Three indexes to characterise crushing and screening of reclaimed asphalt pavement

Martins Zaumanis, Lukas Boesiger, Bernhard Kunz, Henry Mazzoni, Peter Bruhin, Samuel Mazor and Lily Poulilakos

EMPA, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland; Armann Schweiz AG, Langenthal, Switzerland; BHZ Baustoff Verwaltungs AG, Zürich, Switzerland; Catram AG, Chur, Switzerland

ABSTRACT
The more reclaimed asphalt pavement (RAP) is used in asphalt production, the more properties of the pavement depend on the characteristics of the RAP. Crushing and sieving of RAP into different fractions are the most used means of RAP processing that can allow ensuring consistency and the desired properties of the produced mixture. Currently, however, there is no method to compare different RAP processing methods. Here we propose three indexes to evaluate crushing and screening of RAP – Chunk index, Breakdown index, and Filler increase index (CBF indexes). These indexes are derived from the black and white grading curves of RAP and, therefore, can be of practical use for asphalt producers. Through full-scale validation with four different crushers, we found that the indexes allow for a quantitative comparison of different RAP processing methods and can be used to optimise the configuration of a particular crushe. A calculation tool is attached to the paper.

1. Introduction
Re-use of Reclaimed Asphalt Pavement (RAP) for the production of new asphalt mixtures is continuing to gain popularity (EAPA 2020, Williams et al. 2020), and advancements in many areas are helping to sustain this growth:

- Researchers are improving the mixture design process to ensure a long pavement life cycle (Free et al. 2018, Zaumanis et al. 2019b).
- Chemical companies are developing rejuvenators that allow the binder to serve another service period (Koudelka et al. 2019, Zhang et al. 2019).
- New asphalt production plants are being developed, enabling the addition of higher content of RAP without overly ageing the bitumen (Liu et al. 2017, Ding et al. 2018, Zaumanis et al. 2019a).
- Road owners are permitting ever higher rates of RAP in production and demonstrating successful test sections (West et al. 2011, Blanc et al. 2019).
- International regulations and government agencies are pushing toward more sustainable construction practices and placing recycling as a high priority (Schut et al. 2015, European Commission 2019).

What is often forgotten from this chain is the very first step – the RAP itself. The more RAP is added into the asphalt mixture, the more the properties of the pavement depend on it. It is impossible to maintain a consistent final product without a consistent source of material that comprises it. High-quality pavement cannot be produced from low-quality materials.

The properties of RAP depend on two parameters: (1) the properties and homogeneity of the pavement that is being milled and (2) the RAP management and processing practices. While little can be done to change the pavement itself, appropriate management and processing of RAP can enable to preserve the RAP properties and therefore allow the use of high RAP content in high-quality mixtures. The approaches for RAP management include milling in layers to separate different mix types, creating separate stockpiles for different RAP sources, fractionating RAP to different sizes, crushing to reduce the size of RAP agglomerations, crushing to reduce the maximum aggregate size of RAP, and homogenising stockpiles comprised of different RAP sources (De Lira et al. 2015, West 2015).

Processing of RAP, including crushing and/or fractionation, is probably the most widely used strategy for RAP management. The types of machines are used for crushing RAP include horizontal impact crushers, roller or mill-type breakers, granulators, hammer mill impact crushers, jaw crushers, cone crushers, and combinations of these (NAPA 1996, West 2015). For fractionation, different combinations of sieve sizes can be installed and the sequence of crushing and sieving can be varied. Finally, there might be alternative methods for processing RAP, for example, decomposition of RAP mortar from aggregates (Huurman et al. 2016).

Currently, there is no method to quantitatively compare the impact of the processing operations on the properties of the produced RAP. An approach for systematically assessing the crushing and sieving operations could enable making informed decisions when comparing different crushers and when optimising the configuration of a particular crushing/sieving operation. Ultimately, this could improve the RAP
management procedure and allow to tailor the properties of RAP for maximising its use in asphalt production or in cold central plant recycling.

The objective of the study is to develop a quantitative method for determining the impact of industrial-scale reclaimed asphalt pavement crushing and sieving operations on the properties of the material.

2. Materials and methods

2.1. Materials

Five different sources of RAP were used in the experiment; referred to as 1, 2, 3, 4 and 5. The source 1 is a milled RAP; source 5 consists of RAP slabs that were obtained by ripping the pavement; sources 2, 3 and 4 are a blend of milled RAP and RAP slabs. The exact origin of these materials within Switzerland is unknown (Figure 1).

Four different crushers were used in the experiment:

- GIPO Impact Crusher GIPOKOMBI RC 131 FDR DA
- Ammann Shredder RSS 120-M
- Benninghoven Granulator MBRG 2000
- SBM Impact Crusher REMAX 1213 Maxi

Two of the crushers (GIPO and Ammann) were set up to work in parallel and were loaded simultaneously with the same material (sources 1 and 2). The other two crushers (Benninghoven and SBM) were located at different places and processed material from separate sources. The crushers during the experiment as well as the RAP fractions that they produced are illustrated in Figure 2.

This experiment is not aimed at answering which is the best crusher. Rather, it was important that crushers from different manufacturers and different crusher setups are used for processing various materials. This is ensured and will provide evidence for the application of the proposed methodology in a range of different situations.

The four crushers (denoted after the first letter, G, A, B, S respectively) were used to process the five source RAP materials resulting in seven different samples as illustrated in Figure 3. The different materials are abbreviated as illustrated in Figure 3 by including the source and the first letter of the crusher name. For example, the sample Milled-1-G is a milled material from the source 1 and processed with the GIPO crusher.

All four crushers were set up to reduce the size of the RAP chunks and sieved the material into the following fractions:

- GIPO cruiser first sieved the source material on a 11 mm sieve producing a 0/11 mm fraction (abbreviated as 0/11s; s-sieved). The main material flow then passed through a crusher and was sieved again on an 11 mm sieve as well as on a 22 mm sieve, producing fractions 0/11 mm (0/11c; c-crushed) and 11/22 mm.
- Ammann shredder crushed the material and then sieved it to fractions of 0/11 mm and 11/22 mm.
- Benninghoven granulator crushed the material and then sieved it to 0/22 mm fraction.
- SBM crushed the material and then sieved it to 0/16 mm fraction.

The produced materials were sampled, tested and, if more than one fraction was produced, re-combined according to the estimated weight percentage of the produced fraction. The weight percentage of each produced fraction is summarised in Table 1. For example, if crusher A produced 70% 0/11 mm fraction and 30% 11/22 mm fraction, the test results of the separate fractions were mathematically re-combined at these same proportions. This ensures that the tested materials are representative of the amount of material produced from one unit of the source material. In other words – if one ton of RAP was passed through the crusher and produced three different fractions, we recombined the fractions proportionally to the produced amount to make sure that we also evaluate the same one ton.

It has to be noted that for production purposes the materials would not be recombined. Having multiple fraction sizes allows more flexibility for designing and producing asphalt mixtures, often resulting in a higher attainable RAP content.

The white grading curves of the used source materials are displayed in Figure 4 and the binder content along with the RAP aggregate density are summarised in Table 2. These results show that the two slab/milled RAP blends (source 2 and 3) are very similar in terms of gradation, aggregate density,
toughness, and binder content. This allows assuming that the differences in the results for sources 2 and 3 can be mostly attributed to the differences between the three crushers and the crusher configurations that were used in the experiment.

The gradation of sources 1, 4 and 5 is slightly finer compared to the other two materials, and the toughness, measured as Micro-Deval abrasion value, is slightly lower for the sources 4 and 5. The aggregate density is within a similar range for all materials. The binder content in source 1 (milled RAP) is approximately 1% higher compared to the other materials while the softening point is within 7°C range for all materials.

Generally speaking, the RAP properties are within a typical range for Switzerland. The differences between the material properties are relatively small and are unlikely to cause significant differences in the evaluation of the crushing and screening of the RAP.

2.2. Sampling

Any granular material, including RAP, segregates during flow based on size, shape and density. When RAP falls from the conveyor belt, it forms a stockpile where the larger chunks migrate away from the centre and down to the bottom of the pile. It is therefore important to follow sampling procedures that allow obtaining representative samples.

To minimise the impact of segregation when sampling RAP, the material is most often sampled from different heights from within the middle of the stockpile (e.g. by following EN

| Table 1. Estimated weight-percentages for the processed material fractions for each crusher. |
|-----------------------------------------------|-------------------------------------------------|-------------------------------------------------|-----------------|
| Processed material | Source material | Crusher | 0/11 sieved only | 0/11 after crushing | 11/22 | 0/22 | 0/16 |
| Milled-1-G | Source 1 (Milled RAP) | Gipo | 40% | 30% | 30% |
| Milled-1-A | Source 1 (Milled RAP) | Ammann | 60% | 40% |
| Blend-2-G | Source 2 (Slab/milled RAP blend) | Gipo | 35% | 35% | 30% |
| Blend-2-A | Source 2 (Slab/milled RAP blend) | Ammann | 30% | 70% |
| Blend-3-B | Source 3 (Slab/milled RAP blend) | Benninghoven | 100% |
| Blend-4-S | Source 4 (Slab/milled RAP blend) | SBM | 100% |
| Slab-5-S | Source 5 (RAP slabs) | SBM | 100% |
We followed this procedure for sampling RAP from the source stockpile. For sampling the processed RAP, we developed a procedure to pick up the material directly as it falls from the conveyor belt (Figure 5). We expect this to further limit segregation and thus reduce variability compared to sampling from a stockpile.

### 2.3. Methods

The gradation (particle size distribution) was determined according to EN 933-1 and the particle density according to EN 1097-6 using pycnometers. For every sample, at least two replicate tests were performed. The material for each replicate test was sampled from a different box, to account for any variability during sampling of the material at the job site.

#### 2.3.1. Extraction and binder properties

To obtain the RAP aggregate and bitumen, extraction was performed using toluene according to EN 12697-1. This procedure also allowed determining the binder content.

After extraction, the binder was recovered using a rotary evaporator according to EN 12697-3. Softening point was then determined on the recovered binder according to EN 1427.

#### 2.3.2. White curve

The white curve (RAP aggregates without binder) was determined according to EN 933-1 by sieving extracted RAP aggregates for 10 min dry, followed by 10 min water sieving of the entire tower. The tower, holding 30 cm diameter sieves was shaken at a frequency of 50 Hz and amplitude of 1.6 mm. Each sieve with the material was then placed in an oven at 110°C until completely dry.

The recovered aggregates were also used to determine the Micro-Deval abrasion according to EN 1097-1. The test portion was combined out of 65\% of 8.0–10.0 mm and 35\% of 10.0–11.2 mm aggregates.

#### 2.3.3. Black curve

It is particularly important to define the sieving conditions for determining the black curve (RAP together with binder). This is important because, unlike in the case of the white curve, binder present in RAP causes particles to agglomerate. Depending on the sieving parameters (frequency, amplitude, time) the agglomerates might break apart to a different extent resulting in dissimilar grading curves even if the same material is used. This was evident in a round-robin study performed by RILEM (Tebaldi et al. 2018).

For the present research, dry sieving was performed to determine the black curve with the main sieving machine parameters illustrated in Figure 6. The sieving tower was rotating at 42 RPM around its axis while circling at 180 RPM. The amplitude was 40 mm and at each rotation, the sieve hit five rubber stoppers that made it shake. A sieving tower of 50 cm diameter sieves was used since this larger diameter allowed to sieve more material (around 4 kg per grading curve), thus reducing the potential variability due to sample size reduction. A larger sample size is particularly useful for determining the black curve because RAP is typically less homogeneous and holds larger pieces compared to plain aggregates. Before sieving, the RAP was placed in the oven at 40°C for at least 16 h until completely dry.

### 3. Determining the indexes

Processing of RAP can include crushing with the objective of reducing the maximum size of the materials and sieving with
the objective of providing a certain RAP gradation. Both of these objectives are related to modifying the grading curve of the RAP agglomerations (chunks) or the aggregates within RAP. For this reason, in developing a method for evaluation of RAP processing, we rely on the analysis of grading curves. Moreover, asphalt producers normally have the equipment for determining the grading curves available, thus making the procedure suitable for practical application.

Four different grading curves can be obtained from RAP processing:

1. **Source black curve** – gradation of RAP in the stockpile after milling or ripping the pavement.
2. **Source white curve** – gradation of extracted RAP aggregates in the source stockpile.
3. **Processed black curve** – gradation of RAP after all finalising all processing operations (crushing, fractioning, homogenising, etc.)
4. **Processed white curve** – gradation of extracted RAP aggregates after finalising all processing operations (crushing, fractioning, homogenising, etc.).

As an example, the four grading curves for the material Blend-3-B are illustrated in Figure 7. As a rule, the black curve is always coarser than the respective white curve because the binder holds together pieces of aggregates. Processing of RAP reduces the particle size thus moving both the black and white curves upward. These changes are evident in Figure 7.

We used the four grading curves to develop three indexes that allow quantitative analysis of RAP crushing and screening: **Chunk Index, Breakdown Index, and Filler Increase Index**. These indexes are calculated from the area below the grading curves as summarised in Figure 8. A full explanation for determining the indexes is provided in the following sections.

### 3.1. Chunk index

RAP can be obtained either by milling or by ripping the old pavement into slabs (e.g. using a bulldozer or excavator). In either case, RAP will hold chunks of many individual pieces of aggregates that are held together by a binder as illustrated in Figure 9. A RAP piece can hold only one particle with a thin binder film (Figure 9(b)), or it can consist of a combination of large and small particles (Figure 9(c)) or many small particles (Figure 9(d)). The size of these chunks can vary greatly depending on the method of demolishing the old pavement as well as other external factors. For example, when milling a pavement the size of the chunks depends on the type of the milling machine, the depth of milling, the moving speed of the machine, toughness of the aggregates, the rotation frequency of the drum, the pavement type, its age, and even the environmental conditions (West 2015, Wirtgen 2019, Zaumanis et al. 2021c).

In case a pavement is demolished by ripping, the RAP chunks will typically be larger compared to milled material and the variation in chunk size will be greater.

Large RAP chunks consisting of multiple aggregates are not desirable in the asphalt production process. In the heating process during asphalt production, a RAP chunk similar to
Figure 9(d) will require a longer time before the bitumen viscosity inside of the chunk is reduced enough so that it disintegrates as compared to a chunk similar to Figure 9(c). This means that large chunks might prohibit thorough blending of RAP with virgin binder and aggregates. Poor blending will lead to problems with mix homogeneity, including varying binder film thickness, inhomogeneous aggregate distribution within the mixture, different binder viscosity at different places in the mixture, and possibly a layer of RAP binder that does not blend with other materials ('black rock') (Zaumanis and Mallick 2013, Ding et al. 2016, Sreram et al. 2018, Zaumanis, Cavalli, et al. 2018, Lo Presti et al. 2019).

Ensuring that the chunks are small enough for asphalt production is thus the first objective of RAP processing.

Based on this reasoning, the absolute size of each separate piece, in principle, is irrelevant for ensuring mixture homogeneity. What matters is how many aggregates are held together in one chunk. This can be expressed as the difference between the processed black and processed white curves. Processed black curve reflects gradation including RAP chunks, while processed white RAP curve reflects a situation when the chunks are broken apart. In a theoretical scenario, when each piece of aggregate would be separated during processing, the two curves would overlap. In this case all the RAP bitumen would come in direct contact with the heat source simultaneously because there would be no chunks (all the particles would resemble Figure 9(b)). The only difference between the curves would arise from the binder film thickness (typically around 4–13 μm (Kandhal and Chakraborty 1996, Cavalli et al. 2017)), which, for all practical purposes of evaluating RAP gradation, can be neglected.

**Chunk index** demonstrates the difference between RAP chunks and a theoretical scenario when all the RAP particles are separate. It is calculated as the difference between the area below the processed white and processed black curves. This is expressed in Equation (1). A smaller Chunk index is desirable since it shows that the two curves are closer together, meaning that fewer individual aggregate particles are stuck together in chunks of RAP.

\[
\text{Chunk index} = A_{PW} - A_{PB} \tag{1}
\]

where \( A_{PW} \) is the area below the processed white curve where the sieve size is raised to the 0.45 power and \( A_{PB} \) is the area below the processed black curve where the sieve size is raised to the 0.45 power.

The sieve size is raised to the power of 0.45 in the equation because it reflects the way gradation is often displayed visually. Moreover, such a representation of the grading curve is used in the Superpave design because the maximum density in this graph appears as a straight line from zero to the maximum aggregate size (Roberts et al. 1996).

Other ways of calculating the Chunk index were considered, including calculation of area in normal and log scale, % difference between the curves, and % change of the curves. The presented method provides the most intuitive results for all the different curves.

An example of the processed white and processed black curves for Blend-3-B material are illustrated in Figure 10. In this chart, the nominal sieve sizes that were used in the experiment are displayed on the bottom horizontal axis, while the sieve size raised to 0.45 power is displayed on the top horizontal axis. The difference between the black and white curves is the visual representation of the Chunk index and it is highlighted with shading.

Chunk index can also be calculated for the material in the source stockpile (Equation (2)). This is helpful as it allows to compare the how by how much crushing has reduced the Chunk index compared to the source material.

\[
\text{Source chunk index} = A_{SW} - A_{SB} \tag{2}
\]

where \( A_{SW} \) is the area below the source white curve where the sieve size is raised to the 0.45 power and \( A_{SB} \) is the area below the source black curve where the sieve size is raised to the 0.45 power.

**Figure 9.** RAP chunks often consist of aggregate particles held together by binder.

**Figure 10.** Chunk Index example.
It has to be noted that the Chunk index was calculated only until 63 mm sieve although not all RAP chunks passed this sieve; for sources 2–5 some of the chunks were significantly larger (see Figure 1(b)) because they were ripped instead of milling. In such a situation, it is important to report the maximum sieve size and keep it constant to allow an approximate comparison of the different sources.

3.2. Breakdown index

Reduction of RAP aggregate particle size in most cases is undesirable because it can limit the maximum amount of RAP that can be added to produce new asphalt. Lack of coarser aggregates in RAP is especially pronounced when it is intended for the production of base and binder course mixtures. In these courses, significantly higher RAP content is permitted compared to surface layers almost everywhere in the world.

To avoid the breakdown of aggregates, the RAP chunks should break through mastic as illustrated in Figure 11(a). In reality, however, the processing equipment also breaks aggregate particles as illustrated in Figure 11 b. Breaking of aggregates makes the white curve of the processed RAP finer compared to the white curve of source RAP and generates filler in the process. The amount of particles that are reduced in size will depend on the toughness of the aggregates, bitumen properties, the type of equipment that is used for crushing, and its configuration.

Breakdown index demonstrates how much finer the RAP aggregates have become as a result of RAP processing. It is calculated as the difference between the area below the processed white and source white curves. This is expressed in Equation (3) and demonstrated in Figure 12. A smaller Breakdown index is desirable because it shows that the two curves are closer together, meaning fewer aggregates were broken during processing.

$$\text{Breakdown index} = A_{PW} - A_{SW}$$

where $A_{PW}$ is the area below the processed white curve where the sieve size is raised to the 0.45 power and $A_{SW}$ is the area below the source white curve where the sieve size is raised to the 0.45 power.

In rare cases, the RAP management plan might actually require a reduction of RAP aggregate size. This might be the case when the aggregate size is too large for the desired mixture or when all available RAP is crushed to a single size (e.g. when the available storage area is too small for multiple stockpiles).

Reduction of RAP aggregate size will inevitably lead to the generation of filler and is, therefore, the least preferred processing approach (West 2015). However, if this approach is used, the Breakdown index should be excluded from the evaluation of RAP processing.

3.3. Filler increase index

As a result of milling and processing, it is not unusual for RAP to have filler content (material below 0.063 mm) between 10% and 20% (Zaumanis, Oga, et al. 2018). Such an excessive filler content will not allow fulfilling the volumetric and grading curve requirements of the asphalt mixtures (Copeland 2011, West 2015, Zaumanis, Oga, et al. 2018). Contrary to popular belief, this excessive filler content and not the aged binder is what often sets the limitation for how much RAP can be added to the mixtures. While countermeasures like the use of rejuvenators can be used to compensate for the aged binder (Baghaee Moghaddam and Baaj 2016, Behnood 2019), the only countermeasure for reducing the filler content of RAP is to reduce the amount of the RAP fraction that contains the filler.

The increase of filler content is already a part of the Breakdown index. However, because of its often-primary role in restricting the maximum RAP content, it is important to highlight the increase in filler content by using a separate index.

Filler increase index demonstrates how much filler is generated during RAP processing. It is calculated as the difference between the filler content of the processed white curve and the source white curve. This is expressed in Equation (4) and demonstrated in Figure 13 for the Blend-3-B material. A smaller Filler increase index is desirable because it shows that less filler was generated during processing.

$$\text{Filler increase index} = PW_{min} - SW_{min}$$
where $PW_{\text{min}}$ is the material passing through the smallest sieve for processed white curve, %; $SW_{\text{min}}$ is the material passing through the smallest sieve for source white curve, %.

### 4. Results and discussion

In order to validate the three proposed indexes in practice, we used four different crushers to produce seven different materials as previously shown in Figure 3. An overview of all the grading curve shapes that were used for calculating the Chunk, Breakdown, and Filled Increase indexes (referred to as CBF indexes) is presented in Figure 14. All the individual grading curve results are available as a dataset in a repository (Zaumanis 2021a): https://doi.org/10.5281/zenodo.4446825.

A spreadsheet for calculating the indexes is also provided to the reader in a repository (Zaumanis 2021b): https://doi.org/10.5281/zenodo.5500153.

The results of the seven processed materials serve to validate the indexes in two main ways:

1. Determine if the indexes distinguish between different materials and crushers (in their current configuration).
2. Determine the variability of each index.

Figure 15 summarises the results of the three indexes for all the processed materials. The lightest-colored bars represent a material for which the source was milled RAP (source 1), the mid-tone represents source RAP consisting of a blend of slabs and milled material (sources 2, 3 and 4), and the darkest bar shows the results of RAP originating from slabs (source 5).

By evaluating the differences between the different materials, it is important to consider the variability of each index. The reader is reminded that at least two replicates were tested for each material. The replicate specimens were sampled from different boxes, meaning that the variability is an indication of the repeatability of the test itself, and it also encompasses variability due to sampling. The error bars in Figure 15 demonstrate the range of the test results.

From the three indexes, the Chunk index has the smallest range while Breakdown index and Filler increase index have a relatively larger range. Breakdown and Filler increase indexes are derived from comparing white grading curves before and after processing. Inhomogeneity in source RAP during processing or obtaining of an unrepresentative sample at one of the stages, unlike for the Chunk index, would increase the variability of these two indexes.

Overall, even taking into account the variability of the calculated indexes, distinct differences can be seen between the results depending on which crusher was used. For example, all three indexes of Blend-3-B material are significantly different compared to the other materials. Blend-3-B was produced using a different crusher thus indicating that the indexes can distinguish between different machines and/or setups.

Another clear difference is that the Filler increase index of Milled-1-G and Milled-1-A samples is higher compared to the Blend-2-G and Blend-2-A samples. Since both of these materials were processed with the same crusher (G and A), the only difference between these two pairs is the RAP source. For Milled-1-G and Milled-1-A the source is milled RAP while for Blend-2-G and Blend-2-A it is a blend of slabs and milled RAP. This demonstrates that the indexes also distinguish between different sources of materials.

Finally, by comparing the Chunk index of the source RAP (‘×’ in the chart) and processed RAP (bars) we can observe by how much processing has reduced the chunks. Naturally, Chunk index of the milled RAP is much smaller compared to that of the slab/milled RAP blends and the Chunk index of slabs is the highest. Comparing similar source materials gives a good indication of the chunk reduction potential of the RAP processing equipment.

Furthermore, plotting the Chunk index of the source RAP can allow to decide if crushing is necessary at all. For example, it can be seen that for the Milled-1-A source RAP the Chunk index is is only slightly higher than the processed Chunk index after the crusher B (Blend-3-B). A further comparison of these two grading curve shapes in Figure 14 reveals that the major difference between the curves is the maximum size of the RAP chunks. If such a maximum chunk size is acceptable for ensuring homogeneous blending during asphalt production, a reasonable option might be to use the source RAP in production or only screen the RAP into different fractions while avoiding crushing (and the inevitable generation of filler).

### 4.1. Possible causes of variability

It can be seen in Figure 15 that Breakdown index for Milled-1-G and Blend-2-A processes, as well as Filler increase index for Blend-2-G materials are negative (−5%, −0.5% and −0.3% respectively). From a physical perspective, this is impossible because it would mean that crushing increased the RAP aggregate size and reduced filler content. Even though the negative values are small, it gives an opportunity to analyze the possible causes of variability. The grading curves of these samples are illustrated in Figure 16.

For any given situation of determining the three indexes, five most likely causes for variability can be identified:

1. Variability of the source RAP during sampling;
We kept the sieving parameters constant during the research meaning that cause No. 5 is probably not the main reason for the negative results. The processed fraction mass was estimated during production (cause No. 3) thus a significant error here is also unlikely. We can then deduct that the most likely cause of the negative indexes is the variability of source RAP during sampling (cause No. 1), sampling of unrepresentative material (cause No. 2), or problems with sample size reduction (cause No. 4).

Sampling of representative material (cause No. 2) and subsequent reduction of RAP sample size (cause No. 4) is not trivial when sampling of RAP that contains slabs. This is because of the large RAP chunks that are present in the source stockpile and need to be reduced for laboratory testing.

Variability of source RAP during sampling (cause No. 1) would affect the Breakdown index and Filler increase index because these are calculated by comparing the grading curves before and after processing. In this experiment, for the cases where two crushers (G and A) operated simultaneously, approximately 20 min passed between the start of sampling of RAP from the source stockpile and finishing of sampling from the processed materials. When only one crusher is used, this time is shorter. Keeping the time short is important because an increase in the source RAP aggregate size and reduction of filler content between the sampling could lead to negative indexes.

Taking additional measures to reduce the effect of these three sources of variability would improve the reliability of the calculated indexes. For example, the time interval between samples before and after the crusher would be minimised and crushing of homogeneous material should be ensured. To reduce the variability from sampling and sample size reduction, improved sampling procedures could be developed. We consider the procedure of sampling from the conveyor belt (see Figure 5) to be appropriate.

### 4.2. Reporting and interpreting the indexes

The core principle behind all three indexes is illustrated in Figure 17. In summary, the CBF indexes demonstrate to what extent RAP processing reduces RAP chunks instead of crushing the RAP aggregates. For all three indexes, a lower result is desirable.

The CBF indexes, however, should not be evaluated in isolation. For example, a very gentle process (e.g. only screening of RAP into different fractions) might not generate much fines, thus resulting in small Breakdown and Filler increase indexes. At the same time, such a process will fail to break apart large RAP chunks, resulting in an unacceptable Chunk index.

The opposite scenario is also possible. Crushing the RAP to dust will minimise the Chunk index, but it will also generate a much finer grading curve compared to the original. This will result in large Breakdown and Filler increase indexes and thus likely limit the maximum content of RAP in new asphalt mixtures.

For these reasons, it is important to evaluate the CBF indexes simultaneously. Bar charts do not show this connection intuitively. Instead, we propose to use a radar chart as illustrated in Figure 18. The perception of the results here is more intuitive because a smaller triangle area is an indication of a more favourable process. Plotting of the three indexes can thus enable to easily compare different RAP management cases and as a result – optimise processing of RAP.

Since the indexes are in different ranges, scaling of the chart’s axes is necessary for a meaningful graphical representation. Based on the range of observed results, the axes are scaled in proportion 1: 2: 20 for Chunk index: Breakdown index: Filler increase index respectively. It might be necessary to change the scaling factors for other material/crusher combinations.

As an example, the results from three of the seven processed materials are plotted in Figure 18. A comparison of the CBF index radar charts allows concluding that the crusher A
performs significantly better than the crusher B for all three indexes.

Further analysis of the two materials produced by crusher A demonstrates that for the milled material (Milled-1-A) the crusher generates more filler compared to the material containing slabs (Blend-2-A) while at the same time the Chunk index is reduced only slightly. Based on this information, the operator of crusher A might decide to change the crusher configuration to allow larger chunks in the processed Milled-1-A material with the aim of reducing the Filler increase index.

Exactly how to balance the requirements for each of the CBF indexes will depend on the particular situation.
Ultimately, ensuring the best performance of the mixture for which the processed RAP is used should be the goal. Consider these two examples:

- If maximum RAP content in asphalt mixture is limited by the filler content, attention should be placed toward optimisation of the process to reduce the Filler index.
- If RAP in the mixture is added cold, filler content will not be a major concern since only a small RAP content can be added anyway. Instead, the focus should be on ensuring good blending of the materials. In cold RAP addition, the limited heat transfer from virgin aggregates might not be sufficient to break apart large chunks of RAP, thus attention should be placed toward minimising the Chunk index.

There can be many more scenarios but the two examples demonstrate that the weight of the different indexes should be established for the particular situation. We encourage further research to provide guidelines on how to establish these weights.

5. Conclusions

Increased use of Reclaimed Asphalt Pavement (RAP) in asphalt production governs a necessity to actively seek the best management practices for preparing RAP. We developed three indexes that allow evaluating key parameters of RAP processing:

- **Chunk index** demonstrates the size of RAP agglomerations.
- **Breakdown index** demonstrates the reduction of RAP aggregate particle size during processing.
- **Filler increase index** reflects the amount of generated filler content during RAP processing.

These three indexes, collectively named the CBF indexes, can be calculated by determining the black RAP curve (together with binder) and white RAP curve (without binder) before and after RAP processing operations. This is a practical approach because almost any road laboratory possesses the equipment to perform these tests. A calculator for the CBF indexes is provided in a repository (Zaumanis 2021b): https://doi.org/10.5281/zenodo.5500153.

In order to validate the CBF indexes, we performed a case study using four different crushers: GIPO, Ammann, Benninghoven and SBM. These machines crushed five different sources of RAP to produce a total of seven different materials. The results allow concluding the following:

1. The CBF indexes should be viewed as a set (as opposed to each index individually). Therefore, we propose using a CBF index radar chart for displaying the results and comparing different processes.
2. The CBF indexes allow distinguishing between different processes and different materials using quantitative indicators. No inter-relationship between the indexes was observed indicating they each demonstrate a different property.
3. The variability of the results was small for the Chunk index and relatively larger for the Breakdown and Filler increase indexes.
4. We identified five potential causes of variability in the CBF indexes. In this experiment, the most likely cause of variability was the change of source RAP properties during sampling and the difficulties of obtaining a representative sample of RAP because of the large chunks.

RAP processing equipment is usually selected based on parameters, like cost, energy efficiency, maintenance, wear, and mobility. The CBF indexes can add another quantifiable parameter – performance – to the list. Once a RAP processing unit is in operation, the CBF indexes can help in optimising its configuration to enable maximising of RAP use in asphalt production.

![Figure 17. Principle of Chunk Index, Breakdown Index, and Filler Increase Index.](image1)

![Figure 18. Plotting of the three indexes in a radar chart allows comparing different RAP processing setups (examples from Milled-1-A, Blend-2-A; Blend-3-B). Radar charts of all other processes are provided in the appendix.](image2)
Further research is encouraged to determine the relative weights of the three indexes for different combinations of asphalt plant types and RAP materials. The validity of the CBF indexes for evaluating milling of asphalt pavement should also be determined. We have initiated such research and will report the results in subsequent publications.

Acknowledgments

This paper is part of a project titled ‘HighRAP’ which is funded by the Swiss Federal Roads Office (FEDRO), Swiss Federal Office for the Environment (FOEN), Office of Waste, Water, Energy and Air (AWEL) of Canton Zürich, Office for the Nature and Environment (ANU) of Canton Graubünden and industry partners, including Ammann AG, BHZ AG, Reproad AG, EWP AG, and Catram AG. The authors greatly appreciate the contribution of these entities and the valuable input of their representatives. The views and opinions presented in this paper are those of the authors and do not necessarily reflect the opinions of the sponsoring agencies.

Disclosure statement

Lukas Boesiger is employed by Ammann Schweiz AG. A crusher produced by Ammann Schweiz AG was one of the four crushers used in the experiment. Lukas Boesiger did not participate in testing or data processing for any of the crushers.

The other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

This work was supported by Swiss Federal Roads Office (FEDRO) [grant number ASTRA2019/001]; Swiss Federal Office for the Environment (FOEN) [grant number: UTF 594.06.19]; Office for the Nature and Environment (ANU) of Canton Graubünden; Office of Waste, Water, Energy and Air (AWEL) of Canton Zürich; Ammann Schweiz AG; BHZ Baustoff Verwaltungs AG; REPROAD AG; EWP AG; and Catram AG.

Data availability

The data gathered in this research is available at: Zaumanis (2021a). A calculator for determining the three indexes is available at: Zaumanis (2021b).

ORCID

Martins Zaumanis http://orcid.org/0000-0003-4768-7500
Lily Poulikakos http://orcid.org/0000-0002-7011-0542

References

Bagheae Moghadam, T., and Baaq, H., 2016. The use of rejuvenating agents in production of recycled hot mix asphalt: a systematic review. Construction and Building Materials, 114, 805–816.
Behnood, A., 2019. Application of rejuvenators to improve the rheological and mechanical properties of asphalt binders and mixtures: a review. Journal of Cleaner Production, 231, 171–182.
Blanc, J., et al., 2019. Full-scale validation of bio-recycled asphalt mixtures for road pavements. Journal of Cleaner Production, 227, 1068–1078.
Cavalli, M.C., Partl, M.N., and Poulikakos, I.D., 2017. Measuring the binder film residues on black rock in mixtures with high amounts of reclaimed asphalt. Journal of Cleaner Production, 149, 665–672.
Copeland, A., 2011. Reclaimed asphalt pavement in asphalt mixtures: state of the practice. McLean, VA: Federal Highway Administration.
De Lira, R.R., Cortes, D.D., and Pasten, C., 2015. Reclaimed asphalt binder aging and its implications in the management of RAP stockpiles. Construction and Building Materials, 101, 611–616.
Ding, Y., Huang, B., and Shu, X., 2016. Characterizing blending efficiency of plant produced asphalt paving mixtures containing high RAP. Construction and Building Materials, 126, 172–178.
Ding, Y., Huang, B., and Shu, X., 2018. Recycling efficiency evaluation of asphalt plant. In: Advances in Materials and Pavement Performance Prediction - Proceedings of the International AM3P Conference, 2018. Doha: CRC Press/Balkema, 243–246.
EAPA, 2020. Asphalt in figures 2019. Brussels: European Asphalt Pavement Association.
European Commission, 2019. Report from the Commission to the European parliament, the council, the European Economic and Social Committee and the Committee of the Regions on the implementation of the circular economy action plan. Brussels.
Free, F., et al., 2018. Innovations in asphalt mixture design procedures. Transportation research circular E-C237. Washington, DC: Transportation Research Board (TRB).
Huurman, M., et al., 2016. Low Emission2 Asphalt Pavement, LE2AP. In: 6th Eurosphalt & Eurobitume Congress. Prague: Eurosphalt & Eurobitume.
Kandhal, P.S., and Chakraborty, S., 1996. Effect of asphalt film thickness on short- and long-term aging of asphalt paving mixtures. Transportation Research Record: Journal of the Transportation Research Board, 1535 (1), 83–90.
Koudelka, T., et al., 2019. Rheological evaluation of asphalt blends at multiple rejuvenation and aging cycles. Road Materials and Pavement Design, 20 (sup1), S3–S18.
Liu, S., Shukla, A., and Nandra, T., 2017. Technological, environmental and economic aspects of asphalt recycling for road construction. Renewable and Sustainable Energy Reviews, 75, 879–893.
Lo Presti, D., et al., 2019. On the degree of binder activity of reclaimed asphalt and degree of blending with recycling agents. Road Materials and Pavement Design, 21, 1–20.
NAPA, 1996. Recycling hot mix asphalt pavements. Lanham, MD: National Pavement Association.
Roberts, F.L., et al., 1996. Hot mix asphalt materials, mixture design and construction. NAPA Education Foundation Second Edition. Lanham, MD: National Asphalt Pavement Association.
Schut, E., Crielaard, M., and Mesman, M., 2015. Circular economy in the Dutch construction sector: a perspective for the market and government status final. Utrecht: Rijkswaterstaat.
Sreeram, A., et al., 2018. Evaluation of RAP binder mobilisation and blending efficiency in bituminous mixtures: an approach using ATR-FTIR and artificial aggregate. Construction and Building Materials, 179, 245–253.
Tebaldi, G., et al., 2018. Cold recycling of reclaimed asphalt pavements. In: M. Partl, et al., eds. Testing and characterization of sustainable innovative bituminous materials and systems, RILEM State-of-the-Art Reports. vol. 24. Cham, Switzerland: Springer Nature, 239–297.
West, R., et al., 2011. Use of data from specific pavement studies experiment 5 in the long-term pavement performance program to compare virgin and recycled asphalt pavements. Transportation Research Record: Journal of the Transportation Research Board, 2208, 82–89.
West, R.C., 2015. Best practices for RAP and RAS management. Lanham, MD: National Asphalt Pavement Association (NAPA).
Williams, B.A., Willis, J.R., and Shacat, J., 2020. Asphalt pavement industry Survey on recycled materials and warm-mix asphalt usage 2019 (information series 138) 10th annual survey. Greenbelt, MD: National Asphalt Pavement Association (NAPA).
Wirtgen, 2019. Wirtgen cold milling manual: technology and application. Windhagen: Wirtgen GmbH.
Zaumanis, M., et al., 2019a. Determining optimum rejuvenator addition location in asphalt production plant. Construction and Building Materials, 198, 368–378.
Zaumanis, M., et al., 2019b. Performance-based design of 100% recycled hot-mix asphalt and validation using traffic load simulator. Journal of Cleaner Production, 237, 117679.
Zaumanis, M., 2021a. Dataset for the paper “Three indexes to characterize processing of reclaimed asphalt pavement.” Zenodo, https://doi.org/10.5281/zenodo.4446825.

Zaumanis, M., 2021b. Chunk, Breakdown and Filler Increase calculator from paper “Three indexes to characterize crushing and screening of reclaimed asphalt pavement.” Zenodo. https://doi.org/10.5281/zenodo.5500153.

Zaumanis, M., et al., 2021c. Impact of milling machine parameters on the properties of reclaimed asphalt pavement. Construction and Building Materials, 307, 125114. https://doi.org/10.1016/j.conbuildmat.2021.125114.

Zaumanis, M., Cavalli, M.C., and Poulikakos, L.D., 2018. Effect of rejuvenator addition location in plant on mechanical and chemical properties of RAP binder. International Journal of Pavement Engineering, 21, 507–515.

Zaumanis, M., and Mallick, R.B., 2013. Finite element modeling of rejuvenator diffusion in RAP binder film – simulation of plant mixing process. Multi-Scale Modeling and Characterization of Infrastructure Materials, 8, 407–419.

Zaumanis, M., Oga, J., and Haritonovs, V, 2018. How to reduce reclaimed asphalt variability: a full-scale study. Construction and Building Materials, 188, 546–554.

Zhang, R., et al., 2019. The impact of bio-oil as rejuvenator for aged asphalt binder. Construction and Building Materials, 196, 134–143.
Appendix

CBI index radar charts of all tested materials.