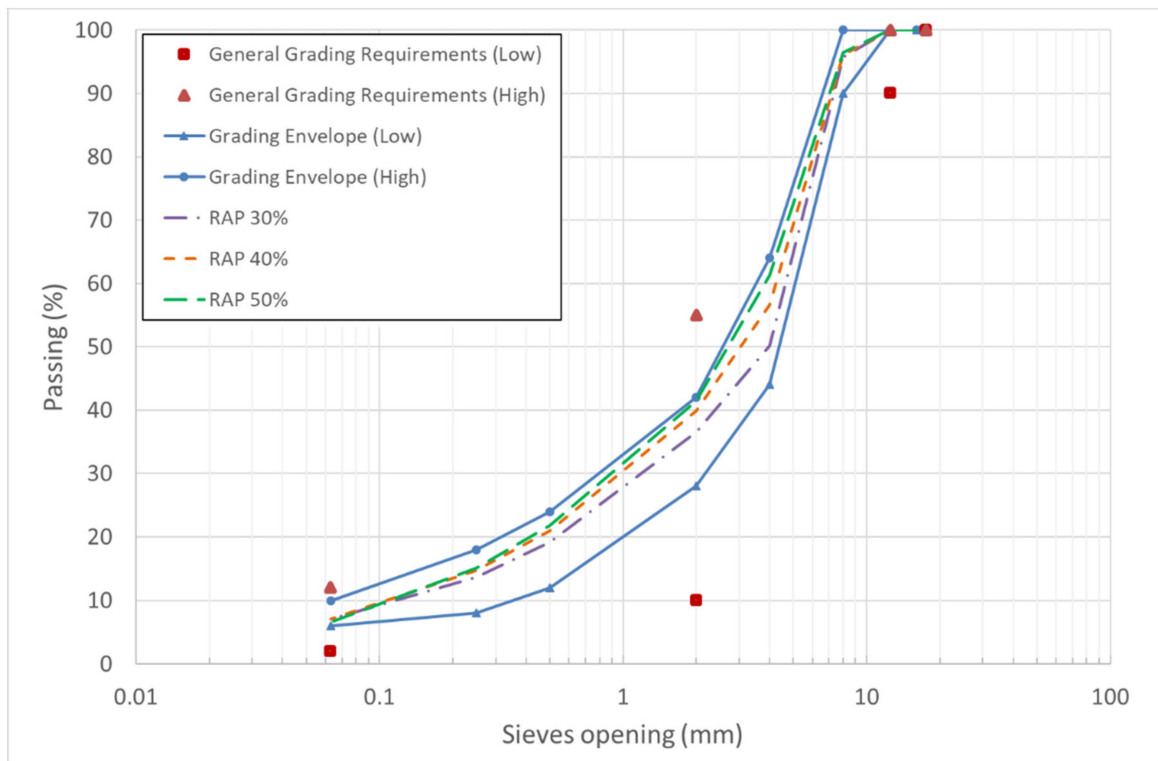


Figure 5. Target composition gradations.

Table 5. RAP, virgin aggregates and mixes gradations.

Sieves Opening d (mm)	Grading Envelope Passing (%)	RAP and Virgin Aggregates Gradations			MIX Gradations		
		RAP Passing (%)	6/8 (G _c 90/15) Passing (%)	0/2 (G _f 85) Passing (%)	RAP 30% ⁽¹⁾ Passing (%)	RAP 40% ⁽²⁾ Passing (%)	RAP 50% ⁽³⁾ Passing (%)
16	100–100	100	100	100	100	100	100
12.5	100–100	100	100	100	100	100	100
8	90–100	98.45	92.3	100	95.69	96.15	96.45
4	44–64	90.05	6.3	100	50.17	56.67	61.29
2	28–42	54.75	2	95.3	36.49	39.89	41.44
0.5	12–24	29.07	0.4	50.9	19.10	20.96	21.81
0.25	8–18	19.12	0.25	38.75	13.61	14.73	15.08
0.063	6–10	5.54	0.15	26.7	7.08 ⁽⁴⁾	7.09 ⁽⁴⁾	6.56 ⁽⁴⁾

⁽¹⁾ RAP 30% Mix = 30% RAP + 50% 6/8 (G_c 90/15) + 20% 0/2 (G_f 85); ⁽²⁾ RAP 40% Mix = 40% RAP + 42% 6/8 (G_c 90/15) + 18% 0/2 (G_f 85);

⁽³⁾ RAP 50% Mix = 50% RAP + 36% 6/8 (G_c 90/15) + 14% 0/2 (G_f 85); ⁽⁴⁾ 3% of filler was replaced with monohydrated lime.

The RAP percentages taken into account for the preparation of recycled asphalt mixtures are 30%, 40%, and 50%. The three examined mixtures were named RAP 30%, RAP 40%, and RAP 50%, respectively. Figure 5 and Table 5 show the target composition of these mixtures and Table 5 notes show the RAP and virgin aggregate percentages.

Recycled asphalt concrete mix design was conducted according to the Marshall methodology. In order to determine the total binder optimum percentage (blended binders), for each mixture, five mixes were prepared with a total bituminous binder percentage of 4.0%, 4.5%, 5.0%, 5.5%, and 6.0%. The total bitumen optimum percentage was 5% for all the examined mixtures.

It should be noted that the PGs of the used blended binders with different RAP percentages were PG64-16, PG70-16, and PG70-16, respectively (Table 4). In this study, a preliminary basic mechanical characterization of the recycled asphalt mixtures was also carried out by performing: Marshall tests [37], Indirect Tensile Stress tests [38], and Porosity determinations [39]. Overall results summary is shown in Table 6.

Table 6. Mechanical basic characterization.

Asphalt Mix	Void Content (%)	Marshall Test			Indirect Tensile Test
		Stability (kN)	Flow (mm)	Quotient (kN/mm)	Resistance (MPa)
RAP 30%	5.62	14.85	3.1	4.79	1.65
RAP 40%	5.45	13.75	3.0	4.58	1.60
RAP 50%	4.98	13.25	2.9	4.57	1.63

The basic mechanical performance of all recycled asphalt mixtures was satisfactory; in fact, Marshall Stabilities were all of category higher than MS_{max} 12.5 and the Marshall Flows were all of category F_{3,0} [34]. It should be noted that as RAP percentage increased, Marshall Stability values decreased slightly. In particular, there was a reduction of 7.4% for the RAP40% mixture and 10% for the RAP50% mixture compared with the RAP30% mixture. The indirect tensile resistance, on the other hand, did not change significantly as RAP content changed.

5. Conclusions

The recycling of degraded road pavements requires extensive experimental investigations, especially when RAP percentages to be reused are high (>30%). The guidelines developed by the SuPerPave[®] Mixtures Expert Task Group allow for the mix design of

recycled asphalt concrete to be approached in a rational way. This rational approach was applied to studying the mix design of recycled asphalt concrete mixtures for wearing course layers with high RAP percentage (30%, 40%, and 50% by weight). Then, it was evaluated the compatibility and reliability of the above guidelines with respect to the requirements imposed by European standard EN 13108-1.

In this paper, we studied the rheological performance characteristics' determination of the bituminous binder blend consisting of a RAP binder and virgin binder addition. In the blending strategy phase, unlike SuPerPave[®] guidelines, neither the "blending at know RAP percentage" nor the "blending at a known binder grade" method was applied. Instead, an original "hybrid procedure" was adopted, which involves the use of a single virgin binder of known characteristics, and requires the choice of RAP percentages and requires that the analytical calculation of critical blend temperatures (T_{blend}) be carried out with reference to SuPerPave[®] specifications. The results obtained in this way were experimentally verified by operating on specially prepared blends of the RAP binder and virgin binder (blended binder). This verification allowed us to highlight their remarkable convergence to the estimated critical temperatures calculated with the SuPerPave[®] approach.

The next phase of recycled asphalt mixtures mix design involved the study of dry aggregates mixtures' particle size gradation. This was performed according to EN 13108-1, and it was necessary to integrate aggregate gradation with limestone of good mechanical properties and to replace 3% of the natural filler with monohydrated lime.

Finally, a basic mechanical characterization of the designed mixtures was carried out in order to express a preliminary judgement on the effectiveness of their performance characteristics, which turned out to be fully satisfying the minimum European standards.

The authors remark that the research may have future developments in different areas such as, for example, the study of the effects produced by the use of FCA (Functional Chemical Activant), the mixture's mechanical characterization in relation to the fatigue phenomena (FC—Fatigue Cracking), permanent deformation (rutting), durability, etc.

Based on the abovementioned limitations, the results confirmed the full reliability of SuPerPave[®] rational mix design methodology. The experimental results also showed that the basic mechanical performance was fully satisfactory with respect to European requirements/standards, thus confirming the effectiveness of the rational approach to the road pavements recycling.

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