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Can crumb rubber modifier effectively replace the use of polymer modified bitumen in asphalt mixture?

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Abstract (150 words)

Laboratory scale mechanical performances on six plant produced mixtures three semi-dense surface courses and three dense binder courses modified with engineered crumb rubber (ECR) using the dry process are presented. . The two types of mixtures produced and investigated fulfilled for the most part, the requirements of the Swiss and/or US standards regarding volumetric properties, water sensitivity and rutting. In advanced testing where no requirements exist, the dense ERC mixtures performed similar to the reference polymer modified mixtures i, and slightly worse for semi-dense mixtures in high temperature tests, wherethe binder becomes viscous in the rubber-binder composite and its ability to transfer loads is reduced. The ERC mixtures performed similarly or better than the reference in low temperature tests. Across the advanced testing data set, all obtained results were well within acceptable values for both ECR and reference polymer mixtures indicating that crumb rubber can effectively replace polymer in asphalt mixtures.

Key words: Crumb Rubber Modified Asphalt; Performance; Dry Process; Plant Production

1. Introduction

Worldwide, 1.5 billion tires are sold yearly resulting in 4 billion tires that are still often stockpiled or landfilled at the end of their service life. In Europe, there are 1 billion tires that need to be recycled each year. The fate of end of life tires varies per country. In Switzerland, every year 70000 tons of waste tires are produced and transported mostly to the cement industry for incineration or exported for further processing and re-use. The cement industry receives this waste material and charges tire collectors a fee. In many other countries the cement factory pays for the tires. The fee received by recyclers or used tire collectors rarely exceed 30 €/ton and is decreasing in most countries due to an excess supply of waste tires.

After the introduction of the European Union's Landfill directive in 2006 (European Community Directive 99/31/CE) which forbids the landfill disposal of used tires, the disposal and unknown tire recovery route has been reduced considerably. Waste tires are a significant global problem and at the same time they are a source of potential useful raw materials which could be used in various applications. For instance, enhancing the performance of road pavements could be one of them.

Various research projects show that crumb rubber (CR) from scrap tires can be used to replace conventional construction materials in roads. For more than 20 years, wet and dry processes have been developed for inclusion of such products in asphalt mixtures with proven performance. Research has shown that the wet process where the CR is added to liquid bitumen resulted in good performance (Moreno, Sol et al. 2013). However, this process has the disadvantage that special equipment is needed in the mixing plant for the addition and storage and the mixing with aggregates that has to be done in a relatively short amount of time limiting the storage possibility of the pre-modified bitumen. Due to this hindrance, most asphalt mixing plants view the uptake of this technology negatively. The dry process where the CR is added to the mixture (sometimes even as a substitute for certain aggregate sizes), does not require storage and, from a practical point of view, is more desirable and, therefore, has a higher chance for wider uptake by the industry. There are two options to the dry process: the «semi-wet process» and the «dry process.» The semi-wet process involves pre-swelling of the rubber in heated bitumen before it is added like an aggregate during the mix production process. The dry process involves the use of a chemically modified or engineered crumb rubber (ECR), not bitumen modified, that is added during the mix production process. The dry process demands experienced personnel due to the control of the swelling process of the tire rubber crumbs after the mixing phase and sometime even after compaction (Santagata et al 2016). This issue has been tackled by very recent technologies tailored to provide improved control of the swelling phenomena by pre-treating tire rubber crumbs with pre-digestion with bitumen and/or chemical activation of the tire crumbs' surface. These technologies are effectively used through a dry process, however they are also commonly identified as semi-wet process (Shen and Xie 2012). Although the dry and semi-wet processes have not been exploited as much as the wet process, more recent research shows that dry and wet and semi-wet processes can yield similar performance to bitumen modified with polymers such as styrene butadiene styrene (SBS), as long as it is well implemented (Cao, 2007; Eskandarsefat 2018; Nguyen 2018). The different experiences with the wet and dry process are reflected in the TRL (Technology Readiness Level) of the two processes estimated at 7-9 in the former and 5-7 in the latter (Piao et al. 2020). This is due to the wider use of the wet process for a variety of reasons. However, in the United States, modern dry process ground tire rubber has been used for nearly two decades, with millions of tons of CR modified mixture placed (Shen and Xie, 2012). This latter experience reports similar performance of CR to polymer modified mixtures.

The use of CR in asphalt mixtures varies worldwide; three states in the United States, California, Florida and Arizona, mandate the use of crumb rubber and other states permit its use as an alternative to polymer-modified binders. In Europe, Sweden, Czech Republic, Spain, Portugal and Italy currently use CR. Spain, in particular, has already produced guidelines and specifications for the use of rubberized asphalt in the country (Signus, 2017, Moreno et al 2013, Shen & Xie 2011). Italy completed a major project in Turin and after laying down few kilometers of rubberized asphalt, using both the wet and dry methods in different layers resulting in positive performance, the city council has introduced this type of asphalt within their standard choices for road pavements (Santagata and Zanetti, 2012).

In general modifying asphalt mixtures using CR in wet or dry process can improve hot mixture asphalt performance properties (Cao 2007, Lo Presti 2013). Furthermore, use of tire rubber in road pavements has shown additional benefits such as improved deicing characteristics (Chen et al. 2013) and enhanced acoustic properties (Herisanu and Bacria 2013, Luong et al., 2014, Vázquez et al. 2020). Nowadays, crumb rubber modified asphalt (CRMA) mixtures allows to design low noise pavements and as such reduces the exposure of residents living along the traffic corridors to noise. In fact, it allows producing both porous asphalt (high air voids) and dense SMA (low air voids) that combined with the rubber provide the pavement with better acoustic characteristics over conventional surface courses. Nevertheless, it should be noted that in general the noise reduction properties are a function of the amount of CR that could have a detrimental effect on the mechanical performance.

Use of crumb rubber can contribute significantly to sustainability of road transport. Resulting in long term performance of the built environment as well as preservation of natural resources. It has been reported that CR modified asphalt is a viable sustainable resource use. (Feraldi, Cashman et al. 2013) have investigated through an LCA approach the potential environmental impacts from shifting all US scrap tire to the material recycling treatment route. The analysis was done by comparing energy recovery by cement kiln to material recovery through ambient temperature mechanical granulation used in asphalt mixtures using the wet process. The results show that shifting scrap tires from energy recovery methods to material recycling methods results in significant potential environmental benefits in terms of waste management hierarchy. Likewise, this study assesses how CRMAs could contribute to an effective climate change mitigation path considering the whole life cycle. During the mixing process of CR with hot bitumen volatile organic compounds (VOC) are released at a lower amount than SBS modification. The works cited in this study focused on the wet process and highlighted that using a certain type of CR that is mechanically produced with added plasticizer, for use in asphalt, 75% less energy and 30% less VOCs are upon application produced (Feraldi, Cashman et al. 2013).

Nowadays, there is a need to transport more and heavier loads on the road infrastructure placing higher demands on the pavements requiring expensive performance enhancing additives such as polymers. As commented previously, recent research results indicate that the use of CR can reduce the amount of high cost SBS polymer modifiers that are used for performance enhancement. As SBS modification, the addition of CR to asphalt binder improved the viscoelastic characteristics and viscosity compared with neat asphalt binder (Loderer, Partl et al. 2018). Every year 6.5 Mt of new asphalt mixture is produced in Switzerland requiring 0.332 Mt of bitumen (ca 5%), of which 0.081 Mt (25%) is modified with polymer. Assuming a rate of 10% binder modification with engineered crumb rubber (ECR), this will result in using 8135 t of ECR. This scenario would use up 10% of all waste tires (70000 t) in Switzerland. In addition, this scenario could potentially be also cost effective as CR can substitute polymer modification as performance enhancing additive. Asphalt mixture modified with polymer are typically 20-30 CHF/t more expensive than comparative standard asphalt mixtures. Using ECR would decrease the cost premium by 20 to 25%. Therefore, it is clear that along with the environmental benefit to the use of ECR through waste reduction, an additional reduction of the asphalt mixture production cost could be achieved.

Despite the reported advantages, ECR-asphalt technologies are still struggling to be fully adopted worldwide, Switzerland being no exception. In order to accelerate the technology adoption, reliable information on improved product performance and manufacturing process is needed. The “competition” is first and foremost the use of other polymer modifiers (such as SBS) that are directly derived from petroleum products. The polymer modifiers are generally produced by bitumen producers (refineries) and therefore there is little incentive for those stakeholders to replace SBS by ECR.

The main barriers to widespread adoption of CRMAs mixtures can be identified as:

- Mixed experience with the performance of CRMAs in the field, often related to a combination of poor quality control of the CR in use, process implementation failures and lack of training
- Uncertainty regarding the dry-process performance in the field due to typical poor control over the swelling phenomena
- Wet-process initial investment costs. Plant modifications are necessary and costly.
- Lack of know-how of the CRMA’s production process at medium-scale asphalt companies
- Lack of awareness from road authorities about the properties and benefit to produce crumb rubber modified mixture using the dry process.
- CRMA typically labeled as more expensive, since they are usually compared with conventional mixes despite having superior properties.
- Lack of specifications.

The present work attempts to aid in lifting some of the barriers listed above by presenting two plant produced mixtures with crumb rubber using the dry process and their laboratory scale mechanical performance. To this end, a comparative analysis of the laboratory mechanical performance of four CRMAs designed mixtures (two wearing courses and two base courses) is presented with the relative reference mixtures typically incorporating polymer modified bitumen (PmB). The aim of the investigation is to understand the feasibility of systematically replacing asphalt mixtures using PmB with cost-effective CRMAs obtained through the dry process using pre-treated crumb rubber technology engineered to provide asphalt technologists with better control over the swelling phenomena.

2. Experimental

2.1. Materials

Two types of CRMAs were produced by using the dry process in two asphalt mixing plants in Switzerland. A dense binder course for high volume roads (AC B 22 H) and a semi-dense mixture SDA 4-16 surface course. The mix design was provided by the mixing plant. Both mixtures require PmB and high quality aggregates. Binder was extracted from the mixture according to EN 12697-1 using toluene and recovered by rotary evaporator according to procedure described in EN 12697-3. Gradation of the mixtures was determined according to EN 12697-2 after extracting the binder. As shown in **Table 1** and Figure 1**,** the AC mixture is a dense mixture and the SDA mixture is a gap graded mixture with high porosity and high binder content. It should be noted that the SDA mixture is considered as a low noise pavement and is used as an effective noise abatement measure in Switzerland. Two variations of CR modified mixtures, adjusting the CR and bitumen contents only, plus a reference mixture with PmB were produced per type of mixture resulting in a total of six mixtures as shown in **Table 1**. The aggregate gradation of the CR modified mixtures were not adjusted and, therefore, the same gradation was used for the three variations of each type of mixture. The binder type for the CR modified mixtures was a straight run 70/100 bitumen. The binder content was slightly increased to account for the absorption of the light fractions by CR. In this manner the effect of the CR modification could be isolated. All mixtures were produced in two plants in 800 kg batches and transported in 25 kg carton boxes to the lab for further testing. The reference mixtures SDA1-Ref and AC1-Ref are the normally produced PmB based mixtures as specified in the Swiss standards SN 640-431-1c and SN 640-436 respectively and the second and third were CR modified with 0.7% and 1.0% content for the SDA mixture as well as 0.3% and 0.4% CR for the AC mixture. Furthermore, the AC mixture is produced with 30% RAP (recycled asphalt pavement). In the calculations, the binder content of the RAP was not considered as active and therefore only the amount of new bitumen was increased when using CR as shown in **Table 1**. The CR used was supplied by a Swiss producer, it is produced by mechanical (ambient) shredding that results in particles < 600 µm (30 mesh). The particles are treated with a proprietary chemical modified for use in the dry fabrication process and are referred to as ECR (Engineered Crumb Rubber) in this document. This type of ECR has shown good field performance. For example, Shen et al (2012) have demonstrated that field performance of dry process rubber pavements and polymer pavements are similar.

Table 1 Mixture Properties, BC=Bitumen content; ECR=Engineered Crumb rubber; SDA Semi dense asphalt; PmB=Polymer modified binder

Type	**Designation**	**BC [M%] (administered)**	**BC [M%] (recovered)**	**Binder Type**	**ECR [M%]**
SDA 4	SDA1-Ref	6.20	6.00	PmB 45-80-65 (CH-E)	--
	SDA2-0.7%CR	6.52	6.30	70/100	0.7 (10.7 W% of bitumen)
	SDA3-1.0%CR	6.63	6.60	70/100	1.0 (15.1 W% of bitumen)

AC B 22 H (with 30% RAP)	AC1-Ref	4.20 (2.80 % new bitumen)	4.00	PmB 45-80-65 (CH-E)	--
	AC2-0.3%CR	4.35 (2.95 % new bitumen)	4.70	70/100	0.3 (12.0 W% of new bitumen)
	AC-0.4%CR	4.40 (3.00 % new bitumen)	4.50	70/100	0.4 (16.0 W% of new bitumen)

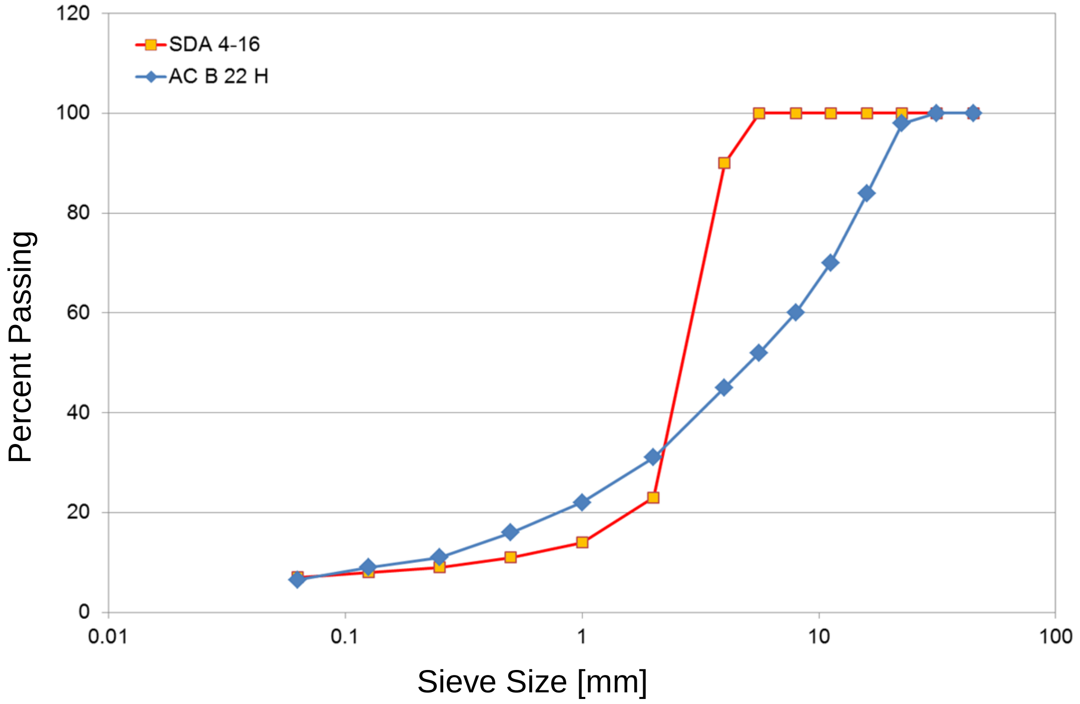


Figure 1 Aggregate gradation

The fabrication procedure of CRMAs plays an important role in the quality of the resulting mixture as adequate time needs to be planned for the interaction of rubber with bitumen. In this experiment, the components were mixed in the following order: hot mineral aggregates (T=180°C), RAP (T=160°C) (when relevant) were mixed, thereafter ECR was added directly or in plastic bags in the mixer followed by the bitumen 70/100 (T=165°C) and then filler (T=140°C). After the mixing process the asphalt mixture was emptied in a container or silo and allowed to rest for 30 minutes at ca. 160°C. This resting period allows the rubber-asphalt necessary interaction but at the same time, for the Swiss case, it is the typical time needed to reach a job site (hauling time) from the plant therefore it can be stated that for application in the field no extra resting time will be needed. Production samples of the modified mixes were collected and taken to a lab for analysis.

Once in the lab, the mixtures were re-heated and test samples and slabs were compacted at 150°C and allowed to cool before testing. It is important to highlight that for some of the experiments associated to the performance requirements described in the Swiss standards (i.e. water sensitivity and rutting), the SDA compacted samples, with higher CR and air void contents, were weighted down during the cooling (below 130°C) . This follows the instructions of the CR technology provider on the basis of the claim that *in situ* compaction of these CRMAs does not show any sign of post-compaction issues since it is typically done for a longer time and lower temperatures than laboratory compaction. Hence, in order to mimic field conditions, it is necessary to avoid the typical expansion experienced in laboratory due to the swelling and/or elastic recovery of CR after compaction of CRMAs at temperatures above the ca 130°C (Yu et al., 2014, Bressi et al. 2018). Samples prepared according to this protocol are indicated with a "W" in their designation. The reader is referred to the supplementary information for these results.

Both mixtures have volumetric and performance requirements as specified in the Swiss standard SN 640-431-1c and SN 640-436 for AC and SDA mixtures respectively (Table 2).

Table 2 Mixture volumetric and performance requirements according to the Swiss standards.

Mixture Type	**Void Content [V%]**	**Binder Content [M%]**	**Rutting (@30'000 cycles) [%]**	**Water sensitivity ITSR [%]**
SDA 4-16	14…18	≥ 6	To be reported only	≥ 70
AC B 22 H	4…7	≥ 4	≤ 7.5	≥ 70

2.2. Characterization Methods

Figure 2 shows the outline of the experimental program for the two type of mixtures tested. The experiments include the conventional ones such as volumetric properties, water sensitivity and rutting as well as non-conventional test methods such as Hamburg wheel tracking, Cantabro, disk shape compact tension (DCT) and scuffing. The experimental program was designed to determine the performance of the mixtures at various temperatures and loading conditions such as rutting and cracking. More experiments were planned for the SDA surface course due to the particular challenges of this type of mixture in terms of particle loss and cracking.

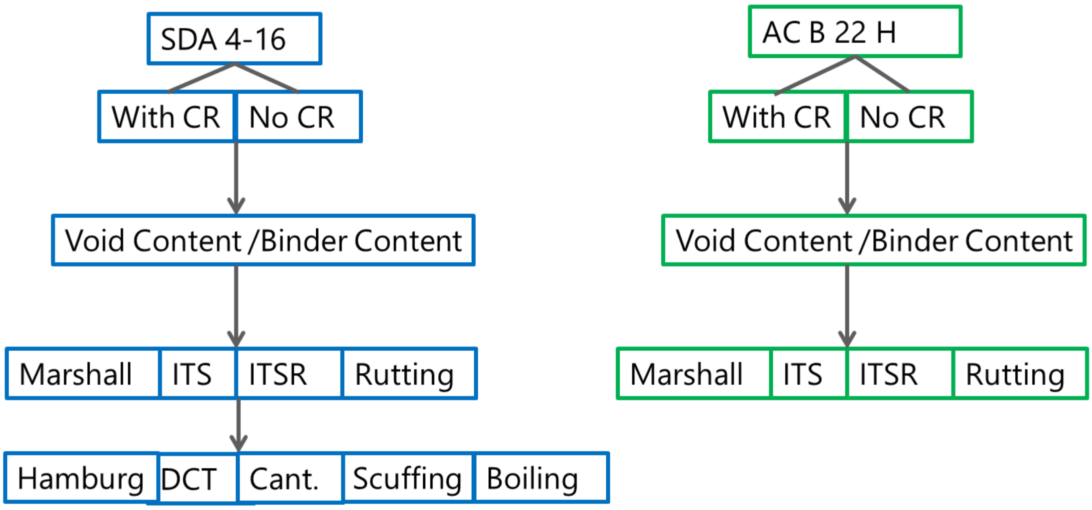


Figure 2 Experimental program

2.3. Marshall Test

The European Standard EN 12697-34:2012 specifies a test method for determining the stability, flow and the Marshall Quotient values of specimens of asphalt mixtures (100 mm diameter and 60 mm height) prepared using the impact compactor method. In Switzerland the compaction requirements are 50 blows per side. After preconditioning at 60°C in water bath, the specimens are loaded at a constant rate of deformation of (50 ± 2) mm/min until the maximum reading is obtained on the load-measuring device. Maximum force and displacement are recorded.

2.4. Water sensitivity tests using the indirect tensile strength ratio (ITSR)

Water sensitivity of the test samples was determined using the European standard EN 12697-12 Method A. Whereby, a set of six cylindrical test specimens produced using the Marshall hammer with 35 blows per side (100 mm diameter and 60 mm height) are divided into two equally sized subsets and conditioned. One subset is maintained dry in a climate chamber at 22°C while the other subset is saturated and stored in water at elevated conditioning temperature (40°C) for 68 to 72h. After conditioning, the indirect tensile strength of each of the two subsets is determined in accordance with EN 12697-23 at the specified test temperature of 22°C (equation (1)). The ratio of the indirect tensile strength of the water conditioned subset compared to that of the dry subset is determined in accordance to equation (2) and expressed in percent.

$$ITS = \frac{2F}{\pi D h} \qquad (1)$$

$$ITSR = 100 \cdot \frac{ITS_w}{ITS_d} \qquad (2)$$

Where, ITS is the indirect tensile strength (MPa), F is the force (N), D and h are the diameter and the height in mm respectively. ITSR is the indirect tensile strength ratio, in percent (%); ITS_w is the average indirect tensile strength of the wet group in; ITS_d is the average indirect tensile strength of the dry group.

2.5. French Wheel Tracking Test (FWT)

One of the methods used to characterize rutting of the mixtures was the French Wheel Tracking Test (FWT) according to the European standard EN 12697-22. The test assesses the susceptibility asphalt materials to deform by the repeated passes of a loaded wheel at constant temperature of 60°C. Two samples with dimensions 500 mm x 180 mm x 50 mm for the SDA mixtures and 180 x 500 x 100 mm for the AC mixtures were compacted in the laboratory using a wheel rolling compactor. During the rutting test, each cycle consists of two passes (outward and return) of the loaded wheel. Tire of outside diameter between 200 mm and 205 mm fitted to the wheel is used. The tire, a solid rubber, is treadles and has a rectangular cross profile with a width of 50 ± 5 mm and a thickness of 20 ± 2 mm. Mean rut depth is calculated using the recorded rut depth at 10 profiles on the two samples, i.e. 5 on each sample and each profile is an average of three points. The rut depth must fulfil requirements after 30000 passes. The Swiss requirements are listed in **Table 2**. In addition to the rut depth an adapted wheel-tracking rate was calculated as the average rate at which the rut depth increases with time under repeated passes of a loaded wheel. In this study, the wheel-tracking slope is calculated as

$$WTS = (d_{10000} - d_{3000})/7 \quad (3)$$

Where, WTS is the wheel-tracking slope, in millimeters per 10^3 load cycles;

d_{3000}, d_{10000} is the rut depth after 3000 load cycles and 10000 load cycles, in millimeters (mm). The result of the test is the average WTS of the two specimens.

2.6. Hamburg Wheel Tracking Test (HWTT)

The Hamburg Wheel Tracking Device was originally developed in Germany, in the mid-1970s, but has been extensively used in the United States as a mixture evaluation tool (Izzo and Tahmoressi, 1999; Solaimanian et al. 2002, Hill et al., 2013). Permanent deformation (rutting) in asphalt mixtures is caused by gradual accumulation of volumetric and shear strains in the asphalt layer. The asphalt surface deforms vertically downwards in the wheel paths, sometimes accompanied by lateral upheaval due to shear flow. The Hamburg test was performed in the University of Missouri-Columbia (USA) and simulates the traffic loading conditions on cylindrical specimens of the asphalt mixture by running a loaded steel wheel, weighing approximately 71.7 kg, over the samples in the heated water bath. The water bath is maintained at a temperature of 50 °C, as specified by AASHTO T-324, and the water-bath immersion allows the test to investigate both the rutting susceptibility and the moisture sensitivity of the tested asphalt mixture. The deformation of the 150 mm gyratory compacted specimen, is recorded as a function of wheel passes. While thresholds vary by agency and by virgin binder grade, a rutting limit of 12.5 mm (1/2 inch) at 10000 passes was adopted as a conservative threshold for this study. This level is considered conservative for a municipal-type mixture applications, as it represents a medium traffic category typically used with the Hamburg test (range = 5000 passes for lower volume roads, and 20000 passes for very high traffic applications such as expressways). Based on the composition of the SDA4-16 mixture, it is assumed that it will be placed on roadways that experience light to moderate traffic.

2.7. Boiling Water Moisture Sensitivity Test

In order to further validate the Hamburg Test results, an additional moisture sensitivity test was performed in the laboratory of the University of Missouri-Columbia and used to estimate the binder-aggregate adhesion, as specified in ASTM D3625/D3625M: “Standard Practice for Effect of Water on Bituminous-Coated Aggregate Using Boiling Water”. The procedure includes obtaining and heating up a representative sample of plant-produced mixture at a minimum of 85°C. Approximately 250 g of the mixture was placed in the boiling water for 10 min. At the end, the excessive binder on the surface of the water is skimmed off, the water is decanted and the mixture is laid on a white towel for analysis of the retained coated area of the aggregates. The assessment is qualitative by visual rating of the operator.

2.8. Cantabro Particle Loss Test

The European Standard EN 12697-17 defines the test method to determine the particle loss of an asphalt sample, it is also known as the Cantabro particle loss test. Five samples are weighed (W_1) and individually introduced in a *Los Angeles* drum. After 300 revolutions at a speed of 30-33 rev/min of the drum, their mass is weighed again (W_2). The particle loss (PL) in percent is the average value for the five samples determined using equation (4).

$$PL = 100 \times \frac{(W_1 - W_2)}{W_1} \quad (4)$$

2.9. Scuffing Test

The scuffing test (Figure 3) was performed) on samples that were prepared from SDA mixtures following the European specification CEN/ TS 12697-50. The method is used for surface layers that experience high shear stresses. These shear stresses occur in the contact area between the tire and the pavement surface and can be caused by slow maneuvers of the vehicle. Due to these shear stresses, material loss will occur at the surface of these layers. **Figure 3** shows the experimental set up at Karlsruhe Institute of Technology in Germany where the experiments were done. Two samples of each type of material with dimensions of 260 mm x 260 mm x 40 mm were tested using the standard testing parameters of 40°C and 10 double passes that includes twisting of the asphalt sample.

Figure 3 Experimental set up of the scuffing test is Germany

2.10. Cracking tests using disk-shaped compact tension (DC(T))

Disk-shaped compact tension (DC(T)) tests were performed to characterize the low-temperature cracking behavior of the mixtures. The cracking tests were performed at the University of Missouri-Columbia (USA). Specimens were compacted using the gyratory compaction method at Empa to the design void content and shipped to Missouri where the crack notch and holes were drilled to prepare the sample for testing. Wagoner et al. (2005) developed the DC(T) fracture test for asphalt materials undergoing fracture in Mode I which is documented in detail by ASTM D-7313. The test is controlled using a crack-mouth opening displacement (CMOD) gauge which opens at a rate of 1 mm/min. The loading profile associated with this Mode I opening is captured using an in-house LabVIEW code which reads the load and CMOD at a rate of 50 data points/s. The primary outputs from the DC(T) test include: CMOD fracture energy and peak load. In particular, the CMOD fracture energy provides a measurement of the total energy required to propagate the existing crack through a unit area of material. Research by Dave et al. (2010) and Buttlar et al. (2019) has shown that this measurement correlates with transverse cracking.

The test temperature chosen for this study was –12 °C to facilitate comparisons with previously published results (Hill et al. 2013).

2.11. Electron Microscopy

For imaging samples at micro-scale, an environmental scanning electron microscopy (ESEM) Phillips ESEM Quanta FEG650 in the high vacuum mode was used. The ESEM images are a result of the interaction of the electron beam with the atoms of the sample. The higher the atomic number the brighter the images. The specimen preparation followed the procedure developed previously where a cut sample is impregnated with epoxy resin and polished in order to be imaged in the electron microscope (Poulikakos & Part 2011).

3. Results and Discussion

Table 3 shows the characteristics of all six mixtures investigated. Voids in mineral aggregate (VMA) is the inter-granular space occupied by asphalt binder and air in a compacted asphalt mixture. Likewise, VFB refers to the portion of the voids in the mineral aggregate that contain asphalt binder. The richness modulus (SN 640 431-1c-NA) is an indication of the amount of binder film and a value between 3 and 4 is recommended in some countries. The results shown in **Table 3** show that with the addition of CR including additional binder content, the richness modulus has increased. Celauro and Praticò (Celauro and Praticò 2018) show that for a given amount of bitumen, higher richness modulus indicates higher effective film thickness which in turn could result in better performance. Furthermore the higher VFB parameter traditionally is an indication of higher binder film resulting in better performance. In the case of the six mixtures investigated, the VFB was equal or higher for the CR modified mixtures. The effect of these on performance will be discussed in the following sections. The mixture analysis indicated that the Marshall (2 x 50 blows) void content of SDA4-16 is not fulfilled but that of SDA4-12 that allows a void content of 10 to 14 percent is fulfilled. All six mixtures fulfil the gradation and binder content requirements

Table 3 Mixture characteristics

Type	Designation	Max Density [Mg/m3]	Bulk Density [Mg/m3]	VC [v-%]	VMA [v-%]	VFB [v-%]	Richness Modulus
SDA 4-16	SDA1-Ref	2.426	2.093	13.7	26.0	47.2	3.9
	SDA2-0.7%CR	2.415	2.070	14.3	27.0	47.2	4.2
	SDA3-1%CR	2.427	2.099	13.5	27.0	49.8	4.3
AC B 22 H (with 30% RAP)	AC1-Ref	2.523	2.400	4.9	14.3	65.8	2.7
	AC2-0.3%CR	2.516	2.410	4.2	15.3	72.5	3.1
	AC3.0.4%CR	2.519	2.398	4.8	15.4	68.6	3.0

Table 4 shows the binder properties after recovery from the six mixtures. Considering that the base binder was a 70/100 pen, it is interesting to note that the penetration has been considerably reduced after recovery perhaps due to aging during the process. The AC mixture analysis shows that all three mixtures fulfil the gradation and binder content and void content requirements (**Table 2**). These mixtures contained 30% RAP and therefore penetration and softening point (**Table 4**) of the recovered binder is below that of 70/100 as expected. Furthermore it is noted that the softening point of the CR modified mixtures that is a result of the type of base bitumen, are generally lower than the polymer modified ones that in turn have a direct influence on their mechanical performance as seen in the following sections. Furthermore When comparing the AC results to the SDA results it should be noted that the difference in binder content of 6-6.6% vs. 4-4.7% respectively as well as the aggregate gradation have a direct effect on the results.

Table 4 Conventional properties of the recovered binders

Type	**Designation**	**Penetration [0.1 mm]**	**Softening Point [°C]**
SDA 4-16	SDA1-Ref	39	68.2
	SDA2-0.7%CR	52	50.8
	SDA3-1%CR	56	49.8
AC B 22 H	AC1-Ref	39	57.6
	AC2-0.3%CR	44	53.2
	AC3-0.4%CR	42	53.8

3.1. Marshall Test

There are no requirements for Marshall test values (EN 12697-34 /SN 670434) in Switzerland for AC B 22 H or SDA mixtures. However, these tests provide a basis for comparison of the mechanical performance of the studied mixtures. Note that in this test the samples are preconditioned and tested at 60°C. The test results shown in **Figure 4** indicate similar values for CR modified mixture AC2, AC3 as the differences observed fall within the error margin. In the case of SDA, the stability values of the CR modified mixtures SDA2 and SDA3 were 30% and 28% lower than reference respectively, whereas the Flow was within the error margin. This decrease of stability can be attributed to the lower softening point of the binder for the CR-modified SDA samples, which lies well below the test temperature of 60°C, compared to the SDA reference where the binder softening point was determined to be higher at 68.2°C (**Table 4**). This also explains why the effect to stability for the AC samples is much less, since softening point for all samples, including reference, was measured to be below 60°C.

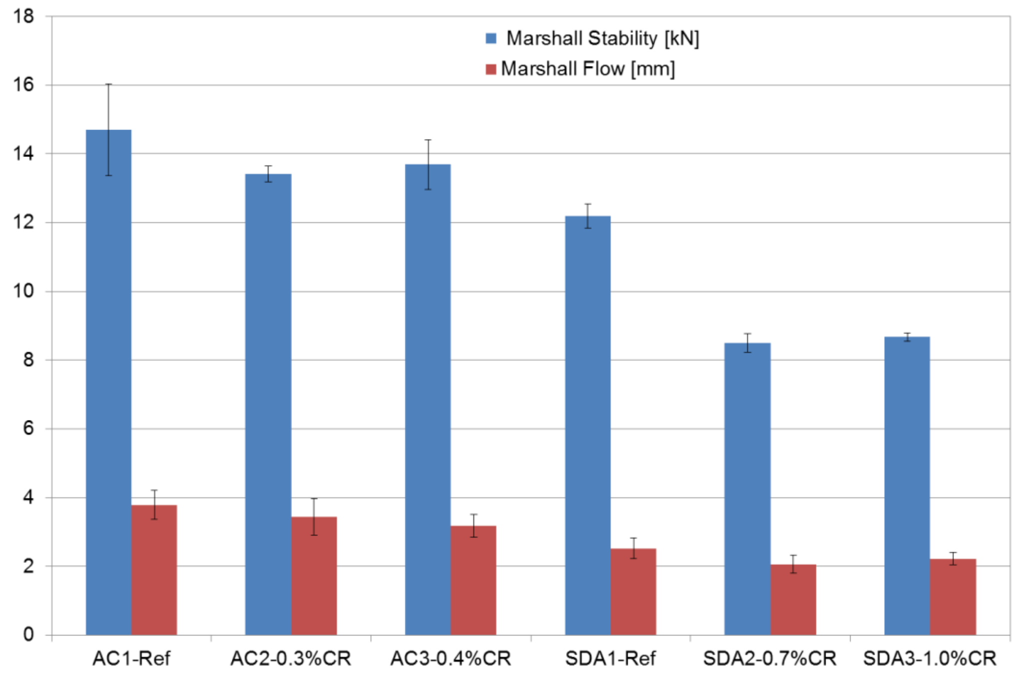


Figure 4 Results of Marshall Stability and Flow tests, error bars indicate standard deviation

3.2. Indirect Tensile Strength

Results shown in Figure 5 indicate that AC B 22 H with 0.3% CR (AC2) and 0.4% CR (AC3) surpass the indirect tensile strength of AC B 22 H with PmB (AC1) in dry and wet state. In the case of SDA mixtures, with 0.7% CR (SDA2) these mixtures surpass the indirect tensile strength of SDA with PmB (SDA1) in dry and wet state. SDA with 1.0%CR (SDA3) replicates the dry state but is below the wet state strength of reference mixture. Comparing these results to the Marshall test (**Figure 4**) shows the clear effect of temperature on strength. SDA1, SDA2 and SDA3 perform similarly in the ITS test while there is a clear difference in the Marshall test results. As the samples for Marshall tests were conditioned at 60°C, the ITS tests were done at room temperature (22-25 °C), well below the softening point of the binders.

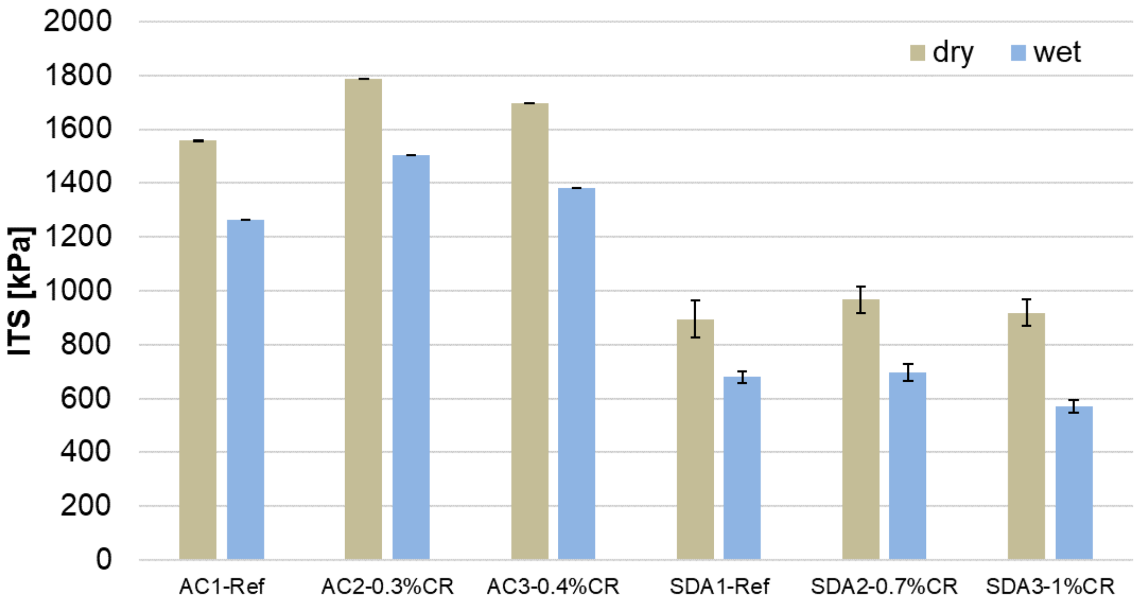


Figure 5 Indirect tensile strength for dry and wet samples, error bars indicate standard deviation

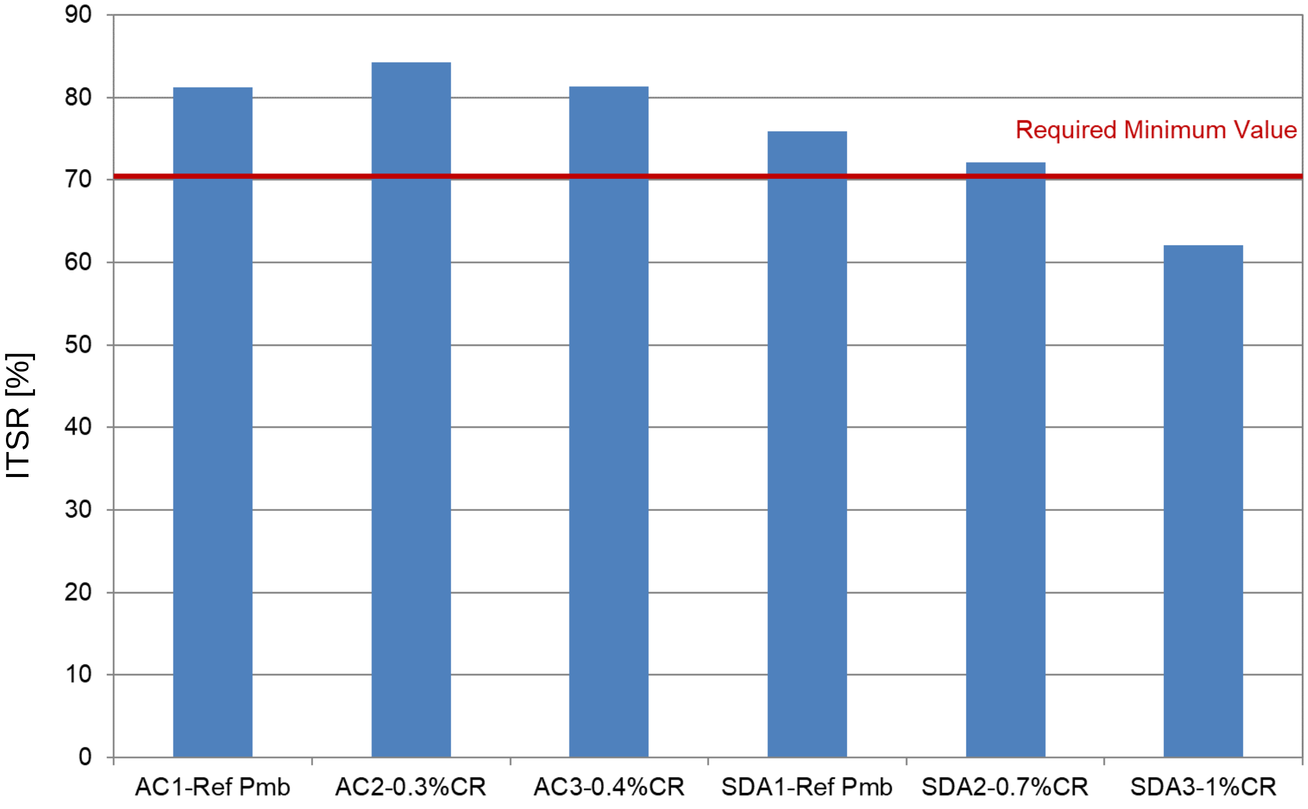


Figure 6 Indirect tensile strength ratio (ITSR) for all mixtures, minimum requirement of 70% (defined by Swiss standards) shown in red

The results of the water sensitivity tests shown in **Figure 6**

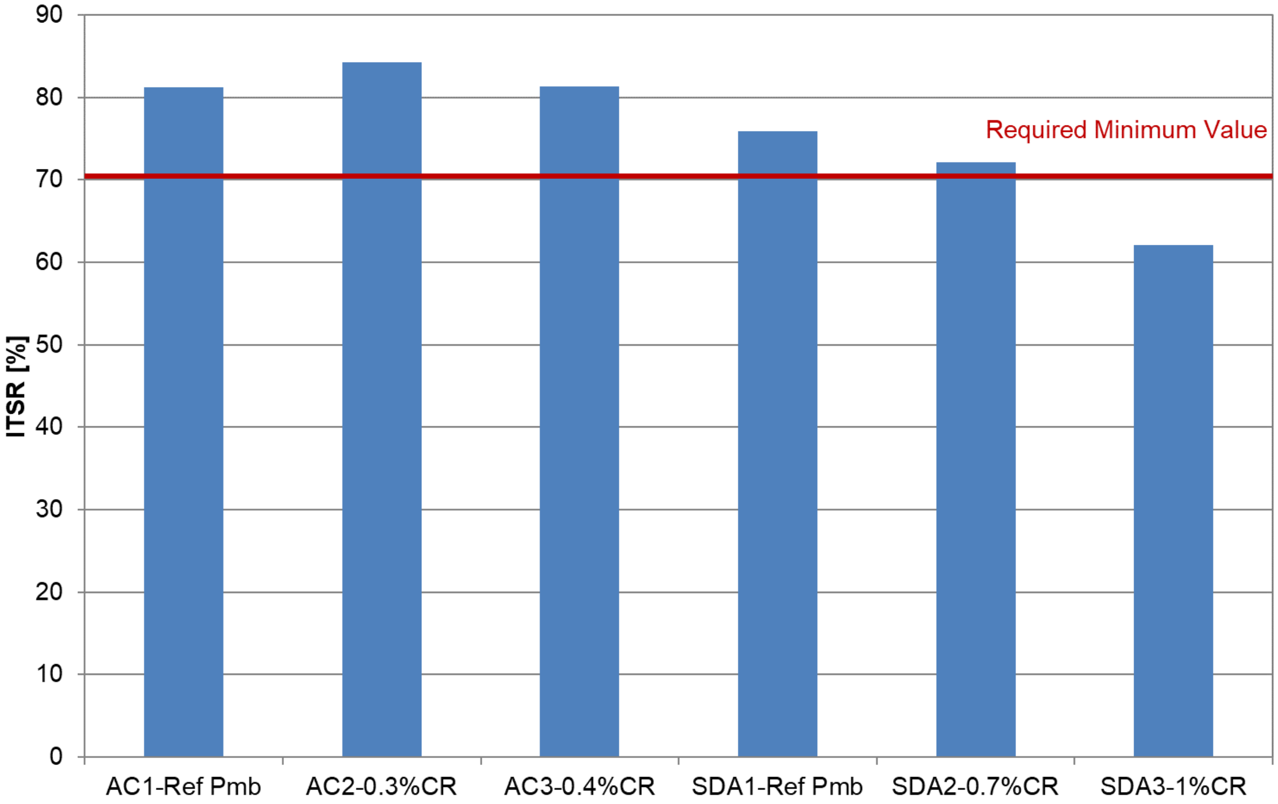


Figure 6 indicate that all three AC mixtures pass the Swiss requirements of 70%. Addition of CR had no negative effect on water sensitivity of these mixtures and resulted in similar response than the reference mixture with PmB. The results of the water sensitivity tests for the SDA mixtures show that only the SDA with 0.7%CR passes the Swiss requirements of 70% and that there seems to be a negative trend with increasing amount of CR addition. With a closer look to the ITS results above, where the dry strength of both type of mixtures reaches best values at moderate CR modification, the addition of CR seems to have a negative impact on wet strength only for the SDA samples. This may be explained by the open graded porosity of the semi-dense mixture design, allowing for much more water intrusion to the bulk asphalt material, while on the other hand the bulk of the AC samples was exposed to much less water within the same test. This results shows that the incorporation of CR could have a negative effect on mixtures with high air void content in terms of water sensitivity. Nevertheless, this issue may be less critical for the actual application in the field as implied here from the lab results. This topic will be further discussed in the supplementary information by referring to results using an alternate specimen compaction method.

3.3. French Wheel Tracking Tests

The results of rutting test using the FWT are shown in **Figure 7** and **Figure 8**. The rutting performance of CR modified AC mixtures with 0.4%CR (AC3) was very similar to the reference polymer modified mixtures (AC1) with very similar slope of the rut depth vs number of cycles curve (**Figure 8**), showing similar reaction to rut depth development with increasing number of cycles. The samples with 0.3%CR (AC2) show a different deformation level that cannot be attributed to the CR content exemplified by a largely higher starting rut depth. This can be contributed to a lower compaction level of these samples. Nevertheless, as shown in **Figure 8**, the WTS of this mixture (AC2) which is an indication of the rate of increase of the rutting, is similar to the other mixtures. The SDA CR mixtures show slightly more rutting in comparison to the reference PmB, however the amount of CR (0.7% or 1%) did not make a difference. This difference response compared to the reference can be attributed to the difference in softening point of the binder. The two mixtures investigated (SDA and AC) showed in most cases a slightly higher slope for the CR modified mixtures. The slope is much smaller for SDA mixtures as these gap graded mixtures have a slower rutting rate in comparison to the AC mixtures but ultimately end up with a similar rutting depth after the same number of loading cycles. Rutting performance is affected by mixture structure, binder content and RAP content such as in the case of the AC mixture with 30% RAP. However although the CR modified AC mixtures can be more susceptible, the value is well below the required 7.5%. Furthermore, using the alternate specimen preparation method discussed in the supplementary information, this response was enhanced. A significant effect of the weighing down of the samples can be seen as shown in Figure S3 and Figure S4. Once the samples were weighted down for SDA3 (1%CR) very similar performance to the polymer modified reference can be seen. Regarding the rate of rutting that shows the development over time the weighing down had a positive effect (Figure S4).

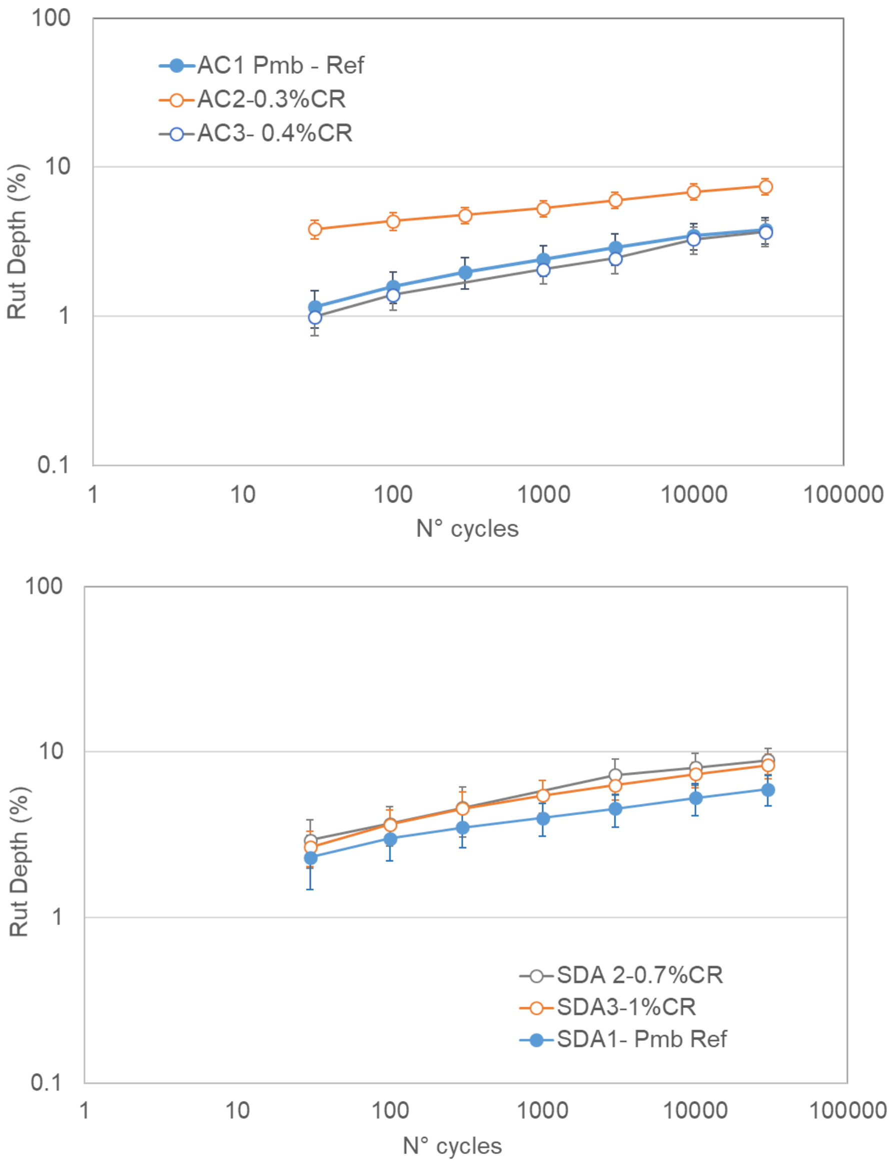


Figure 7 French wheel tracking tests results for AC 22 (above) and SDA (below)

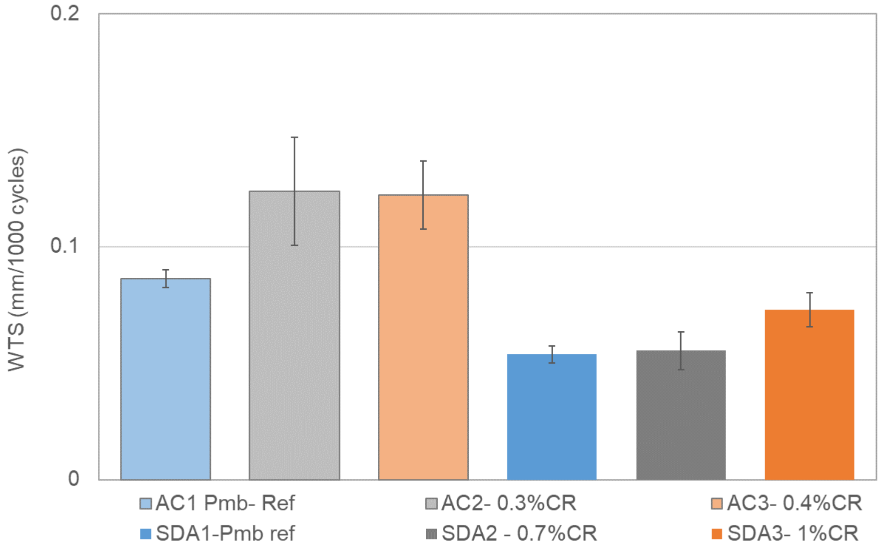


Figure 8 Slope of the rutting curve for AC22 and SDA mixtures, error bars indicate standard deviation

3.4. Hamburg wheel Tracking Test

The results of the Hamburg testing are shown in **Figure 9**. In terms of rut depth, the PmB mixture (SDA1-Ref) was the best performing, followed closely by the SDA2-0.7%CR mixture, and finally the SDA3- 1.0%CR mixture. All three mixtures easily passed the 12.5 mm maximum rutting requirement for the Hamburg test at 10000 wheel passes, even considering the largest measured rut depth in the SDA3- 1.0%CR mixture at 10000 passes (6.24 mm<<12.5 mm max). Thus, if these mixtures are to be used in low to medium traffic settings (commensurate with less than or equal to 10000 Hamburg wheel passes), then all three study mixtures should be appropriate for deployment.

The stripping inflection points (SIP) for the three mixtures were 14440, 15970, and 9680 wheel passes respectively. This suggests that the SDA2-0.7%CR had the best moisture resistance, followed closely by the PmB mixture (SDA1). Even in the case of the SDA3-1.0%CR mixture, the 9680 wheel pass level is large enough to satisfy typical stripping inflection point criteria for moderate-traffic applications in the US. Thus, in summary, all three study mixtures easily met rutting and stripping criteria for 10000 pass Hamburg (medium traffic) testing based on comparison to typical US requirements.

As seen in the Hamburg tests and FWT, the rutting evolution i.e. the evolution of the slope of the rutting curve is an important indication of rutting performance. Both tests indicate that SDA with 0.7% CR (SDA2) performed very close to the reference (SDA1) and SDA with 1.0% CR (SDA3) performed slightly worst in terms of evolution of rut slope. The fact that the mixture with a higher level of CR experienced a higher rutting level is counterintuitive and does not concur with most past findings. A possible explanation is that the experimental mixture with 1.0% CR needs to be redesigned to ensure sufficient binder is present to account for the uptake of asphalt light molecular fractions that occurs during the resting time of dry process mixtures. This would avoid introducing potential moisture sensitivity which can occur in designs with low binder content.

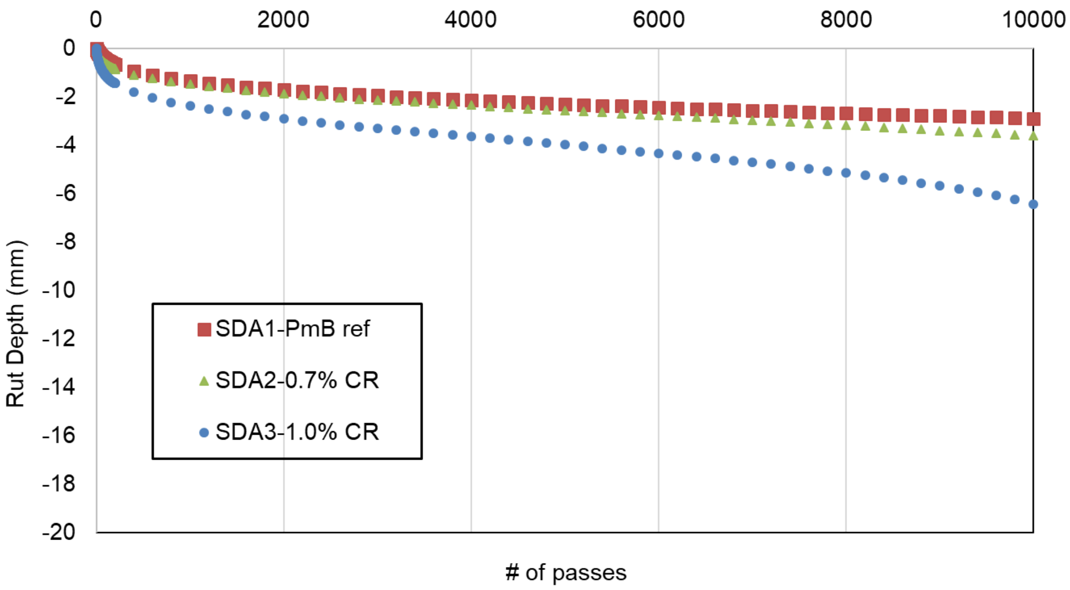


Figure 9 Results of Hamburg wheel tracking test for SDA mixtures SDA1 (PmB), SDA2 (0.7%CR2) and SDA3 (1.0%CR2) at 50°C and 10,000 passes

3.5. Boiling Water Moisture Sensitivity Test

The boiling water test was performed for the SDA mixtures and visual inspection was done to check if there was any loss of coating of binder over aggregates. As shown in **Figure 10**, none-of-the-three mixtures exhibited visual stripping or adhesion deficiencies after the boiling test. Although the Hamburg test provides a very severe assessment of moisture sensitivity -— these three mixture designs appear to effectively resist rutting in light and medium duty applications.

This provides further evidence that all three studied mixtures will be viable for low-to-moderate traffic levels from the standpoint of moisture resistance.

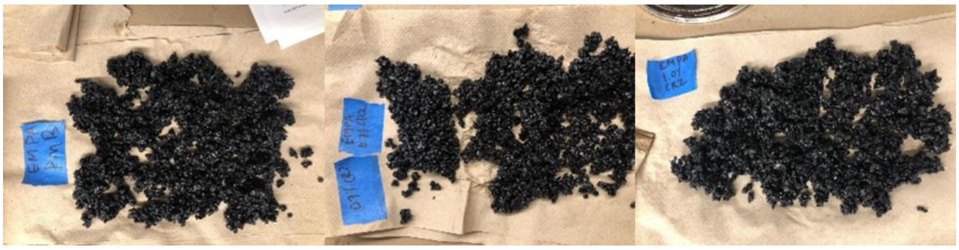


Figure 10 Results of the boiling water test. From left to right SDA1 (PmB), SDA2 (0.7%CR) and SDA3 (1.0% CR) modified mixtures

3.6. Cantabro Particle Loss Test

The susceptibility of the SDA mixtures for particle loss was also investigated using the Cantabro test. The results shown in **Figure 12** indicate that the CR modified mixtures were more susceptible to particle loss in comparison to the polymer modified reference mixture and the susceptibility increases with increasing CR content. However, it is noteworthy that no requirements exist for particle loss of SDA. In some countries a requirement of 10% exists for porous asphalt with a void content of 20%. In this study, the maximum value measured for SDA was 4.8% which is well below this limit. Furthermore it should be noted that the Cantabro test does not reflect the interaction of the wheel with the pavement and it can be seen as a material performance indication. The wheel pavement interaction aspect is further investigated in the scuffing test.

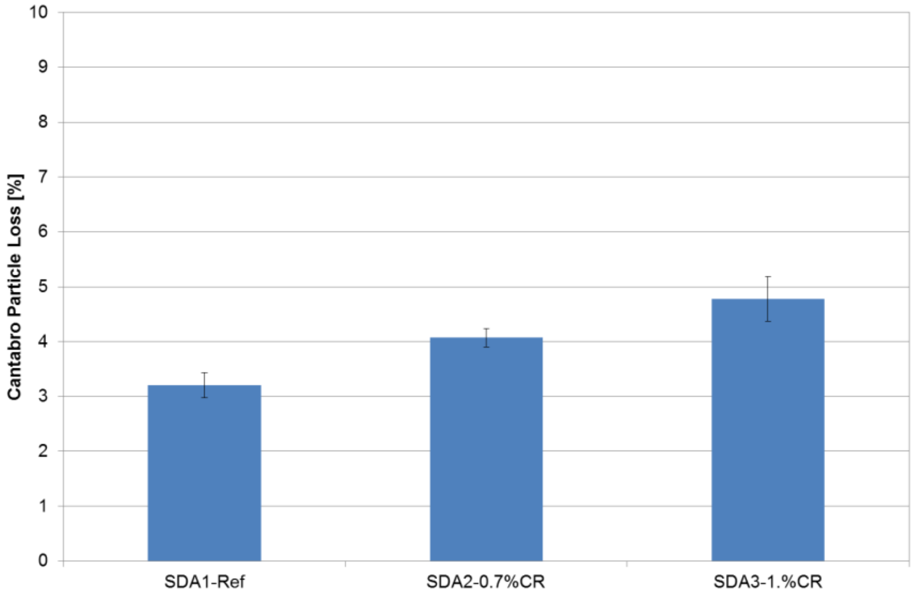


Figure 11 Cantabro particle loss values for SDA mixtures, error bars indicate standard deviation

3.7. Scuffing Test

The scuffing test results shown in **Figure 12** indicate that the reference polymer modified mixtures has considerably less particle loss compared to the two mixtures modified with rubber and that particle loss increases with amount of CR. However, it should be noted that this test is normally performed for porous asphalt and a particle loss of 190 g is still considered acceptable. Therefore, the highest particle loss measured for SDA3-1%CR that was 15 g is within the acceptable limits. Furthermore, since this test is done at an elevated temperature of 40°C, the difference in bitumen can be a contributor to this result in addition to the amount of CR.

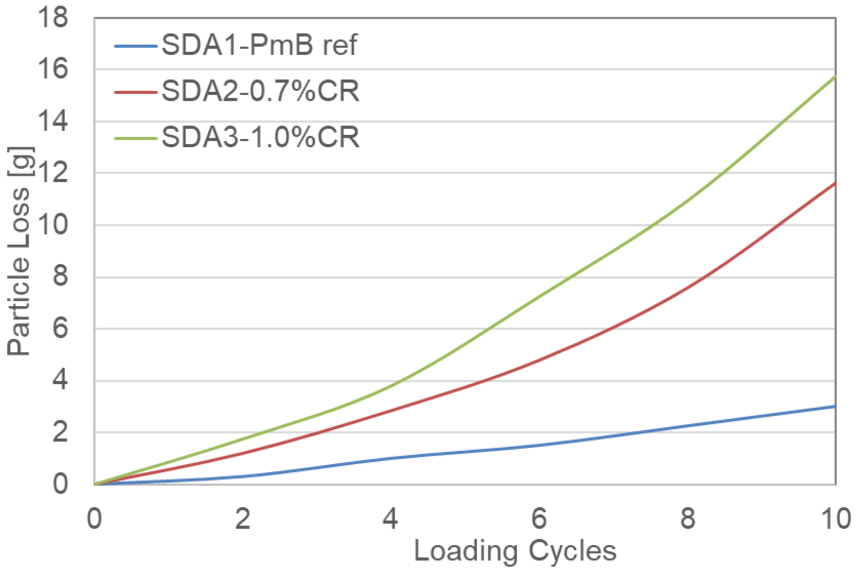
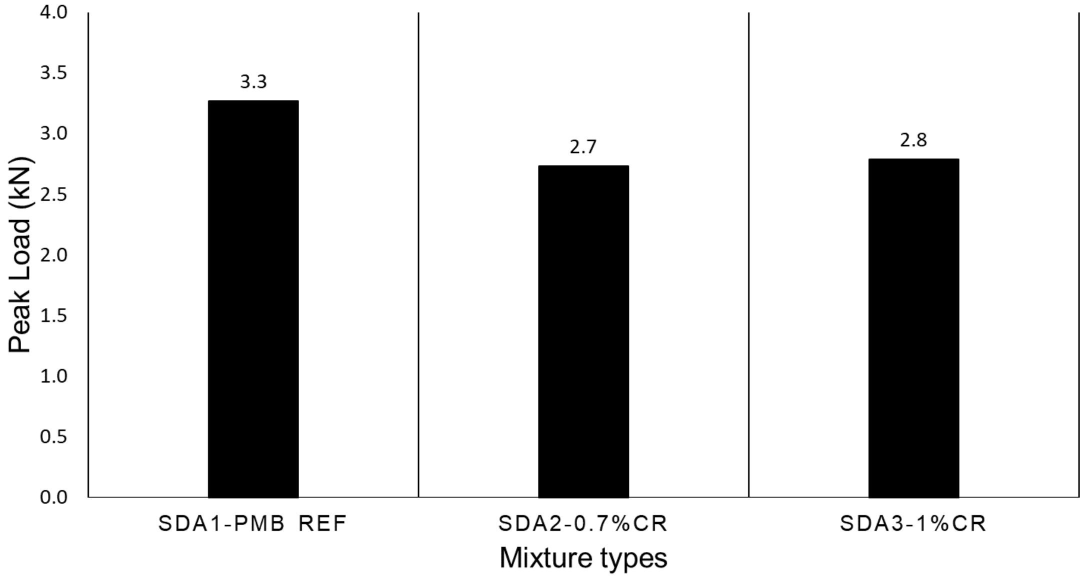


Figure 12 Particle loss using the scuffing test, average results of two samples shown

3.8. Cracking test (DC(T))

The results of the DC(T) test for the SDA mixtures shown in **Figure 13** compare the cracking behavior of the two CRMAs to PmB reference mixture. Results indicate that the SDA2-0.7%CR mixture matches the performance of the reference SDA1 with PmB, within statistical scatter. The SDA3-1.0%CR has about 85 J/m^2, or 15% higher fracture energy than the ref mixture with polymer. These results are consistent with previous findings [Rath et al., 2019], where dry process crumb rubber can be used to created mixtures with equal or greater resistance to low temperature cracking as compared to wet process CR or polymer modified mixtures. In general, however, relative differences between CR and polymer modified mixtures will depend on the particulars of the polymer (type and amount), and the base binder used for both the polymer and the CR mixtures.



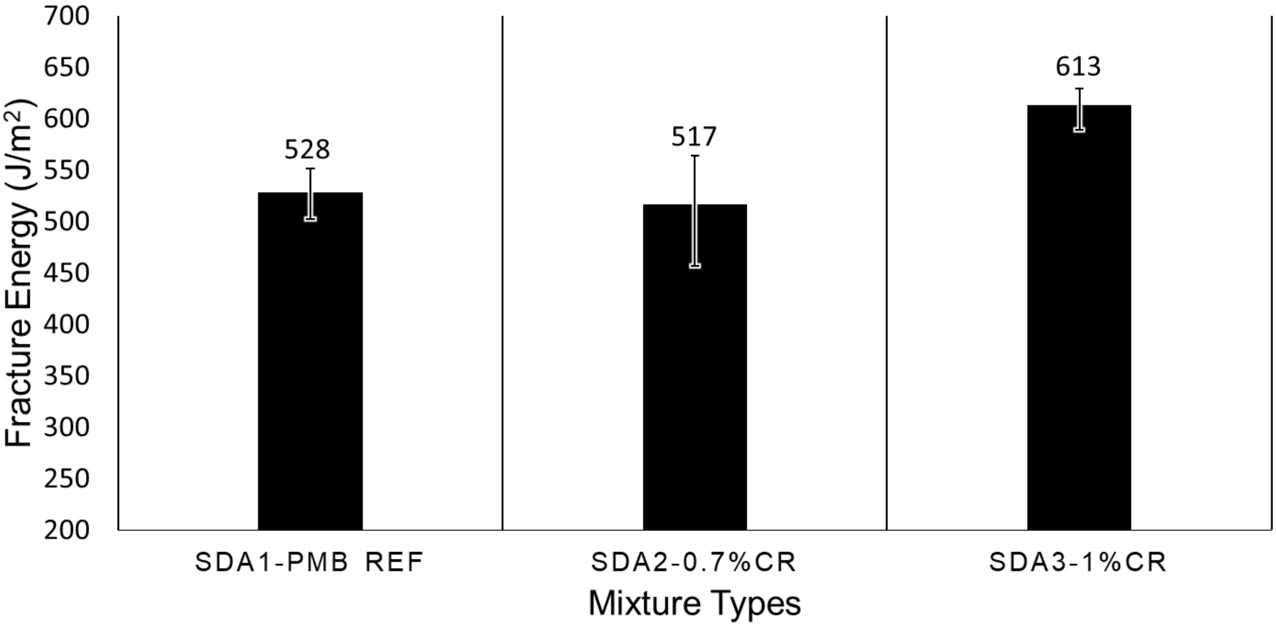


Figure 13 Results of cracking test (DCT) for the SDA mixtures peak force above and fracture energy below, average values shown, error bars indicate maximum and minimum values

3.9. Discussion and perspectives

The results presented in the previous sections and summarized in **Table 5** indicate a trend in the behavior of CRMAs in most cases examined, in comparison to the PmB mixtures. Although rubber swelling or dilating may change the volumetric properties and as a result affect the mix performance, the results presented above indicate that the plant produced mixtures had similar void content (within1%). When the sample temperature at testing time is higher, the CR modified mixtures behave worse (although within acceptable industry limits) than the polymer modified ones when the binder softening point listed in **Table 4** is below the test temperature. This behavior can be explained by the fact that asphalt mixtures are viscoelastic materials and depending on the temperature they can behave elastically at low temperatures and viscous at high temperatures and a combination of the two at intermediate temperatures. The microstructure of SDA was also investigated using environmental scanning electron microscopy (ESEM). An example is shown in **Figure 14**. The figure shows how the particles of CR (indicated with an arrow), are located within the mixture. They can be distinguished from the mastic as they do not contain any filler. As the temperature rises the bitumen becomes viscous with the elastic CR particles intact embedded within it. Therefore, at higher temperatures, the CR particles can contribute relatively less to the mechanical behavior of the mixture and the bitumen's viscous behavior is dominant. Once the temperature is lowered, both materials bitumen and rubber behave more elastically and participate in the mechanical performance. This is a different physical regime in comparison to the SBS polymer modified mixtures, where the macromolecules of the polymer are uptaken by the bitumen and thereby change the mechanical characteristics of the entire binder. This is the reason that at higher temperatures the CRMAs behave worse that the PmB mixtures especially in case of SDA mixtures.

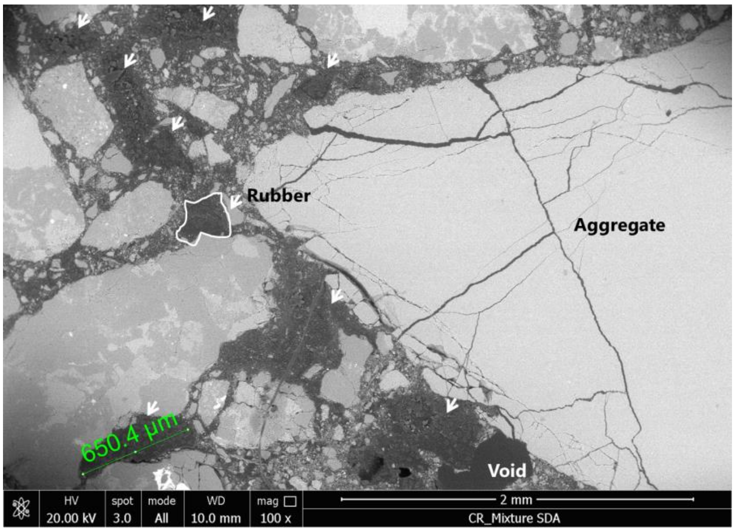


Figure 14 ESEM micrograph of SDA mixture containing crumb rubber shown with arrows, scale bar 2mm

Table 5 Comparison of the performance of CRMAs with PmB mixtures

Property	**SDA Mixtures**	**AC Mixtures**	**Test Temperature [°C]**
Marshall	⬇	➡	60
ITS (dry)	⬆	⬆	22
ITS (wet)	⬆	⬆	22
ITSR	⬆ (1)	⬆	22
French Wheel Tracking	➡	➡	60
Hamburg Wheel Tracking	➡	(2)	50
Cantabro Particle Loss	➡	(2)	25
Scuffing	➡	(2)	40
DC(T)	➡	(2)	-12

Mostly worst performance (⬇); Mostly better performance (⬆)

Same same, slightly worse or slightly better performance and within acceptable limits (➡)

(1) Weighing down of lab samples improved results significantly, see supplementary information

(2) Not relevant or not performed

4. Summary and Conclusions

This work reported on the laboratory scale performance of crumb rubber modified mixtures (CRMA) plant produced using the dry process consisting in pre-treating rubber crumbs for improved control over the swelling phenomena. Two types of mixtures were investigated; a semi-dense surface course (SDA4-16) and a dense base course (AC B 22 H); a total of six asphalt mixtures were designed and characterised. Both types of mixtures require polymer modified bitumen (PmB) or use it as an option in Switzerland. Hence the investigation aimed at assessing whether CRMAs can be engineered to effectively replace commonly used asphalt mixtures with PmB. The results can be summarized as follows:

- Fabrication of CRMAs in the plant using the dry process requires no additional tools and retrofitting of the plant, however the fabrication process needs more care and know-how in comparison to the non-modified mixtures. Therefore, careful training of the personnel involved is imperative to obtain good results. Particular attention should be paid to order of the addition of the components in the mixer, as well as to ensure an appropriate resting time before construction in order to allow interaction of rubber with binder. The resting time used was a minimum of 30 minutes, which shouldn’t affect productivity in Switzerland since it’s comparable to average hauling times.
- The investigated CRMAs and fulfilled most of the requirements of the Swiss and/or US standards regarding volumetric properties, water sensitivity and rutting.
- Where no requirements exist, the CRMAs performed similar to the reference dense mixtures and slightly worse than the reference semi-dense mixtures, particularly in the high temperature tests conducted. In this case the binder becomes soft in the rubber-binder composite. However, the obtained results were within acceptable values.
- Asphalt mixture with PmB resulted to be clearly superior to CRMAs only in the case of the SDA mixtures and in terms of particle loss, scuffing and rutting measured with Hamburg test. It has to be highlighted that investigating the effect of a different sample preparation rutting behavior of the CRMAs turned to be the same for the mixtures with PmB. Hence, this might hold true also for other mechanical parameters
- In order to consider CRMAs as a viable alternative to conventional mixtures modified with PmB, the choice of base bitumen for CRMAs is important and optimization could provide better performance and is recommended.
- Special attention should be paid to laboratory compaction methods to replicate field compaction especially pertaining to temperature

  Additional work is need to develop tailored, performance-related mixture tests for dry process ground tire rubber that can replicate long term field performance

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