Design of 100% RAP Hot-Mix Asphalt to Balance Rutting and Cracking Performance

Martins Zaumanis[1], Maria Chiara Cavalli[3], Lily D. Poulikakos[2]
([1,2,3] EMPA Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, CH-8600, Dübendorf, Switzerland, [1]Martins.Zaumanis@empa.ch, [3]MariaChiara.Cavalli@empa.ch, [2]Lily.Poulikakos@empa.ch)

ABSTRACT

100% RAP hot-mix asphalt was designed with the aim to provide similar performance to conventional AC8 asphalt mixture. Two different gradations of RAP were prepared, each with two different binder contents and a polymer modified bitumen for one of the mixtures. A bio-based rejuvenator was always applied to ensure the targeted binder grade. The mixtures were tested for fracture toughness using semi-circular bend test, rutting using French wheel tracking test and complex modulus in cyclic indirect tension mode on cylindrical specimens. The results demonstrated that at 0°C the fracture resistance of all 100% recycled mixtures was better than that of the reference mix, but the test method was insensitive to changes in binder content. Rutting resistance was higher when coarser recycled asphalt gradation was used. Lower binder content provided higher rutting resistance but also showed much higher modulus compared to the reference mix, which can signal potential for fatigue damage. Overall the results demonstrate that it is possible to design a 100% mixture with rutting and fracture resistance that is at least at the level of the reference mixture, but further research is necessary to verify intermediate temperature and thermal cracking resistance. The authors have initiated such research.

Keywords: asphalt design, performance-based optimization, rutting, cracking

1. INTRODUCTION

When conventional materials are used, empirical relationships have been successfully used for multiple decades to design asphalt mixtures. However, when there is a significant deviation from the traditional practice, these relationships may not hold true anymore. The ambitious aim of designing 100% recycled hot mix asphalt certainly falls into this category [1]. More proof of the performance is necessary than simple volumetric design.

Performance-based mix design principles can be applied in this case. A carefully chosen set of tests that demonstrate the mechanical performance can be used to compare the performance of an un-traditional mixture to conventional asphalt. Assuming that tests are chosen appropriate for the climate and truly reflect the expected field performance of the pavement, one can verify how the new material compares to the conventional mixture. In case of highly recycled asphalt it is most important to verify the cracking performance due to negative aging effect of the RAP binder [2]. At the same time since rejuvenators are added, one must also verify if rutting does not exceed acceptable limits. Balancing of the cracking and rutting performance is possible with multiple means, most notably changing of gradation, and varying the binder content as it was done in this study. **The objective of the research** can then be summarized as follows: design a 100% recycled asphalt surface course and evaluate its cracking and rutting performance in comparison to a conventional reference mixture while verifying the potential to use the chosen test methods for design of mixtures.

2. MATERIALS AND METHODS

2.1. Materials

Reclaimed asphalt was collected in Switzerland. Its exact source is unknown. It had been screened on an 11 mm sieve at the RAP processing facility and has a binder content of 5.6%. It can be seen in FIGURE 1 that its gradation ("RAP fine") is close to the upper limit of the Swiss requirements for AC 8 mixtures. Therefore it was decided to prepare a set of 100% recycled samples without modification of the gradation.

Another set of recycled samples was prepared by screening the RAP on 5.6mm sieve and changing the proportions to achieve grading curve as similar as possible to the reference plant produced AC 8N mixture. This recycled mixture gradation is denominated "RAP coarse". Because of less binder-rich fine particles the binder content at 5.1% is lower than that of "RAP fine".

AC 8N plant produced surface coarse mixture was chosen as a reference. It is intended for traffic volume of up to 300 ESAL. This choice was made to correspond to the existing nominal maximum aggregate size of the RAP and the relatively low traffic volume was chosen because of the unknown source of RAP. The AC 8N mixture has 5.9% binder content.

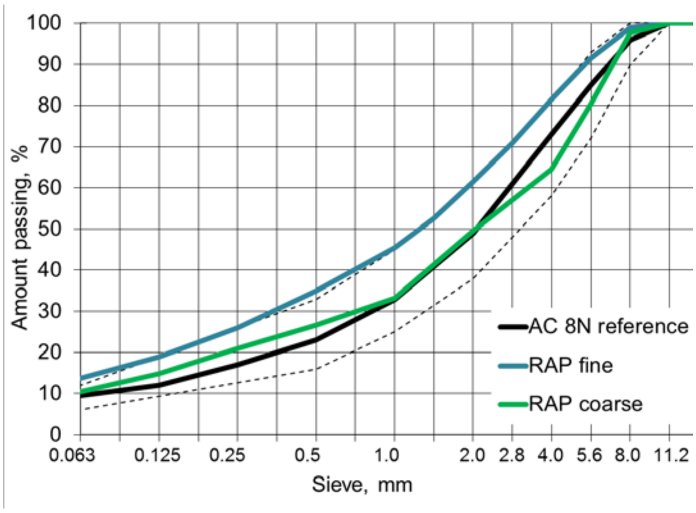

FIGURE 1 Gradation curves

A commercially available rejuvenator based on distilled tall oil was used for the experiments. It is a by-product of Kraft manufacturing process. The rejuvenator was added at 7.3% of RAP binder mass for all recycled samples. This amount was based on an earlier study where the required dose to reach penetration of 60 mm^{-1} was determined.

For each of the recycled mixtures, two binder contents were used: the original and the original +0.5% bitumen. Either 50/70 grade or highly Polymer Modified Bitumen (PMB) was added. The final binder+rejuvenator content of the "RAP fine" gradation samples was 6.0% and 6.5% while for the "RAP coarse" samples it was 5.5% and 6.0%.

2.2. Methods

1.1.1 Laboratory mixing

The materials, except rejuvenator which remained in room temperature, were heated in a laboratory oven to the mixing temperature of 170°C. Thereafter they were blended in an oil-heated laboratory mixer in the following sequence: RAP aggregates were pre-blended for 0.5 minutes after which rejuvenator was introduced at the required dosage and mixed for 1.5

minutes. Finally neat binder (if any) was introduced, followed by 3.5 minutes of mixing. It is considered that rejuvenators should be added directly to RAP, instead of pre-blending with fresh bitumen in order to allow direct contact with the RAP binder. This is expected to facilitate diffusion and activation of RAP binder.

1.1.2 Compaction

All samples that were tested for performance were prepared by French Roller Compactor. The loose mixture was short-term aged at a forced-draft oven at 150°C for 4 h followed by compaction using the roller compactor which was equipped with a steel wheel. The slab was compacted to dimensions of 100mm × 180mm × 500mm to a target density that equals that of Marshall specimens. Marshal samples were brought to compaction temperature of 145°C directly after mixing. This temperature corresponds to the requirements set in Switzerland National standard for the target penetration binder grade of 50/70. Compaction effort of 50 blows from each side was applied.

1.1.3 Rutting test

Rutting resistance of the asphalt mixes was evaluated using French Rutting Tester (FRT). The FRT is run using a rubber pneumatic test wheel that has a pressure of 0.60±0.03 MPa and a load of 500±5 kN is applied to the table and specimen while the wheel moves across the sample. A preconditioning load is applied at a room temperature for 1,000 cycles after which the sample is conditioned for about 16 hours at a temperature chamber that is set to 60°C. The test is run for 10,000 cycles and rut depth is measured using a gauge after 30, 100, 300, 1000, 3000, and 10,000 cycles at 15 pre-defined points across the length of the rut. Two parallel specimens are tested and the mean rut depth at each number of cycles is reported.

1.1.4 Fracture toughness at 0°C

Semi-Circular Bend (SCB) test was used to determine fracture toughness at 0°C according to EN 12697-44. To prepare the SCB test sample a cylindrical sample was cored from an asphalt mixture slab, trimmed to the required height of 50 mm and cut in half. The slabs were prepared using steel compaction wheel to a target density that equals that of Marshall samples. A notch of 10 mm deep and 3.5 mm wide was then cut into the half cylinders to control the crack initiation point. Four samples per mix were tested.

During testing the specimen is positioned in a three point testing frame and a load is applied at a monotonic rate of 5 mm/min along the vertical axis. Load and displacement are measured during the test to calculate maximum stress at failure and fracture toughness of the specimen. These results can then be used to assess potential of a material to resist crack propagation. Ideally the results should be viewed in tandem with fatigue test results, which cover the crack initiation phase and therefore are complementary to this test.

1.1.5 Stiffness

Stiffness of the asphalt mixtures was determined in indirect tension mode on cylindrical specimens (CIT-CY) according to EN 12697-26. For each type of mix four samples of 100 mm diameter were cored from the asphalt slabs and cut to 40 mm in height. The tests were performed by applying a sinusoidal load at frequencies of 0.1, 1 and 10 Hz. The load level was chosen to induce horizontal strains in the specimen in the range between 0.05 and 0.10 that is assumed to be in the linear viscoelastic range for the samples and no permanent damage is induced. Testing temperatures were chosen following a sensitivity study where the initial mix design was tested in 10°C increments from -10°C to +40°C with the aim to find a wide range of stiffness for later input in master curve calculations (explained lower). It was determined that using the three temperatures of -10, 20 and 30°C compared to any other group of three test temperatures ensured the smallest error in calculation of master curve as compared to testing at six temperatures.

Master curve uses the principle of time-temperature superposition to shift data at multiple temperatures and frequencies to a reference temperature so that the stiffness data can be viewed without temperature as a variable. This method of analysis allows for visual relative comparisons to be made between multiple mixes.

A sigmoidal model was used as proposed by Witzack and Fonseca [3], with the shift factors calculated following the Williams-Landel-Ferry [4] relation Eq.(1):

$$\log a_T = \frac{-C_1\,(T - T_{ref})}{C_2 + (T - T_{ref})} \qquad \text{(Eq.1)}$$

Where a_T is a factor for shifting complex modulus at certain temperature T to a reference temperature T_{ref} (20°C in this study). C1 and C2 are material constants and a least squares regression was performed to obtain the parameters.

3. RESULTS AND DISCUSSION

3.1. Cracking and rutting

The fracture toughness and rutting test results, along with the result range of each test sample and air void content (Va) are summarized in FIGURE 2. Va of 2-5% is required for AC 8N mixtures. In this figure the fracture toughness is illustrated on the vertical axis while the rut depth is placed on horizontal axis. The results of AC 8N reference mixture are used as a reference and the dotted lines that go through the test result to allow comparing the performance of other mixtures to it. All the mixtures that perform better in rutting compared to the AC 8N will align to the left from the vertical dotted line. All the mixtures that perform better in terms of fracture toughness will align to the top from the horizontal dotted line. Thus any mixture performing better than the reference in both cracking and rutting will be situated in the upper left rectangle.

It can be seen in the figure that all of the RAP coarse mixtures and the “RAP fine” mixture are situated in the upper left rectangle meaning they perform better than the AC 8N mixture both in fracture toughness test and rutting test. The “RAP fine +0.5% 50/70” mixture performs better in terms of fracture toughness, but has unacceptable rutting performance.

The chart demonstrates that in absolute numbers the rutting resistance of the recycled mixtures is not very high, since often in specifications less than 10% is required. However, since the mixtures are intended for low volume roads, such result is acceptable. Even more so because these mixtures perform better than the AC 8N reference mix. The results also allow to conclude that re-grading of RAP has allowed to improve the rutting resistance, but has no statistical effect on cracking resistance. This is what normally should be expected for low temperature cracking tests. Use of PMB bitumen has not provided any notable improvement in neither rutting nor cracking compared to the paired mixture with the same gradation but 50/70 bitumen.

If the effects of binder content are isolated, one can see that as expected, increasing bitumen content by 0.5% has caused reduction in rutting resistance. At the same time there are no changes in cracking resistance. Although somewhat questionable, similar conclusions regarding binder content effect on low temperature performance have been formed also previously [5]. This allows concluding that fracture toughness should not be used for optimization of mixture design binder content due to the test method insensitivity.

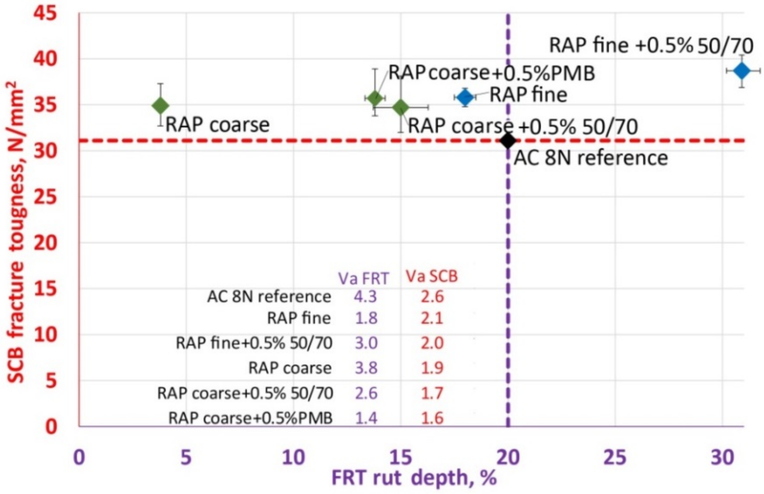

FIGURE 2 Balancing of cracking and rutting performance

3.2. Complex modulus

FIGURE 3 demonstrates the master curves for all mixtures. The figure demonstrates that compared to the AC 8N reference mixture, the recycled asphalt samples have higher modulus in high frequencies (corresponding also to low temperatures) and higher or similar modulus in low frequencies (corresponding to high temperatures). Higher modulus at low frequencies indicates that compaction of the recycled mixtures might require higher energy. Such conclusions concur with findings of other studies [6], [7]. Lower or similar modulus at high frequencies indicates potentially increased susceptibility to thermal cracking. However, as discussed earlier fracture toughness of recycled mixtures at 0°C is actually better than that of the reference mixture.

In the intermediate temperature range where the pavement performs most of the time and also fatigue can be expected, the results are mixed. A commonly used threshold is 10Hz at 20°C because it corresponds to fast moving traffic at intermediate service temperate (this threshold is illustrated in the figure with vertical dotted line). One can see that compared to the AC 8N, the recycled mixtures with no added binder have higher modulus at these conditions. High modulus is desirable for structural purposes; however, all other parameters remaining constant, it will also likely cause earlier fatigue damage. A fatigue and cracking evaluation of the recycled mixture at intermediate temperature would be necessary to conclusively rate the performance of the recycled mixtures compared to the reference. When 0.5% bitumen is added, the modulus is similar or somewhat lower compared to the AC 8N reference. Similar to previous tests, replacing 50/70 bitumen with PMB has not affected the results in any way.

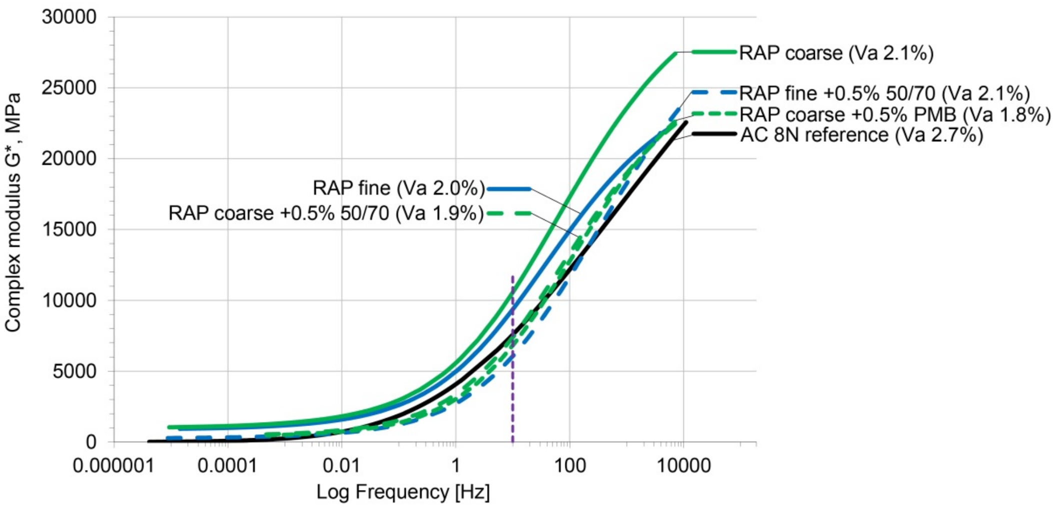

FIGURE 3 Asphalt mixture master curves shifted to 20°C

4. CONSLUCIONS AND SUMMARY

In this study 100% RAP mixtures were designed with the aim to perform similarly to AC 8N mixture. This mixture is used for low volume road surface courses in Switzerland. Two gradations of RAP were used with two different binder contents for each and rejuvenator was always added at 7.3% by binder mass to achieve 50/70 penetration grade. The mixtures were tested for fracture toughness using the Semi Circular Bend test, rutting using French wheel tracking test and complex modulus in cyclic indirect tension mode on cylindrical specimens (CIT-CY). The test results allow concluding the following:

1) All recycled mixtures had higher fracture toughness at 0°C compared to the reference AC 8N mixture. At the same time modulus of recycled mixtures at low temperature (high frequency range) was higher compared to the reference mixture thus an evaluation of low temperature cracking resistance is necessary.
2) Coarser gradation and less binder content, as expected, improved the resistance to rutting of the recycled mixtures. All except one mixture, although it did not have very high rutting resistance in absolute numbers, performed better than the reference mixture. Having relatively low rut resistance is justifiable in this case because the mixtures are intended for low volume roads.
3) A change in binder content did not show statistically significant effect on fracture toughness. This suggests that this test method should not be used as a mix design tool for the purpose of optimization of binder content.
4) The mixture master curves indicated that at high temperature the recycled mixtures have somewhat higher modulus and thus might require higher compaction energy. At intermediate temperature (frequency) range the mixtures with added bitumen had similar or somewhat lower modulus compared to the reference. Compared to this, the mixtures without any additional bitumen had considerably higher modulus. This requires evaluation of cracking and fatigue of the mixture at intermediate temperatures.

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