RAP BINDER IN RECLAIMED ASPHALT CONCRETE THROUGH MIXING CONDITIONS: OBSERVATION, MEASUREMENT AND MECHANICAL CONSIDERATION OF THE BLENDING

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ABSTRACT

When asphalt building materials is manufactured using a high reclaimed asphalt pavement (Rap) content, it is commonly assumed that the whole aged Rap binder takes part in the binder of reclaimed asphalt concrete. In order to understand in which extend methods and industrial tools would influence the blend of reclaimed asphalt concrete components, a laboratory project simulating blending process (mixing temperature, mixing duration) has been undertaken.
The first part involved the development of a microscopic technique to observe the evolution of the blend between Rap and virgin materials. To differentiate Rap and added virgin binder a fluorescent binder is used.
In the second part, a new experimental technique was devised in order to extract gradually the binder of the reclaimed asphalt concrete. This technique measures the homogeneity level of reclaimed asphalt concrete binder through a progressive extraction of asphalt mixes containing Rap.
In the third part, the assumption that whole aged Rap binder is reused is studied trough mechanicals performances of several contents of reclaimed asphalt concrete: rutting resistance, tensile strength and fatigue behaviour. The use of factorial experiment design approach helped to measure these performances under blending process variation.
This project helps to understand the influence of production parameters on reclaimed asphalt concrete correlating performances to the observation and the measurement of the mixing level. A quality control of the blending process validated on high Rap asphalt mixes form two kinds of plants is proposed.

Keywords: HAM recycling, Reclaimed Asphalt Pavement (RAP), environmental performance, infrastructure durability, validation lab test

1. INTRODUCTION

If natural resources are to be preserved and greenhouse gas emissions reduced, then recycling bituminous materials from road deconstruction is an inevitable solution. For the same environmental reasons, new techniques are being developed to reduce the temperature at which asphalt mixtures are manufactured. However, there is some opposition to reducing the production temperatures for reclaimed asphalt concretes because the binder in the recycled asphalt material, also called reclaimed asphalt pavement binder, is by definition thermosensitive. Heat has to be applied to this binder, making it "melt" so that it can then blend with binder added during the recycling operation. We can therefore suppose that insufficient heat (i.e. inadequate "melting") will produce an imperfect blend of new binder and reclaimed asphalt pavement binder.

The work presented here sets out to understand the mechanisms that control the blending of new and recycled constituents, to give a better understanding of reclaimed asphalt concretes, optimise recycling processes and have control over the production quality of reclaimed asphalt concretes as it is this quality that will guarantee the durability of road infrastructure.

First, measurements have been taken during microscopic tests to observe how the constituents were blended together within the reclaimed asphalt concretes. Reclaimed asphalt pavement (RAP) has been observed at intervals during the blending process in order to quantify the mixing kinetics and how they have been influenced by the production parameters of temperature and time taken.

The second aim of the study is to quantify the influence of the degree of blending on the mechanical properties of the reclaimed asphalt concrete. For this, asphalt concretes of apparently identical composition in terms of granulometry and binder consistency has been produced. The influence of mixing time and production temperature on the mechanical properties has been measured for three recycling rates. The mechanical properties considered in this study are resistance to rutting, stiffness modulus and resistance to fatigue.

Thirdly, the degree to which the aged and the new constituents were blended together is measured using specifically designed experimental equipment. The aim is to gradually extract the binder and the aggregates from the recycled asphalt concrete with a bitumen binder solvent. The chemical composition of the products that were gradually sampled (lixiviates) is analysed to provide information on the degree to which the constituents are blended within the reclaimed asphalt concrete. This test has been developed to be applied to an asphalt mixture sampled in a manufacturing plant. It quantifies the influence of production conditions and the reclaimed asphalt concrete recycling rate on the degree of blending.

All justifications and descriptions of the methods used can be found in the PhD thesis [1]. This paper only presents its main results

2. MICROSCOPIC OBSERVATION OF RECLAIMED ASPHALT CONCRETE DURING MIXING: MEASURING THE DEVELOPMENT OF THE DEGREE OF BLENDING OF THE CONSTITUENTS

In 2009, tests by NGUYEN [2] involving large sized (100 mm) artificial reclaimed asphalt pavement and a virgin binder containing iron oxides were reproduced replacing the large sized artificial RAP with RAP produced in a recycling plant. Observation under an optical microscope with white light revealed black patches formed by the agglomeration of fine RAP particles around the aggregates (Fig. 1) (hereafter called clusters). This asphalt mixture had a recycling rate of 50%. However, with this method it was difficult to monitor changes in the cluster, because during the blending process, the virgin binder which was originally red in colour gradually became darker as it mixed with the black reclaimed asphalt pavement binder. This gradual darkening quickly reduced the difference between the red and the black, the colours used respectively to differentiate the virgin binder from the RAP binder.

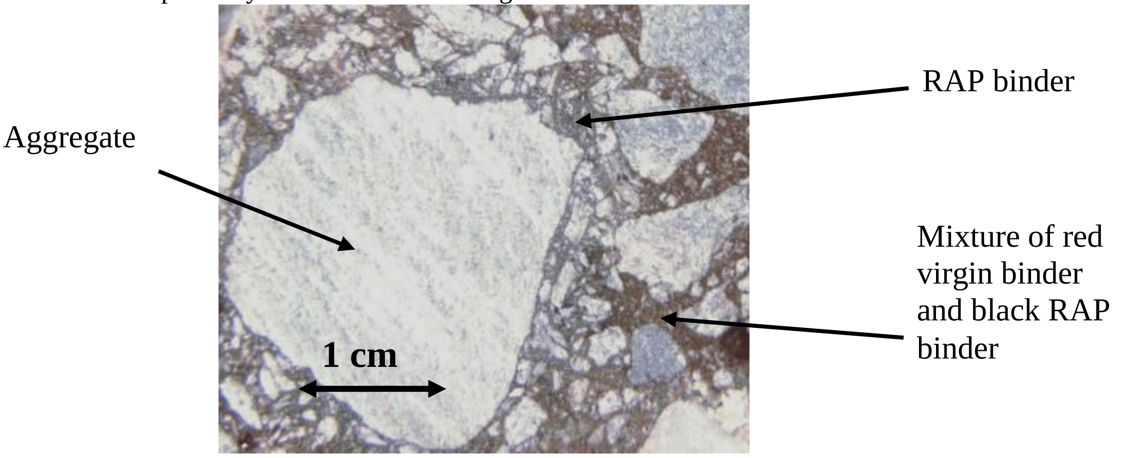


Fig. 1: Cluster of centimetric sized reclaimed asphalt pavement at the surface of the aggregates, highlighted by the addition of binder with iron oxide pigment (red)

While keeping the same principle of using different colours for the virgin binder and the RAP binder, the binder with iron oxide pigment was replaced by a virgin binder that was fluorescent under ultraviolet light and which had the same characteristics as a bituminous binder. This enabled us to introduce an innovative technique by which we could visualise, define and quantify changes occurring in the mixture of constituents of a recycled asphalt concrete while it was being produced in the laboratory. Penetration and ring ball characteristics of this fluorescent synthetic binder are similar to those of a traditional 50/70 $^{1/10}$mm penetration road bitumen i.e. 53 $^{1/10}$ mm and 47°C.
To quantify these changes in the blend of constituents, an observation technique was developed based on analysis of two photographs, one under white light and the other under UV light. For the first time it was possible to differentiate the virgin binder from the RAP binder in the recycled asphalt concrete at a millimetric scale (Fig. 2) during the production process. The resulting images were then processed using an automated image analysis protocol where the recycled asphalt concrete binder could be distinguished on the basis of image contrast. The principle behind this protocol is to use grey-level distribution to determine the area in the photographs that represents binder, then to represent this distribution in a spectrum which presents the information about the mixture in a mathematical format. To make the presentation of the results easier to follow, the aggregates, which by definition are excluded from the binder area, are represented in green and are not taken into account when calculating the spectrum. The spectrum shows the number of pixels in the binder zone in order of luminous intensity, ranging from 0 for the blackest pixels to 255 for the whitest. Thus the darkest pixels in the processed image (excluding green) represent the existence of clusters which can then be quantified from the spectrum provided the intensity is known. This intensity was determined experimentally and fixed at between 40 and 70.

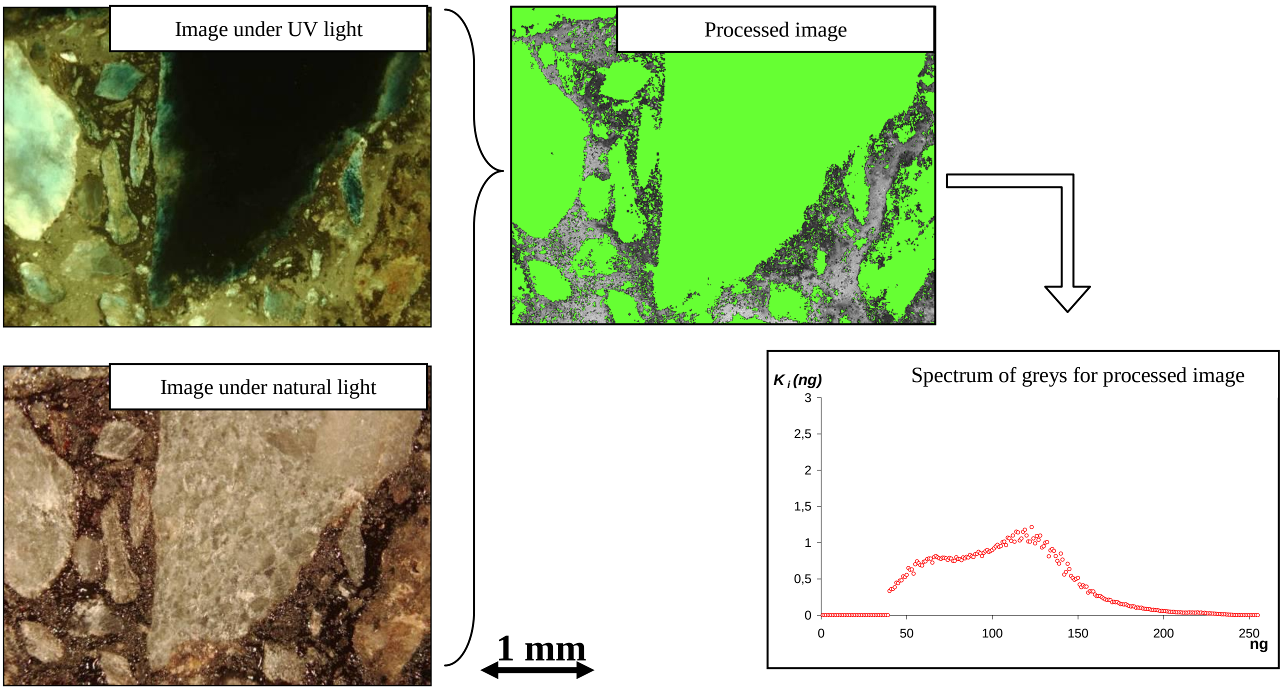


Fig. 2: Principle of process to determine distribution of RAP binder in the recycled asphalt concrete

This combination of observation technique and image analysis protocol was then used to determine by means of indicators the degree of blending of a reclaimed asphalt concrete as a function of mixing time (t_m) and production temperature (T_m). This method was applied to 231 pairs of photographs from observation of recycled asphalt concrete samples produced under controlled conditions. This large number of photographs ensured that we were able to validate statistically the representativity of our observations and the conclusions drawn. Results are shown in figure 3 for the only indicator that will be presented here, A_t (%). This indicator is representative of the presence of clusters during production. This figure shows three sets of points with a decreasing trend and convergence towards the same value of 0.05%. As this corresponds to 10 minutes of mixing, it can be considered as the value for which, independently of production temperature, the recycled asphalt contains no more clusters. This measurement was taken to define the observation limit for indicator A_t (%).
In this figure, note first of all that the large presence of clusters at the beginning of the mixing process in inversely proportional to temperature. Thus, for a production temperature of 110°C, a large proportion of clusters is present at t = 20 s. In comparison, few clusters are present initially for a production temperature of 160°C. At this temperature, and given the uncertainty of the measurements (± 0.05%), these same clusters may be considered as having for the most part disappeared after 54 s of mixing, thus showing that the RAP binder participates to a considerable extent and fairly

quickly when production is at 160°C. It can be therefore assert that the RAP binder is remobilised if production conditions permit.

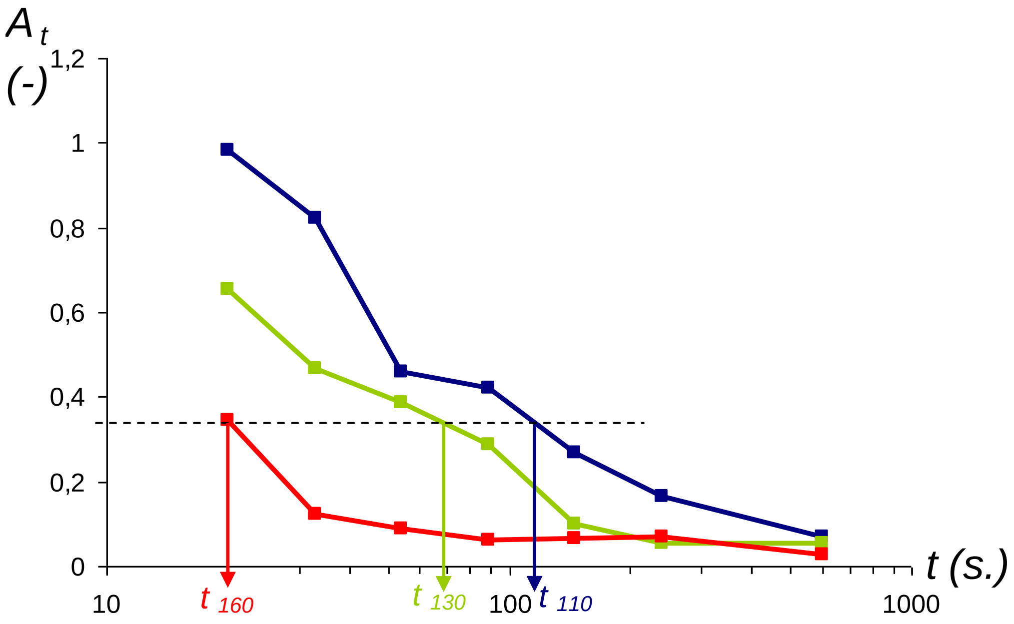


Fig. 3: Kinetics of the disappearance of RAP clusters as a function of mixing time and production temperature (110°C in blue, 130°C in green and 160°C in red)

The green points, showing production at 130°C, and the corresponding curve can be seen, as is logical, between the red series (production at 160°C) and the blue series (production at 110°C). Figure 3 clearly shows that a reduction in production temperature favours the existence of clusters during mixing which, given the composition of the RAP binder, indicates that not all of it is remobilised. It should be noted, however, that an increase in mixing time can compensate in part for a drop in production temperature.
By determining characteristic durations (t_{160}, t_{130}, t_{110}), the graph in figure 3 can be used to show the relationship between a reduction in production temperature and an increase in mixing time. To obtain a quantity of clusters equivalent to 20 s of mixing at 160°C requires 3.5 times more time at 130°C and 6 times more time at 110°C.

These results show that at the beginning of reclaimed asphalt concrete production, clusters of RAP are present but they are reduced by the mechanical mixing action during production. As the temperature drops, there is a considerable decrease in the speed at which clusters are reduced and hence in homogenisation of the reclaimed asphalt binder. As well as showing that, in suitable conditions, the RAP binder may re-participate completely in binding the reclaimed asphalt mixture, these observations provide important new information on the phenomena and mechanisms governing the production of reclaimed asphalt concretes with a high RAP content.
It is also relevant to consider the influence of the clusters that have been identified and the different degrees of blending on the mechanical performance of the reclaimed asphalt mixtures.

3. MEASURING SENSITIVITY TO PRODUCTION CONDITIONS OF THE MECHANICAL PERFORMANCE OF THE RECLAIMED ASPHALT CONCRETES

In this section, we measure the influence of the degree of blending, previously observed visually, on the mechanical characteristics of reclaimed asphalt concretes with a RAP content of between 20% and 70%. This recycling rate is then written C_{GAE}^{GER}, the mass fraction of RAP aggregate in the recycled asphalt concrete aggregate. In the same way as before, different degrees of blending were obtained by adjusting mixing time (t_m) and production temperature of the bituminous recycled asphalt mixtures (T_m) in a controlled way.
The type of asphalt concrete chosen for this series of trials was BBME 0/10 (High Modulus Asphalt Concrete, granulometry 0/10 mm). The mechanical properties studied were rutting (Orn.) [3], stiffness modulus under direct tension at 15°C and 10 Hz (TD15) and at 10°C and 10 Hz (TD10) [4], also resistance to fatigue measured at 10°C and 25 Hz (Fat.) [5].
In order to reduce the number of experimental tests required for this study by half, an experimental design [6] was used (Fig. 4). To ensure that the granulometric graph and binder content of the asphalt mixtures studied was independent of the recycling rate, a major preparation stage was first carried out on the RAP that was being used. This consisted of separating the granulometry 0/10 mm material into three granulometries of 0/4, 4/6 and 6/10 mm. This was essential in order to control the composition of the recycled asphalt concrete studied.

During the formulation stage, it is supposed that all the binder present in the RAP is remobilised. Given this hypothesis, virgin binders of different grades were produced, specifically adapted to each recycling rate (20%, 45% and 70%) so that the penetrability of the binder produced by the combination of binders (35/50 and 160/220 penetration grade of the same brent origin) was independent of the recycling rate. Thus for recycling rates of 20%, 45% and 70%, the virgin binders that were used belonged to classes 35/50 (39 $^{1/10}$mm), 50/70 (66 $^{1/10}$mm) and 160/220 (170 $^{1/10}$mm) respectively. By this way, for each of the different recycling rate, the reclaimed binder in the reclaimed asphalt concrete has a penetrability equals to 32 $^{1/10}$mm after being mixed with the corresponding amout of the Rap bitumen (14 $^{1/10}$mm).

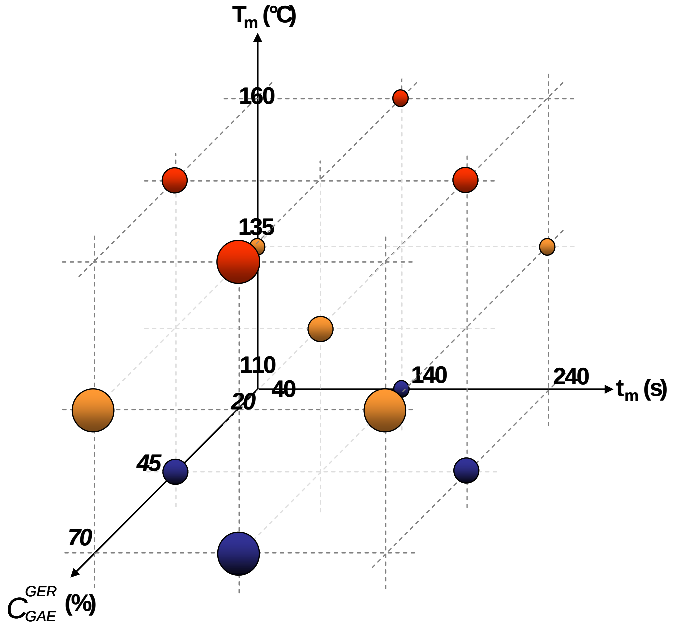


Fig. 4: Experimental points of the BOX-BEHNKEN design

3.1 Measuring resistance to rutting at 30,000 cycles (NF EN 12697-22)

The tests carried out and analysed according to the experimental design showed that for a mixing time of 40 s (Fig. 5), rutting was not dependent on recycling content. In addition, it was 5.1 ± 0.6% for production temperatures of 135°C and 160°C and significantly less when the production temperature was 110°C (4.3 ± 0.6%).

When the mixing time was increased from 40 s (Fig. 5) to 240 s (Fig. 6), rutting increased significantly by 1% for a 20% recycled asphalt mixture, and this was independent of production temperature. For a 70% recycled asphalt mixture, this change was not significant at 0.1 %.

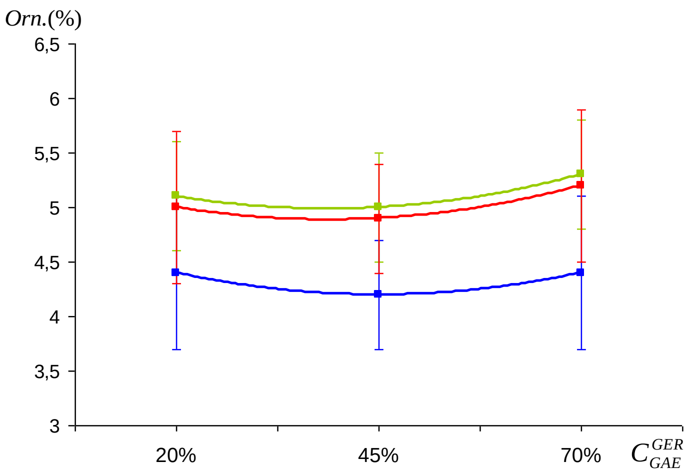


Fig. 5: Rutting as a function of recycling rate for a mixing time of 40 s (110°C in blue, 135°C in green, 160°C in red)

With a mixing time of 240 s (Fig. 6), rutting was reduced by increasing the recycling rate. For production temperatures of 135°C and 160°C, rutting decreased from 5.4 ± 0.5% to 5.1 ± 0.5% between recycling rates of 20% and 70%. For a production temperature of 110°C, rutting decreased from 4.8 ± 0.5% to 4.3 ± 0.5% between recycling rates of 20% and 70%. Note that in both cases the decrease in the measurement for rutting falls within the range of measurement uncertainty.

Independently of mixing time and recycling rate in the asphalt mixture, rutting was significantly lower at a production temperature of 110°C than at production temperatures of 135°C and 160°C.

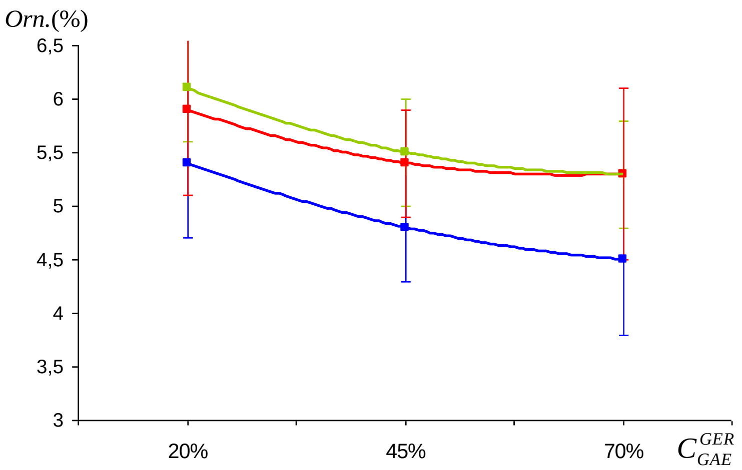


Fig. 6: Rutting as a function of recycling rate for a mixing time of 240 s (110°C in blue, 135°C in green, 160°C in red)

These observations suggest that resistance to rutting is independent of the characteristics of the virgin binder. With reference to observations made in part 2, even for production conditions that give a blend of constituents that is clearly imperfect, the existence of virgin binder that is not mixed with the RAP binder does not give rise to pronounced rutting. The use of RAP even appears to give a certain rutting stability in relation to production conditions. In addition, it should be noted that with regard to rutting the behaviour of asphalt mixtures produced at 135°C and 160°C is identical.

3.2 Stiffness modulus in direct tension (NF EN 12697-26)

Results of the stiffness modulus tests show that for a mixing time of 40 s (Fig. 7), the stiffness modulus is significantly dependent on recycling rate and production temperature. For temperatures of 135°C and 160°C, it dropped from 14170 ± 940 MPa to 10322 ± 920 MPa between recycling rates of 20% and 70% and from 12640 ± 1080 MPa to 8620± 1080 MPa between recycling rates of 20% and 70% at a production temperature of 110°C.

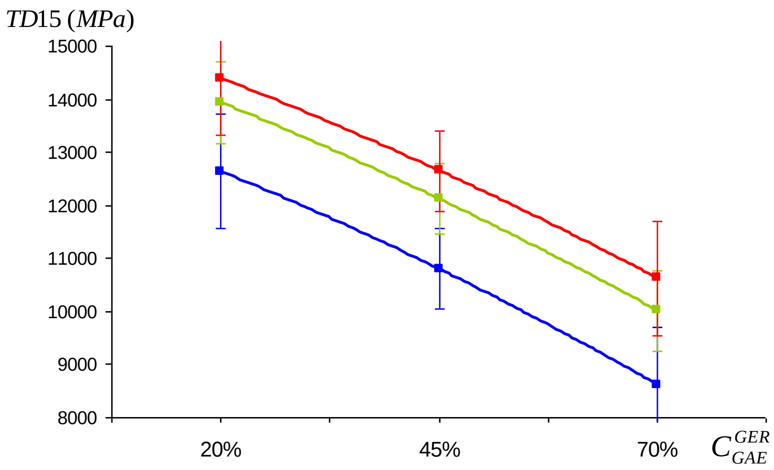


Fig. 7: Direct tension modulus at 15°C as a function of recycling rate for a mixing time of 40 s (110°C in blue, 135°C in green, 160°C in red)

For a mixing time of 240 s (Fig. 8), the stiffness modulus was significantly dependent only on the recycling rate. For all the production temperatures considered, it dropped from 14420 ± 980 MPa to 11320 ± 980 MPa between recycling rates of 20% and 70%. The trend observed previously of a reduction in stiffness modulus when the recycling rate increased is maintained. This suggests that when a reclaimed asphalt concrete with a high recycling rate is formulated, the hypothesis of total remobilisation of the RAP binder is not valid. This would not in itself be sufficient to obtain a stiffness modulus independent of the recycling rate.

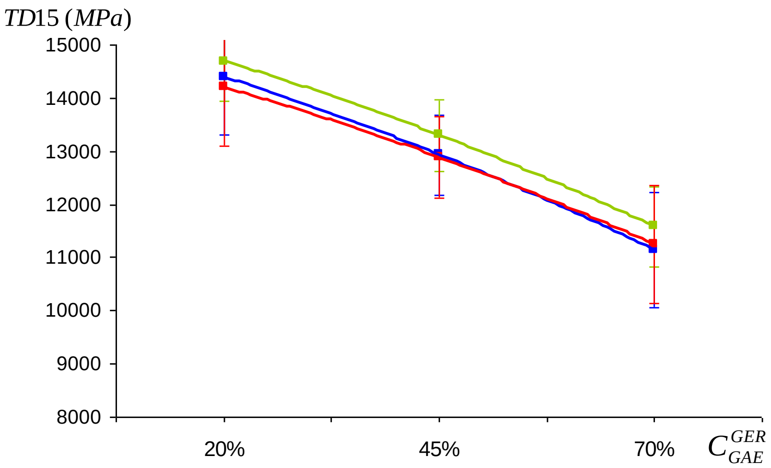


Fig. 8: Direct tension modulus at 15°C as a function of recycling rate for a mixing time of 240 s (110°C in blue, 135°C in green, 160°C in red)

It should be noted that for a production temperature of 160°C, the stiffness modulus is independent of mixing time; after 40 s mixing, this modulus is maximal. To obtain a modulus at production temperatures of 110°C and 135°C which is equal to that achieved at 160°C, the mixing time has to be increased, by 100 s at 135°C and by 200 s at 110°C. This evolution in stiffness modulus confirms the conclusions drawn in part 2 on the relationship between drop in temperature and increase in mixing time. It also confirms the relationship supposed until now between the degree of blending of the constituents and mechanical properties.

When production temperature is 110°C, increasing mixing time from 40 s to 240 s increases the stiffness modulus by 1760 ± 1080 MPa for a recycling rate of 20% and by 2520 ± 1080 MPa for a recycling rate of 70%. The difference between these two increases falls within the range of measurement uncertainty.

Further analyses showed that the binders fall within a penetration range from 24 to 32 $^{1/10}$mm. There is no relationship between the penetration grades of the extracted binders and the measured moduli. In addition, penetration of 31.8 $^{1/10}$mm, the target value when producing virgin binders, is verified.

This significant increase in stiffness modulus when the mixing time is 240 s and the production temperature 160°C suggests that when formulating a reclaimed asphalt mixture with a high recycling rate, the properties of the virgin binder should not be determined on the basis of its total re-participation.

3.3 Fatigue resistance: two point bending test on trapezoidal specimens (EN 12697-24)

Analysis of the stiffness modulus tests shows that for a mixing time of 40 s (Fig. 9), the fatigue resistance of reclaimed asphalt concretes is significantly dependent on mixing temperature. When the recycling rate is increased from 20% to 70%, fatigue resistance of reclaimed asphalt concrete produced at 135°C and 160°C increases from 94 ± 7 ε_6 to 104 ± 7 ε_6. This increase falls within the range of measurement uncertainty. For the same variation in recycling rate, from 20% to 70%, the fatigue resistance of reclaimed asphalt concretes produced at 110°C decreases slightly from 88± 8 ε_6 to 81 ± 8 ε_6.

For a recycling rate of 20%, the fatigue resistance measured is independent of mixing temperature and is equal to 92 ± 8 ε_6.

When the mixing time is increased from 40 s to 240 s this leads to a significant increase in the average value of fatigue resistance for all production temperatures and the trends observed at 40 s of mixing are confirmed: when the recycling rate is increased from 20% to 70%, the fatigue resistance of reclaimed asphalt concretes produced at 135°C and 160°C increases.

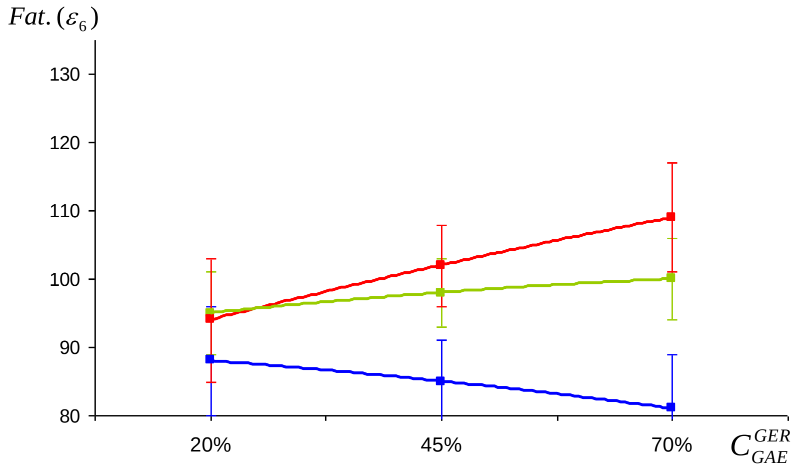


Fig. 9: Fatigue resistance at 10°C as a function of recycling rate for a mixing time of 40 s (110°C in blue, 135°C in green, 160°C in red)

For a mixing time of 240 s, the fatigue resistance of asphalt mixtures with a 20% recycling rate is always independent of production temperature. Increasing mixing time from 40 s to 240 s gives a fatigue resistance of 107 ± 7 ε_6. For asphalt mixtures produced at 110°C, fatigue resistance is independent of the recycling rate at 110 ± 7 ε_6 while for mixtures produced at 160°C, fatigue resistance increases significantly with the recycling rate to between 104 ± 9 ε_6 at 20% recycling and 130± 9 ε_6 at 70% recycling.

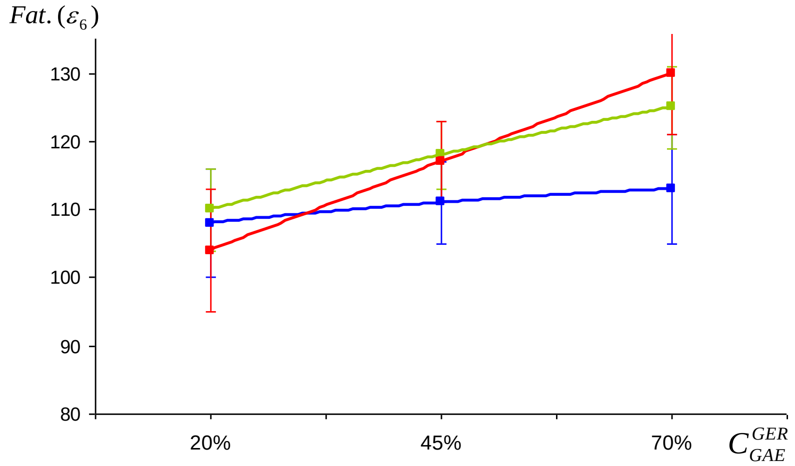


Fig. 10: Fatigue resistance at 10°C as a function of recycling rate for a mixing time of 240 s (110°C in blue, 135°C in green, 160°C in red)

The fatigue resistance of reclaimed asphalt concrete depends significantly on all the parameters in the experimental design. Overall, the mixing time increases the asphalt concrete's resistance to fatigue. Production temperature has a marked influence on fatigue resistance for recycling rates over 20% and in contrast to the asphalt mixture with a low recycling rate, production temperature and recycling rate produce a considerable and significant increase (26 ± 9 ε_6) in fatigue resistance.

In contrast to the earlier conclusions for the stiffness modulus, when production is at 160°C maximum fatigue resistance is not obtained after 40 s. A longer mixing time is needed to "refine" the mix, which combines binders and fine mineral particles of asphalt concrete. Note that when the production temperature is less than 135°C, the fatigue resistance of a reclaimed asphalt concrete differs significantly from the possible maximum, a clear indication of difficulties in "refining" the mixture.

For a median mixing time of 140 s and independently of production temperature and recycling rate, the characteristics measured place the bituminous asphalt concrete studied here in the BBME 0/10 type 2 category. Rutting was less than 7.5%, the direct tension modulus at 15°C was between 10000 MPa and 14000 MPa and fatigue resistance was higher than 100 ε_6.

3.4 Conclusion

The observations described here are based on laboratory-made reclaimed asphalt concretes. They provide totally new information on the relative importance of the different factors related to formulation or production, and their associated trends. When considering the relationship between the conditions that ensure that constituents are blended together and the mechanical performances of the resulting asphalt concretes, a dichotomy emerges between formulation parameters, which set out the maximal possible performances, and production parameters, which strive towards this maximum. To control mechanical performance, we need to know if this optimum can be achieved with the given production parameters, and for this we need to be able to measure the quality of the constituent mix.

4. DEVELOPMENT AND APPLICATION OF A SYSTEM TO MEASURE THE DEGREE OF BLENDING OF RECLAIMED ASPHALT CONCRETES

An experimental procedure was set up to measure the quality of the mix of constituents. From studying the available literature on this subject [7] [8] [9] [10] it became clear that we could use an existing method and we proceeded to soak reclaimed asphalt concrete samples in solvent to obtain several solutions showing the progress of the dissolution. However, because the bituminous binders dissolved too quickly in the solvents used, this method provided only a limited number of solutions. In addition, the tests used to analyse the solutions required that the solvent be separated out by evaporation in order to recover the binder, and they also required a large quantity of binder.

Having examined various other routes [11], we opted for a test based on spraying solvent over a reclaimed asphalt concrete sample to extract the binder more gradually, and hence increase the possible number of solutions. A method of chemical analysis by spectroscopy was also developed which required only a small amount of binder to analyse the extracted solutions, without the need to extract solvent by heating [12].

4.1 Description of the experimental extraction system by lixiviation

A diagram of the equipment is shown in figure 11. The system consists basically of a circuit supplying the solvent, a lixiviation cell where the dissolution takes place and a system for sampling the solutions produced by lixiviation.

The circuit supplying the solvent consists of a system for spraying the solvent, made up of (**1**) an air atomising nozzle with a conical screen to protect the user. Solvent flow from this nozzle is controlled by means of a needle gauge (**2**), a single piston pump (**3**) which draws liquid solvent into a tank (**5**). A discharge valve (**4**) and an expansion tank (**6**) ensure the correct load behind the nozzle and a properly adjusted and regular flow rate. The lixiviation cell consists of a vertical tube (**7**), closed at the bottom in a funnel shape which channels the lixiviate, and covered above by the spray system (**1**) and a steel woven wire mesh screen (**8**) placed on a supporting grid (**9**). The reclaimed asphalt concrete sample (**10**) is placed on this screen. The system for sampling the channelled lixiviate consists of a vacuum pump (**11**) which creates a depression under the screen and draws the collected lixiviate to a sampling station with two storage units (**12** and **13**); filling is controlled by two 3-way valves (**14**, **15**) so that the flasks can be filled in situ. Each flask is associated with a vent-valve device (**16**, **17**) to return it to atmospheric pressure so that it can be easily replaced during the lixiviation process. A container (**18**) upstream from the vacuum pump acts as a safety device in case the lixiviate should be drawn up accidentally.

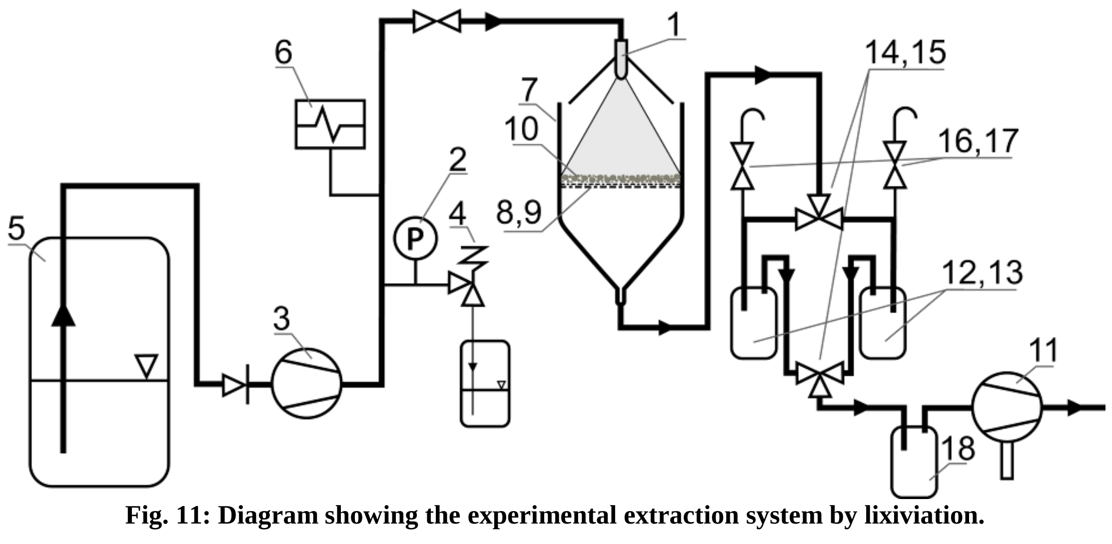


Fig. 11: Diagram showing the experimental extraction system by lixiviation.

4.2 Principle for analysing the lixiviation test results

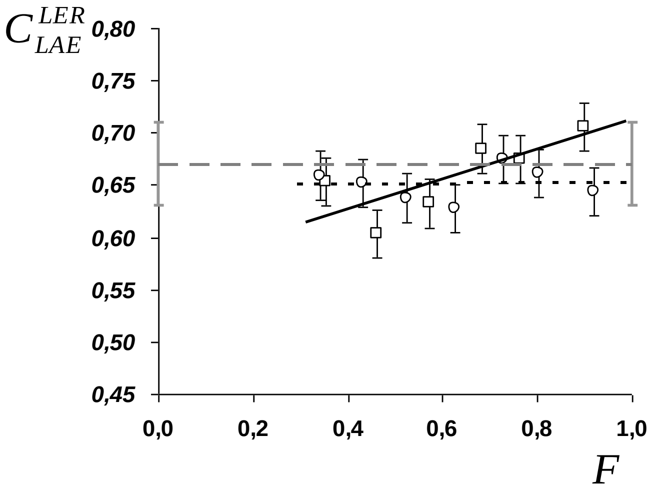
The lixiviation test results are presented in graph form, where the x-axis F represents the progress of the lixiviation in terms of percentage of binder extracted. The y-axis represents C_{LAE}^{LER} the proportion of RAP binder (LAE) in the reclaimed asphalt concrete binder (LER) present in the extracted solutions, which are made up of RAP binder, virgin binder and solvent.

Based on the principle that in the case of a homogeneous mixture (mixed to a high degree), C_{LAE}^{LER} is by definition independent of the progress of lixiviation F, then a non-homogeneous mixture (mixed to only a low degree) would result in an increase in C_{LAE}^{LER} during extraction since the virgin binder would tend to be extracted first, at the beginning of the lixiviation process. Thus to quantify the degree to which the virgin binder and the recycled asphalt pavement binder are mixed, results for the concentration C_{LAE}^{LER} are measured in all the solutions extracted in the staged extraction test. As each solution is linked to a particular moment in the test via F, progress of the lixiviation, it is possible to calculate the average slope $a \pm \Delta a$ for the experimental points. This slope $a \pm \Delta a$ will therefore sum up information about the homogeneity or heterogeneity of a recycled asphalt concrete sample. A steep slope $a \pm \Delta a$ represents a non-homogeneous reclaimed asphalt concrete binder and a zero slope $a \pm \Delta a$ represents a homogeneous reclaimed asphalt concrete binder.

All necessary precautions taken and the methods for further tests used to quantify the concentration of the extracted solutions and determine the scale of F are not described in the present article. The entire experimental protocol is describe in the related thesis [1].

4.3 Experimental validation of the test

In order to check the validity of the test in distinguishing between a homogeneous and a heterogeneous reclaimed asphalt concrete, an asphalt mixture with a 70% recycling rate was produced, varying the production temperature T_m between 110°C and 160°C and the mixing time t_m between 40 s. and 240 s. These samples were identified as $ER_{T_m,t_m}^{0/14}$. This notation gives the 0/14 mm granulometry of the sample, and also its production temperature T_m and mixing time t_m. Figures 12 and 13 show the graphs for samples produced at 160°C and 110°C respectively.



□ : sample $ER_{160,40}^{0/14}$

○ : sample $ER_{160,240}^{0/14}$

Solid line: linear trend showing measurements for $ER_{160,40}^{0/14}$

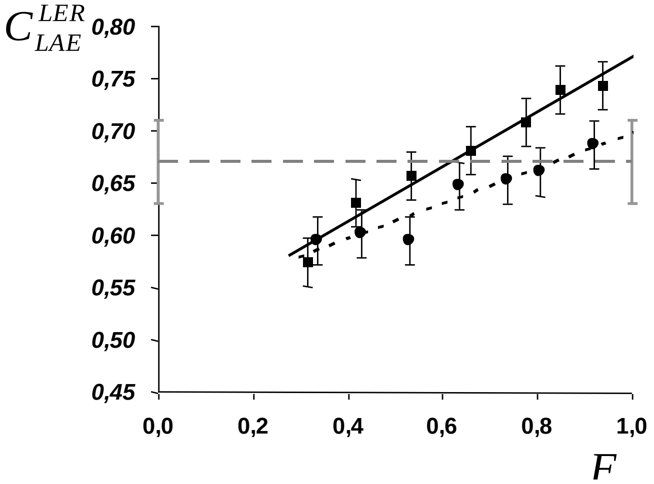
Dotted line: linear trend showing measurements for $ER_{160,240}^{0/14}$

Dashed grey line: mean concentration of RAP binder C_{LAE}^{LER} in recycled asphalt concrete samples.

Fig. 12: Graph showing results from data analysis of lixiviation of recycled asphalt concrete samples produced at 160°C (samples $ER_{160,40}^{0/14}$ and $ER_{160,240}^{0/14}$) showing the evolution in concentration C_{LAE}^{LER} of RAP binder in the extracted binder as a function of mass fraction F of extracted binder

The slope values for samples $ER_{160,40}^{0/14}$ and $ER_{160,240}^{0/14}$, shown in figure 12, are 0.14 ± 0.07 and 0.00 ± 0.05 respectively. The slope values for samples $ER_{110,40}^{0/14}$ and $ER_{110,240}^{0/14}$, shown in figure 13, are 0.26 ± 0.08 and 0.17 ± 0.07 respectively.

The slope values obtained were coherent with the trends observed for the temperature and the mixing time. These values and the associated uncertainties confirm the discrimination capacity of the test.



■ : sample $ER_{110,40}^{0/14}$

● : sample $ER_{110,240}^{0/14}$

Solid line: linear trend showing measurements for $ER_{110,40}^{0/14}$

Dotted line: linear trend showing measurements for $ER_{110,240}^{0/14}$

Dashed grey line: mean concentration of RAP binder C_{LAE}^{LER} in recycled asphalt concrete samples.

Fig. 13: Graph showing results from data analysis of lixiviation of recycled asphalt concrete samples produced at 110°C (samples $ER_{110,40}^{0/14}$ and $ER_{110,240}^{0/14}$) showing the evolution in concentration C_{LAE}^{LER} of RAP binder in the extracted binder as a function of mass fraction F of extracted binder

Irrespective of whether the production temperature is 110°C or 160°C, we observe that a difference in mixing time results in a difference in slope, indicating a difference in homogeneity between asphalt concretes mixed for 40s and those mixed for 240s. The influence of production temperature can be seen since only a long mixing time at 160°C produces a zero slope, indicating a homogeneous asphalt mixture. As for the tests presented in parts 2 and 3, these tests show that production conditions affect the homogeneity of the asphalt mixture and this can be measured using the method described above.

After further analyses for reproducibility purposes, the uncertainties obtained define the area of validity for the observations. This area covers slopes ranging from 0 to 0.3. Because of uncertainties in the measurements, this area of variation is divided into three equal parts. Slopes that fall within the range 0 to 0.1 represent a homogeneous asphalt mixture and slopes within the range 0.2 to 0.3 represent a heterogeneous asphalt mixture. Values from 0.1 to 0.2 represent an area of intermediate homogeneity.

An initial industrial application of this system has been used on samples with recycling rates of 40% and 50% and has shown that the degree of blending in the hot-mix reclaimed asphalt mixtures studied can be described as homogeneous.

4. CONCLUSION

This article presents the principles behind tests carried out for work on a thesis [1]. The purpose of these tests was to gain a better understanding of the industrial recycling process for bituminous materials used in road construction. To achieve this, an observation method for measuring the degree to which constituents were blended together has been perfected. It then led to quantify the extent to which the mixing kinetics of the constituents are dependent on production temperature. It emerged that to obtain a degree of blending that is identical to that obtained at 160°C after mixing for 20 s, mixing time has to be 3.5 times longer at 130°C and 6 times longer at 110°C. To quantify the importance of the degree of blending of the constituents for mechanical properties, asphalt mixtures under controlled conditions for composition and production method has been studied. It seems that even with a low degree of blending, resistance to rutting is acceptable. In addition, when production is at 160°C, the stiffness modulus is maximal from 40 s. Tests for resistance to fatigue show that when reclaimed asphalt concrete is produced at a high recycling rate, a low degree of blending gives rise to non-maximal mechanical properties. It can be supposed that this reflects the level of "refining" of the asphalt concretes. Noting the significance of the degree of blending on the difference between optimal performances and actual performances (on leaving the production plant), an experiment was carried out based on an existing test, to gradually extract reclaimed asphalt binder in the form of several solutions. Quantifying these solutions produced information on the degree of blending of the constituents of the reclaimed asphalt concrete. After the first industrial application of this system, we were able to observe that in the hot-mix reclaimed asphalt concretes studied, the degree of blending could definitely be qualified as homogeneous.

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