# Permeability Potential of Asphalt Mixes via Binary Aggregate Packing Principles Applied to Bailey Method Ratios and Porosity Principles

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**Synopsis**

A brief overview is given regarding the application of the Bailey Method aggregate fraction ratios to determine factors of a grading envelope that control strength characteristics, which contributes to shift the focus to permeability control of asphalt mixes. The Dominant Aggregate Size Range (DASR) approach is examined in parallel, which enables the determination of porosity of contiguous aggregate fraction ranges. The Bailey Method Ratio (BMR) is converted (rational) by using only contiguous fractions in these ratios to determine porosity. A whole range of rational BMRs are described and calculated. This builds on previous published work describing various aggregate fractions, BMRs and DASR porosities which are known to have an indirect control on permeability. It is described how Binary Aggregate Packing (BAP) analysis, with the aid of a BAP 'triangle' diagram, enables the description of the 'Wall effect' and the 'Loosening effect' phenomena which influence and correlate with the potential for interconnectedness of voids or porosity. The inverse of the rational BMRs are the same as BAP ratios in determining the mass ratio of the coarse/fine aggregate fraction. Benchmark criteria of these coarse/fine mass ratios were defined for potential for void interconnectedness. Reworked published data sets were used to show how such permeability can be determined for particularly the finer portion of the aggregate grading by determining the BAP ratios and associated porosity. A data set of asphalt with published permeability problems at longitudinal joints on an airport apron due to density problems were reworked. The revised rational BMR of the micro- or fines portion of the grading skeleton were calculated and showed that the interconnectedness of the asphalt voids is, in fact, low if compacted to the correct density. This corresponded with the original Quality Acceptance (QA) and Quality Control (QC) data of the inner portion of the asphalt mat. It could be demonstrated, using the BAP and revised (inverse) rational BMRs of the micro portion of the aggregate skeleton, that low potential for permeability of this asphalt is confirmed and verified. In this case, permeability was due to lack of compaction to specification at these longitudinal joints.

## 1. Introduction

The Bailey method (Vavrik, et al., 2001) is well-established in the USA as a logical approach to aggregate packing analysis in support of asphalt mix design procedures. The Bailey method is now included in Guideline 35 (SABITA, June 2016) as a valuable method to assist in designing asphalt mixes which relies on the aggregate skeleton as main load bearing mechanism in a paved asphalt layer. Structural strength, particularly resistance to rut and resistance to cracking, receive a lot of attention in asphalt mix design methods with associated test methods that measure these aspects objectively. Durability is also recognised as an important aspect of asphalt mixes but is more difficult to measure reliably and objectively. Permeability is known to correlate well with durability of asphalt mixes, but various practical issues make either field- or laboratory measurements both cumbersome and less likely to be measured in the field with typical quality control tests during the construction control stage.

The Bailey method terminology and Bailey Method Ratios are used throughout for consistency and to provide reference to a known international concept. The definition of various Bailey control sieves and original ratios are defined as follows;

- Maximum Nominal Particles Size (NMPS) as per the Superpave definition "One size larger than the first sieve that retains more than 10 % aggregate". This was changed lately to 15 %. (SABITA, 2016)
- Half Size (HS) is defined as the sieve size closest to or equal to half of the NMPS
- Primary Control Sieve (PCS) is the sieve size closest to 0.22 X NMPS
- Secondary Control Sieve (SCS) is the sieve size closest to 0.22 x PCS
- Tertiary Control Sieve (TCS) is the sieve size closest to 0.22 X SCS
- Additional range descriptors and terminology often use in literature are:
  - Interceptors: The size range between HS and PCS
  - Pluggers: In the original Bailey method description (Vavrik, 2001) they are defined as all aggregate fractions larger than half size. However, "Pluggers" can be divided into:
    - Active or normal pluggers (Pluggers N or P(N)): The size range between HS and NMPS. (Horak et al (2017 (a &b)) referred to this as Pluggers
    - Oversize pluggers larger than NMPS (Pluggers O or P(O)): The oversized aggregate size range larger than NMPS. Horak et al (2017 (a & b)) referred to this as Oversize.
- Three original Bailey Method Ratio (BMR) calculations were defined as the ratio between various aggregate fractions. These BMRs are used for gauging strength contribution in the aggregate skeleton. They were originally defined as:
  - Coarse Aggregate ratio-CA= $\frac{(\%\ \mathrm{HS}-\%\mathrm{PCS})}{(\%\ 100-\%\mathrm{HS})} = \frac{\%\ \mathrm{Pluggers}}{\%\ \mathrm{All\ interceptors}\ \&\ oversized}$ Equation 1
  - Fine aggregate coarse ratio-$FA_c = \frac{\%\mathrm{SCS}}{\%\mathrm{PCS}}$ Equation 2
  - Fine aggregate fine ratio - $FA_f = \frac{\%\mathrm{TCS}}{\%\mathrm{SCS}}$. Equation 3

Porosity has a more direct relationship with permeability in that permeability is facilitated by the interconnectedness of voids in the asphalt mix. Dominant Aggregate Size Ratio (DASR) concept has the same basis principle as the Bailey method in the size ratios that determine the densest possible aggregate packing. However, the DASR method relies on porosity determination (Horak, et al., 2017a & Horak, et al., 2017b) of a range of contiguous aggregate fractions that provide the lowest porosity. Low porosity, below typically 0.5 to 0.4, implies high density of aggregate packing and increased aggregate skeleton strength due to interlock. Higher than 0.5 porosity values in turn implies less dense mixes and or lower structural strength potential.

Denneman et al (2007) showed how it is possible to simplify the DASR porosity calculation when limited to two aggregate fractions that are contiguous (following each other). This allowed investigation of the application of BMRs and calculated porosity of single consecutive aggregate fractions and DASR contiguous aggregate fractions and therefore enable correlation with permeability or inferred permeability. In Table 1 the DASR porosity Equation 4 is defined and the simplified calculation to determine a single fraction, or contiguous range of aggregate fractions, is defined as Equation 5.

*Table 1: DASR and Contiguous Aggregate Fraction Porosity Equations*

| **Equation 4** *(Kim, et al., 2006)* | **Equation 5** *(Denneman, et al., 2007)* |
|---|---|
| $\eta_{DASR} = \frac{V_{V(DASR)}}{V_{T(DASR)}} = \frac{V_{ICAGG} + \text{VMA}}{V_{TM} - V_{AGG} > DASR}$ | $\eta_{(4.75-2.36)} = \frac{\left[\left(\frac{\text{PP}_{2.36}}{100}\right)(V_{TM} - \text{VMA}) + VMA\right]}{\left[\left(\frac{\text{PP}_{4.75}}{100}\right)(V_{TM} - \text{VMA}) + VMA\right]}$ |
| Where: | Where: |
| $\eta_{DASR}$ = $\text{DASR}_{porosity}$<br>$V_{\text{Interstitial volume}}$ = Volume of IC aggregates plus VMA, thus inclusive of bitumen binder volume;<br>$V_{AGG>DASR}$ = Volume of particles bigger than DASR;<br>$V_{TM}$ = Total volume of mix;<br>$V_{T(DASR)}$ = Total volume available for DASR particles;<br>$V_{V(DASR)}$ = Volume of voids within DASR;<br>$V_{ICAGG}$ = Volume of IC aggregates;<br>VMA = Voids in mineral aggregate;<br>$V_{ICAGG}$ = Volume of IC aggregates. | $\eta_{(4.75\text{-}2.36)}$ = Porosity of a typical fraction passing 4.75 mm sieve and retained on 2.36 mm sieve<br>$PP_{2.36}$ = Percentage particles passing 2.36 mm sieve<br>$PP_{4.75}$ = Percentage particles passing 4.75 mm sieve<br>VMA = Voids in mineral aggregate<br>$V_{TM}$ = Total volume of mix |

Khosla and Sadasivam (2006) and Denneman et al (2007) developed criteria for reducing permeability of aggregate mixes. The parameters identified by Denneman et al (2007) and Khosla and Sadasivam (2006) that aids in the control of permeability were improved with the calculation of porosity and by reworking their published data sets (Horak, et al., 2017a). This direct link to porosity was still not sufficient to allow a rigorous or accurate measurement or analysis of permeability potential of an asphalt mix. It did however, confirm the notion that permeability is controlled by the voids of the large aggregate skeleton, therefore, the finer midi-level and micro-level of aggregates in the total aggregate grading envelope which fills those voids. In the process it was also observed that the current BMRs, $FA_c$ (Eq 2) and $FA_f$ (Eq 3) are not composed of contiguous aggregate fraction ranges which makes the calculation of porosity of such ratios impossible. This recognition of their overlapping aggregate ranges in the ratio helped explain why they have not been identified by Khosla and Sadasivam (2006) or by Denneman et al (2007) as good indicators of permeability.

Other researchers also could only correlate the CA ratio (Eq 1) (contiguous aggregate fractions) with permeability with other grading fractions or factors (Horak, et al., 2017a) confirming the value of contiguous aggregate fractions and their link to porosity. In Table 2 the left-hand column shows the whole new and expanded set of rational Bailey Method Ratios (BMRs) where contiguous aggregate fractions were used throughout describing the macro-, midi- and micro fraction ranges of the total aggregate skeleton and grading. Some of these midi level new BMRs were originally also defined by Al

Mosawe et al (2015), stating that it is not just the CA ratio that define structural strength, but BMRs in the midi-range that act as the crux of the structural strength of an asphalt mix.

The next step towards a better description of permeability of asphalt mixes was facilitated by the concept of Binary Aggregate Packing (BAP) as promoted by Olard (2015). Insight to apply the BAP concept is facilitated by the nesting concept of skeleton sub-sets described and illustrated in Figure 1 (Horak, et al., 2017b). This illustration allows for the recognition of BAP concepts as they can then be reduced to contiguous binary aggregate fractions as well in effect by zooming into the voids at each level defined as macro, midi and micro-level aggregate packing or infill.

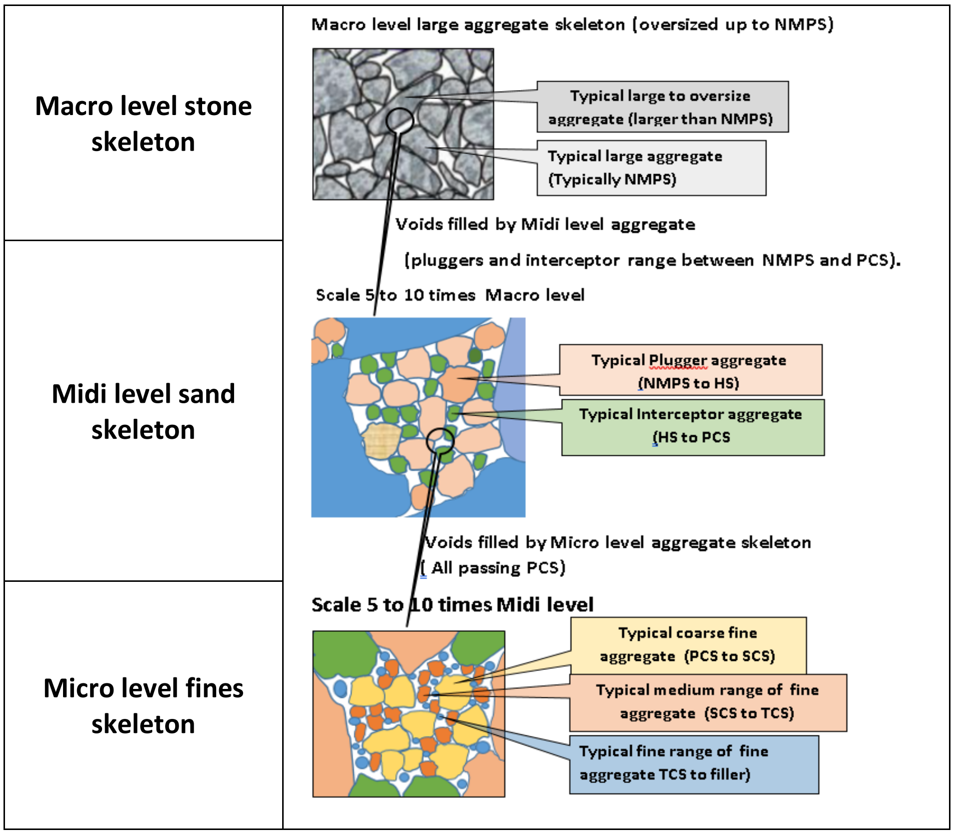


*Figure 1. Illustration of Various Skeleton Infill Structures of Overall Aggregate Matrix.*

## 2. Linking Binary Aggregate Packing Principles with Bailey Method Ratios

The principles of the Bailey aggregate packing are the same as for Binary Aggregate Packing (BAP). A size ratio ranging between 0.2 and 0.29 or less ensures the voids between the large aggregate can be filled by the finer aggregate fraction. The Bailey method uses the fine/large aggregate size ratio of 0.22 as main criteria are shown in the definitions of PCS, SCS and TCS described before. BAP and DASR both make use of porosity determination of contiguous aggregate ratios. The link between Bailey method with the typical aggregate grading envelope and associated description of parameters was the main reason why the Bailey principles was therefore used as reference in the development of BMRs linked to porosity and potentially permeability. Binary aggregate packing 'triangle' diagrams ( (Olard, 2011) and (Butcher & van Loon, 2013)) combine the Bailey concept of size ratio (e.g. diameter of fine/coarse) of a BAP ratio. The basic BAP 'triangle diagram' is illustrated in Figure 2 and is based on the original work by Furnas (1928). The concepts of voids, porosity and specific voids are inter-related and are assumed to entail the same concept of an index of voids between solids prior to filling with binder and in general is referred to as porosity, are shown on the vertical scales in the 'triangle diagram' (Butcher & van Loon, 2013).

Olard (2015) demonstrated that these size ratios (fine/coarse) form a family of curves (concave functions) with variable combined porosities lower than the porosity of either fraction separately (vertical scales of fine (left) and coarse (right) porosities). The porosities of the combined binary fractions also vary in terms of the proportion of the volumetric ratio of coarse/fine (X-axis in Figure 2) along these concave form functions.

In Figure 2 the optimum or lowest point of porosity achievable, the dilation point, is found as the lowest size ratio (fine/coarse) and specific proportion of the coarse to fine aggregate ratio in the binary aggregate fraction combination or mix of the two fractions with the lowest possible porosity, therefore highest density or highest potential structural strength. The resulting changes in the combined void index (porosity or specific voids) of the coarse and fine aggregates are dependent on size ratio (fine/coarse).

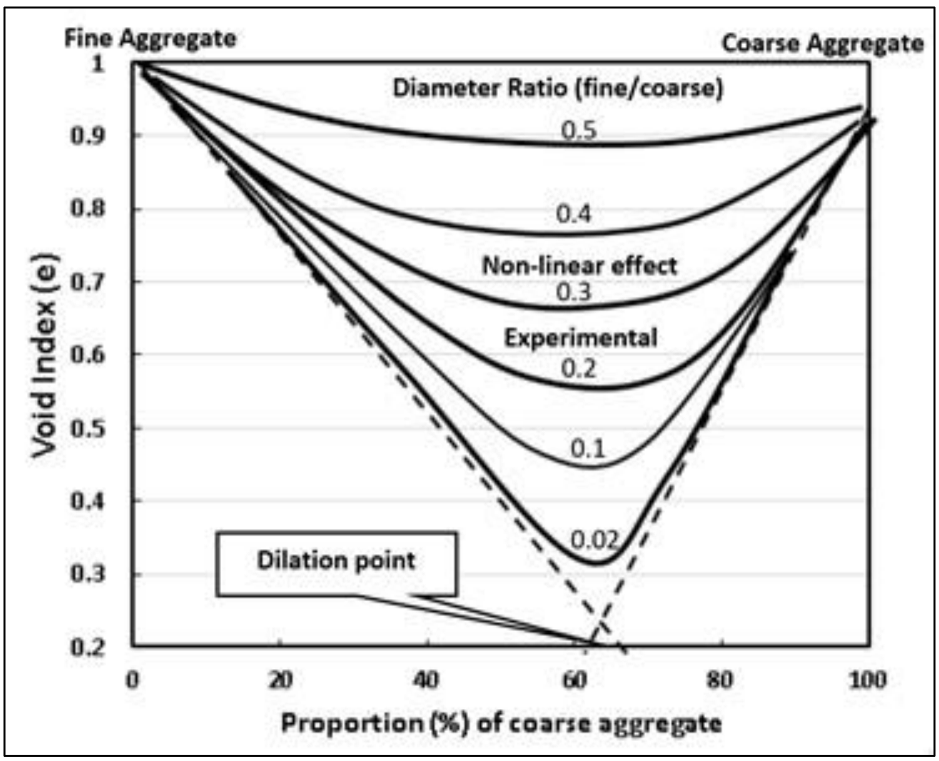


*Figure 2: Typical Binary Aggregate Combination Porosity Influence with Varying Diameter Ratios and Proportion of Coarse Aggregate (Olard, 2011 based on Furnas, 1928)*

Under ideal conditions the two dotted lines in Figure 2 are the outer boundaries of the possible physical zone of potential porosity achievement between the fine and coarse aggregate in the binary aggregate combination. Olard (2015) further simplified Figure 2 by indicating in Figure 3 how the combination of any diameter ratio binary aggregate combination tends to resist porosity reduction due to two physical phenomena. Their areas of influence are indicated in Figure 3.

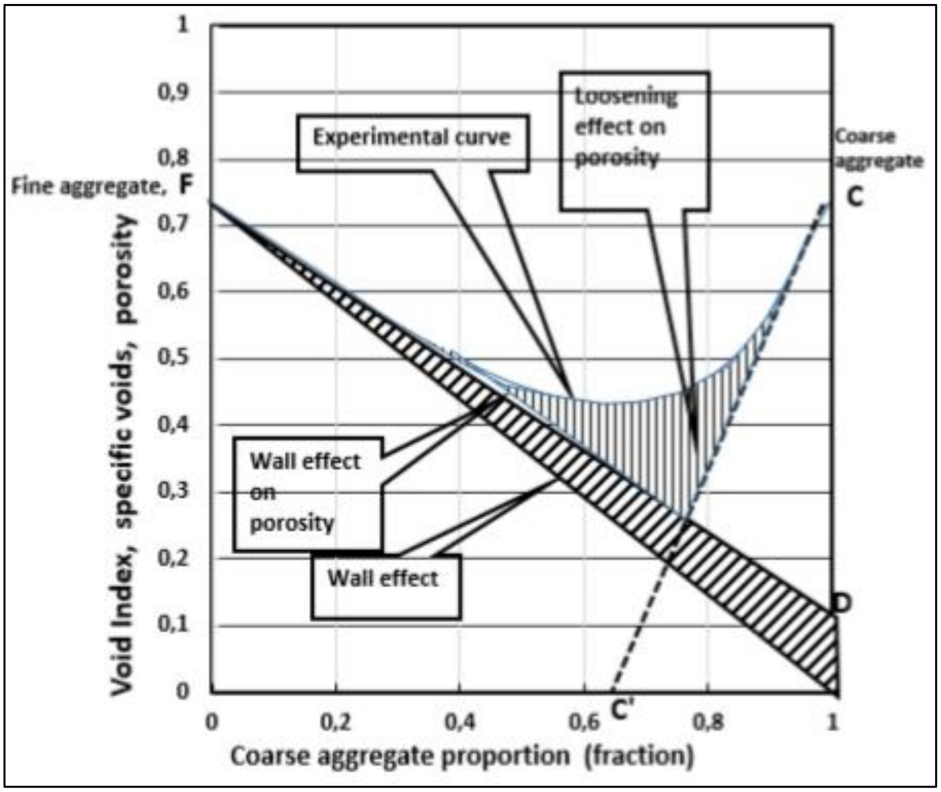


*Figure 3: The Furnas Principles Applied to a Binary Combination of Coarse and Fine Aggregates (Olard, 2015)*

These two porosity phenomena tend to increase porosity via the interplay of size and volume ratios. The phenomena are: The wall effect, caused by voids unfilled against the surface of the large aggregate in the aggregate combination and the loosening or disruption effect due to larger aggregates being pushed aside by an overfill of fine aggregate in the aggregate mass ratio combination. Both concepts are illustrated in Figure 4 (Knop & Peled, 2016) for a realistic aggregate mix situation at typically midi level aggregate skeleton subset. An important recognition is that the wall effect implies voids created along the same plane (surface of the large aggregate), which will also imply higher potential to be interconnected as part of the general percentage of porosity, purely due to their closer proximity along the surface of the larger aggregate. If the wall effect is at its height of effect, it tends to be strengthened by the loosening effect producing additional voids as part of the general porosity, or void distribution, in the aggregate matrix that increases the potential to be interconnected.

The BAP 'triangle diagram' can be simplified in terms of porosity and the coarse aggregate proportion of the combined BAP fraction ratio as shown in Figure 5 (Horak, et al., 2018). This is further enhanced by application of the experimental work on binary aggregate combinations for filter beds done by Mota et al. (2013). The result is shown on the right hand relative vertical scale of Figure 5 expressed in terms of A a relative scale of interconnectedness of the voids. On this relative scale the interconnectedness of voids (therefore, permeability potential) is described based on the variance in coarse aggregate ratio in the BAP. The benchmark ranges of the coarse aggregate percentage (horizontal scale) where first the wall effect alone and then the addition of the loosening effect is combined. This helps to facilitate the evaluation of BAP ratios in terms of porosity or relative increase in interconnectedness and therefore indirectly permeability potential.

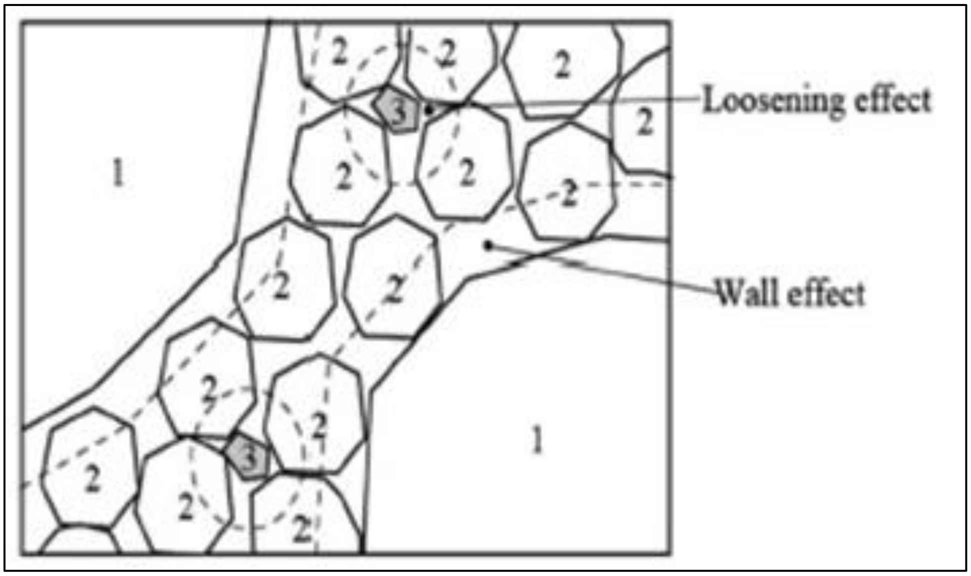


*Figure 4: Schematic Illustration of Porosity Influence Due to the Wall and the Loosening Effect (Knop & Peled, 2016)*

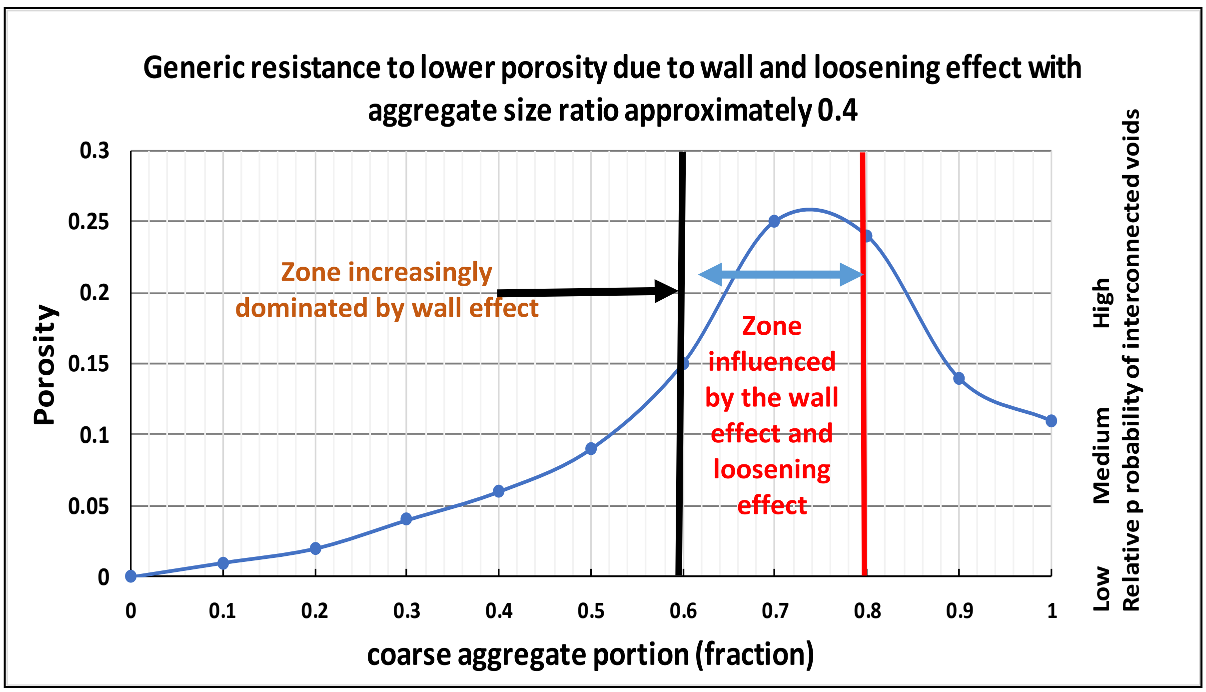


*Figure 5: Resistance to Porosity Decrease Linked to the Effect of Coarse Aggregate Fraction in the Binary Mass Ratio and Associated Probability Effect on Interconnected Voids for a Typical Size Ratio*

Several researchers state that *when the specific gravity of the material is the same for all the aggregate fractions, the volumetric ratio or proportion of coarse and fine aggregates can be taken as equivalent to the proportion of percentages retained on the coarse and the fine aggregate sieves* as the basis of this simplified calculation (Butcher & van Loon, 2013). Therefore, it should be possible to benchmark the various binary aggregate combinations making up the macro-, midi- and micro levels to monitor where adjustments can be made to aggregate gradings to achieve packing efficiency as well as provide permeability control in a rational fashion. In Figure 6 the correlation between the percentage of coarse in the contiguous aggregate fractions are converted to the coarse/fine ratio (mass based) and the 60% and 80% coarse fraction described in Figure 5 are converted to ratio values to indicate wall and loosening effects as the ratio changes.

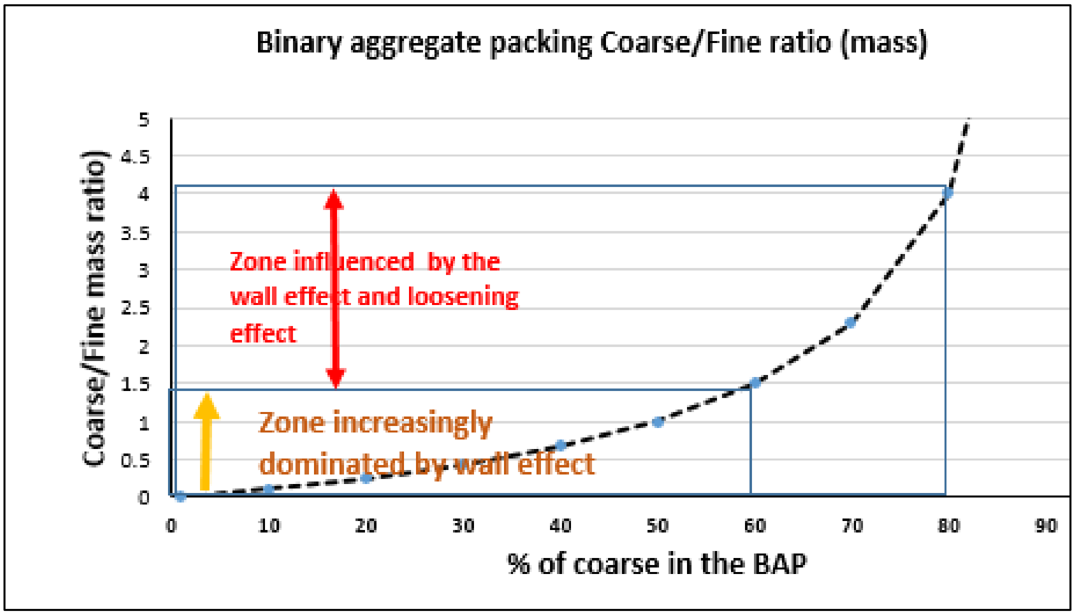


*Figure 6: Coarse aggregate percentage versus the coarse/fine mass ratio of the BAP*

## 3. Applying DASR and BAP Principles to Bailey Ratios

The rational BMRs (as well as the original Bailey ratios as originally defined (Vavrik, et al., 2001)) use the % passing of fine/coarse as a mass ratio. The inverse of this ratio of volume or mass of coarse/fine ratio is needed as defined and used in Figure 2, Figure 3, Figure 5, and Figure 6 on their respective X-axes when using binary aggregate packing (BAP) concepts. As described before, the revised BMRs in the left-hand column of Table 2 is defined in terms of contiguous aggregate fractions. These original CA ratios are the only remaining original BMR as it has contiguous fractions. The rest of the fraction ratios cover the grading envelope from the macro to the midi to the micro level in analogy to the visualization in Figure 1. Porosity can therefore be determined for all these rational BMRs. In order to convert the rational BMRs to the BAP convention of coarse/fine mass ratio to the **revised** rational BMRs, the inverse of the left column rational BMRs is calculated. The difference between the two sets of BMRs are indicated with the subscript ($_r$) and in other cases the abbreviation itself is self-explanatory; P(O)/I instead of the previously described I/P(O) etc. The righthand side **revised** rational BMRs can therefore be used as BAP ratios to link it with porosity calculated and using Figure 3, Figure 5, and Figure 6 can give a relative indication of the possibility of voids being interlinked or indication of permeability.

*Table 2: Rational and revised Bailey ratios with good correlation with DASR porosity parameters*

| Matrix Level | Rational Contiguous Bailey Ratios | Proposed Revised Rational Bailey Ratios in Line with Binary Aggregate Fraction Packing Principles |
|---|---|---|
| Macro | $\frac{PN}{PO} = \frac{(\%\text{NMPS} - \%\text{HS})}{(\%100 - \%\text{NMPS})}$<br>$= \frac{\%\text{Pluggers(PN)}}{\%\text{Oversize or Pluggers (PO)}}$ | $\frac{PO}{PN} = \frac{(\%100 - \%\text{NMPS})}{(\%\text{NMPS} - \%\text{HS})}$<br>$= \frac{\%\text{Oversize of Pluggers (PO)}}{\%\text{Pluggers (PN)}}$<br>$= \frac{\%\text{Retained on NMPS}}{\%\text{Retained on HS}}$ |
| | $\text{CA} = \frac{(\%\ \text{HS} - \%\text{PCS})}{(\%\ 100 - \%\text{HS})}$<br>$= \frac{\%\ \text{Interceptors}}{\%\ \text{All pluggers}}$ | $CA_r = \frac{1}{CA}$<br>$= \frac{(\%\ 100 - \%\text{HS})}{(\%\text{HS} - \%\text{PCS})}$<br>$= \frac{\%\ \text{All Pluggers (P(N)plus P(O))}}{\%\ \text{Interceptors}}$<br>$= \frac{\%\ \text{retained on NMPS and HS}}{\%\ \text{retained on PCS}}$ |
| Midi | $\frac{C_f}{F_c} = -\frac{(\%PCS - \%SCS)}{(\%HS - \%PCS)}$<br>$= \frac{\%\text{Coarse portion of fines}}{\%\text{Interceptors}}$ | $\frac{F_c}{C_f} = -\frac{(\%HS - \%PCS)}{(\%PCS - \%SCS)}$<br>$= \frac{\%\text{Interceptors}}{\%\ \text{Coarse portion of fines}}$<br>$= \frac{\%\text{Retained on PCS}}{\%\text{Retained on SCS}}$ |
| | $\frac{F}{C} = \frac{(\%\text{PCS})}{(\%\text{NMPS} - \ \%\text{PCS})}$<br>$= \frac{\%\text{Fines}}{\%(\text{Plugger (N)} + \text{Interceptors})}$ | $\frac{C}{F} = \frac{(\%\text{NMPS} - \ \%\text{PCS})}{\%\text{PCS})}$<br>$= \frac{\%(\text{Plugger (N)} + \text{Interceptors})}{\%\text{Fines}}$<br>$= \frac{\%\text{Retained on PCS}}{\%\text{PCS}}$ |
| | $\frac{\text{I}}{\text{P(N)}} = \frac{(\%\text{HS} - \ \%\text{PCS})}{(\%\text{NMPS} - \%\text{HS})}$<br>$= \frac{\%\text{Interceptors}}{\%\text{Pluggers (N)}}$ | $\frac{\text{P(N)}}{\text{I}} = \frac{(\%\text{NMPS} - \%\text{HS})}{(\%\text{HS} - \ \%\text{PCS})}$<br>$= \frac{\%\text{Pluggers}}{\%\text{Interceptors (N)}}$<br>$= \frac{\%\text{Retained on HS}}{\%\text{Retained on PCS}}$ |

| Matrix Level | Rational Contiguous Bailey Ratios | Proposed Revised Rational Bailey Ratios in Line with Binary Aggregate Fraction Packing Principles |
|---|---|---|
| Micro | $\boldsymbol{FA_{cm}} = \frac{(\%\mathbf{SCS} - \%\mathbf{TCS})}{(\%\mathbf{PCS} - \%\mathbf{SCS})}$ $= \frac{\%\mathbf{Medium\ fine\ of\ fines}}{\%\mathbf{Coarse\ of\ fines}}$ | $\boldsymbol{FA_{rcm}} = \frac{(\%\mathbf{PCS} - \%\mathbf{SCS})}{(\%\mathbf{SCS} - \%\mathbf{TCS})}$ $= \frac{\%\mathbf{Coarse\ of\ fines}}{\%\mathbf{Medium\ fine\ of\ fines}}$ $= \frac{\%\mathbf{Retained\ on\ SCS}}{\%\mathbf{Retained\ on\ TCS}}$ |
| | $\boldsymbol{FA_{mf}} = \frac{(\%\mathbf{TCS} - \%\mathbf{Filler}}{(\%\mathbf{SCS} - \%\mathbf{TCS}\ )}$ $= \frac{\%\mathbf{Fine\ of\ fines}}{\%\mathbf{Medium\ fine\ of\ fines}}$ | $\boldsymbol{FA_{rmf}} = \frac{(\%\mathbf{SCS} - \%\mathbf{TCS}\ )}{(\%\mathbf{TCS} - \%\mathbf{Filler})}$ $= \frac{\%\mathbf{Medium\ fine\ of\ fines}}{\%\ \mathbf{Fine\ of\ fines}}$ $= \frac{\%\mathbf{Retained\ on\ TCS}}{\%\mathbf{Retained\ on\ Filler}}$ |

## 4. Application of BAP Converted Revised Rational Bailey Ratios to Monitor Permeability

Khosla and Sadasivam (2006) determined the permeability of a structurally competent asphalt mix is often largely influenced by the packing arrangement (specific fractions (e.g. interceptors and pluggers (natural)) alone and micro sized fraction ratios). Horak et. al., (2017b) found it is largely the fines at the micro level that correlate best with permeability by reworking several published permeability studies.

Horak et al (2018) therefore analysed the micro level BAP converted revised rational BMRs at the micro level to test their indicative potential for permeability potential. The published data of Denneman et al (2007), Khosla and Sadasivam (2006) and that of Al Mosawe et al (2015) were re-analysed. Only the extreme ranges of the permeability spectrum were analysed: Either known high permeability or known low permeability. Horak et al (2017b) showed how the lack of interconnectedness of voids in the mid-range of voids can be misleading due to the variance and lack of control of interconnectedness of the voids.

Figure 7 is from the Horak et al (2018) where $\mathbf{FA_{rcm}}$ ratios were calculated and presented as a bar chart next to its porosity calculation. The product of porosity and $\mathbf{FA_{rcm}}$ ratios are also shown on the same vertical scale. The latter product was found to indicate the interplay that often take place between the BAP ratio and porosity. The dataset from the Denneman et al (2007) reworked data confirms the potential for permeability control or monitoring of permeability seems to be more obvious with the micro-level nested skeleton subset binary contiguous aggregate ranges.

The Denneman at al. (2007) data sets show that the porosity values are not significantly different if the good and bad performing data sets are compared. The porosity range is between 0.6 and 0.7 implying this binary aggregate combination does not have the desired low porosity value below 0.5 where packing would be optimum. There is therefore potential for interconnectedness of the voids expressed as porosity here. The Denneman et al (2007) micro-level binary combination mass ratio**,** $\mathbf{FA_{rcm}}$, clearly can discern between the poor and good performing data-sets. The bad performing data set $\mathbf{FA_{rcm}}$ value is showing definite wall effect impact on porosity and is approaching the combined wall and loosening effects zone. The product value **(Product = $FA_{rcm}$ x Porosity)** obviously show the dominance of the **$FA_{rcm}$** and implies the potential for interconnected voids may be high and thus increase the potential for water flow or higher permeability values.

The Khosla and Sadasivam (2006) reworked data show the same trend or sensitivity to coarse/fine mass ratio and combined porosity values at the micro aggregate skeleton subset. In this case, permeability was measured which indicates **$FA_{rcm}$** may in fact be the real discriminating factor between permeable and low-permeable mixes. The porosity values are also in the same range for the high- and low permeability values. Therefore, porosity alone is not the discerning factor; **$FA_{rcm}$** needs to be considered and, as for Denneman et al (2007) reworked data, the product value **(Product = $FA_{rcm}$ x Porosity)** confirms the porosity may perhaps be exposed to both the wall- and loosening effect on porosity. Porosity exposed to the wall- as well as the loosening effect may be indicating a tendency for the voids in the porosity to have interconnectedness of voids.

This distinction is also clear in the case of the Al Mosawe at al. (2015) reworked data set when **$FA_{rcm}$** calculated for subsets of high and medium air void content are compared. The porosity is high for the low air voids and low for the high air voids. This is contrary to expectation as high voids content (%) is known to be directly linked to high permeability and vice versa. In this case the high **$FA_{rcm}$** values clearly coincides with medium- to high porosity or high void content. These voids are exposed to both the wall- and the loosening effects due to the high $FA_{crm}$ value and therefore, may have a higher probability of interconnected voids and resultantly a higher permeability probability. The product in this case is not necessarily a good indicator of permeability but confirms the influence of **$FA_{rcm}$** to the wall and loosening effects and indicating the probability of possible interconnectedness of voids and therefore permeability.

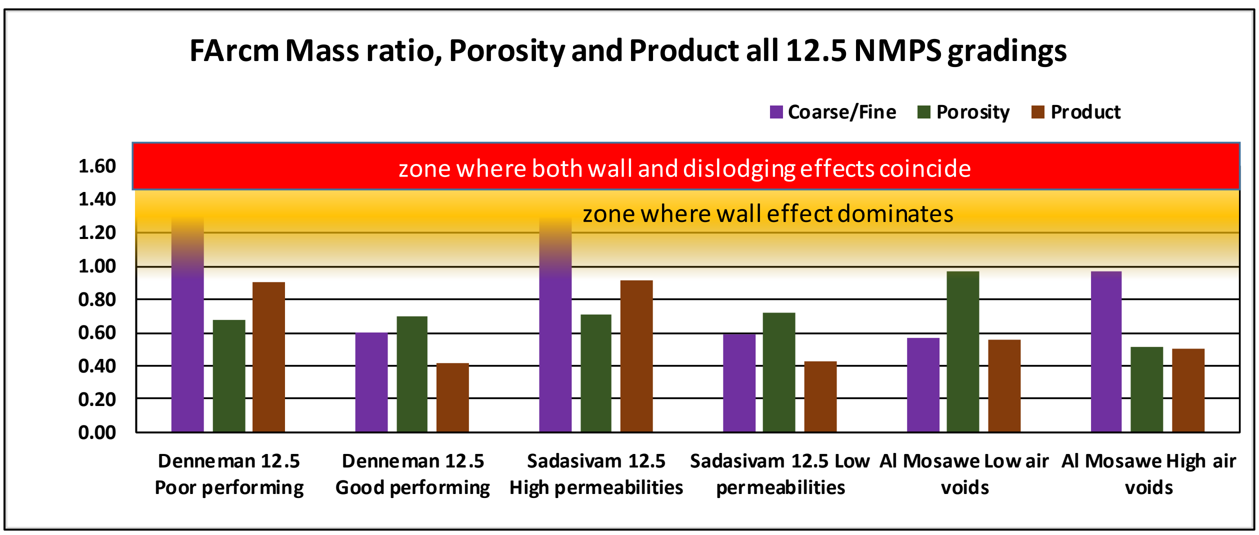


*Figure 7: SCS to TCS fraction Ratio and Porosity and Product (Horak, et al., 2018)*

## 5. Description of Actual Construction Data with Permeability Problems

Stripping and ravelling are durability type distresses often observed on airports. This form of distress is often linked with areas with no traffic and can also be associated with arid as well as wet regions. Stripping can easily go undetected and can lead to de-bonding of asphalt layers. This happened in the case of Hosea Kutaku International Airport (HKIA) (Horak et al, 2009 and 2011) which can cause delamination with serious safety threats associated with loose objects on the airside surfaces (FOD). Stripping and other durability types of distress were observed to often originate at longitudinal joints.

The current asphalt mix design procedures in Southern Africa tend to focus on rut and cracking prevention and have a strong roads design bias. The result is that specifications and quality control procedures also tend to focus mainly on density and voids control. The bias is also enhanced by the focus on the lane mat quality and lesser attention given to the longitudinal joint quality. It is acknowledged elsewhere (Horak et al, 2009) that densities in the close vicinity of longitudinal joints often are allowed to be 2% lower than the densities on the lane mat.

After observing a white deposit at the joints of a 50mm asphalt overlay on the apron of HKIA it was established that the longitudinal joints were not constructed correctly by cutting back and proper densification over the joint. Coring on joints previously uncut confirmed that densities were below specification and voids therefore also too high. Remedial work was done where the mat densities were also failing to meet specifications. Analysis of density results on this project determined afterwards that the average density between the mat and the paired joint densities, shown in Figure 8, were as high as 5%, and the joint densities were as low as 3% below accepted specification limit. However, the fact that joint densities are analysed with the rest of the mat (with higher than specification densities) often resulted in acceptance of the total paved lane. Corrective action was to apply a rich fine slurry rejuvenator to the joint area.

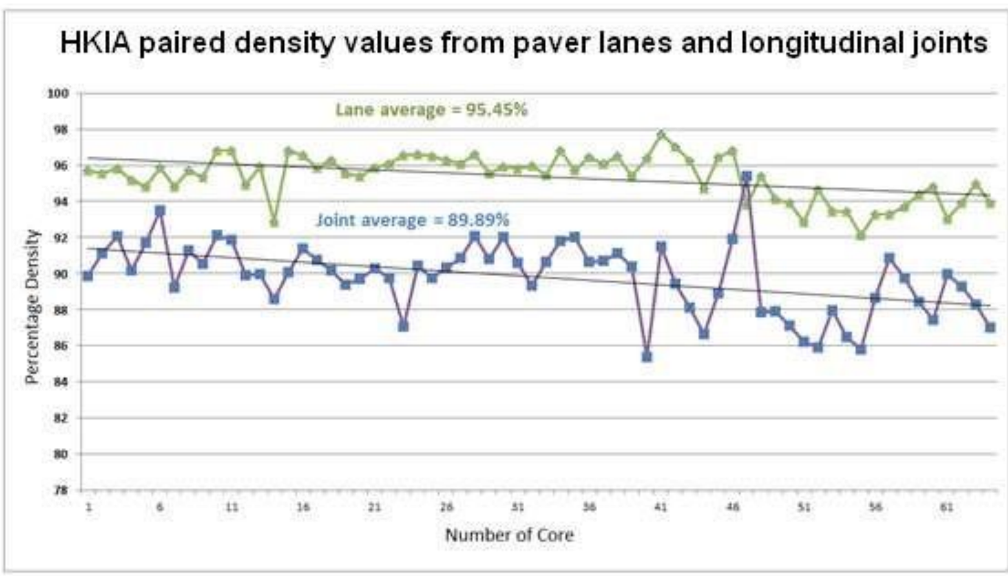


*Figure 8: Paired Densities from Paver Lane and Joints on HKIA (Horak, et al., 2012)*

A coring program enabled cores to be taken at areas with the white deposit, as well as apparently sound areas. In an attempt to find a practical way to shift the density and voids control to actual permeability indicators, the cores were rated or classified visually in terms of inter-connectedness of voids observed on the core samples (Horak, et al., 2012). This classification was followed up with normal quality control type density and voids determination.

A Red, Amber, Green (RAG) benchmark comparison of all tests provided valuable practical guidance to correlate existing density and voids testing with actual durability related aspects of permeability. It was found that density and voids in combination with a visual permeability rating (Horak et al, 2009 and 2012) showed good correlation with actual air and water permeability values. More detailed analyses showed and confirmed very good correlation between density and voids, density and permeability (air and water), voids and permeability (air and water). In Figure 9 the results from the air permeability with the RAG ranges superimposed are shown. This set of results have the same exponential take of tendency as determined by Cooley et. al., (2002) when voids are increasing beyond a threshold value (linked to NMPS and lift thickness) where interconnectedness become dominant in the voids or porosity distribution in the asphalt mix.

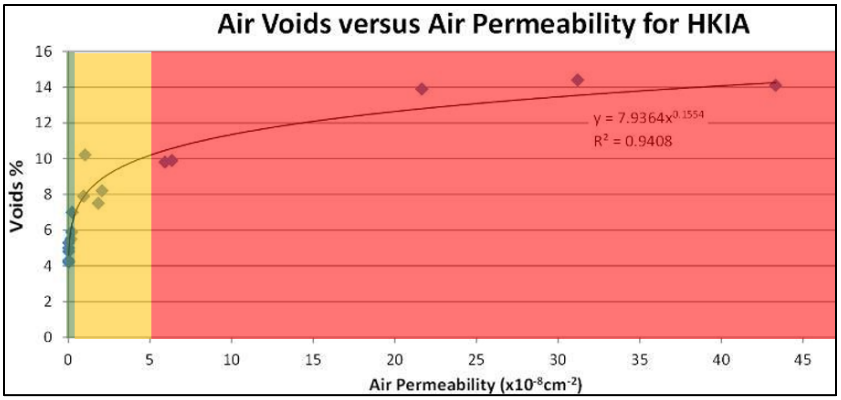


*Figure 9: Air Permeability Versus Air Voids in the Mix on the Apron of HKIA (Horak, et al., 2012)*

## 6. Application of BAP and Revised Rational Bailey Ratios to this Case Study

Even though no early signs of stripping or permeability (e.g. water oozing) have been observed on the apron after nearly 6 years after the overlay rehabilitation of HKIA apron, the question remained whether the permeability problems were only a longitudinal joint construction problem or whether it may have had aggregate grading deficiencies that may lead to durability problems later due to inherent permeability problems. In Figure 10 The grading results from the cores from the HKIA apron were analysed using the revised rational BMRs as per BAP analysis defined in Figure 5 and Figure 6. In this case the calculated micro level ratios $FA_{rcm}$ were calculated and are presented in Figure 10. The normal statistical analyses are shown for average, $10^{th}$ and $90^{th}$ percentile values. It shows results that are densely grouped between the $10^{th}$ and $90^{th}$ percentile values and an apparent low standard deviation around the average value of $FA_{rcm}$. There is only one obvious outlier. The criteria for wall effect and loosening effect were superimposed as a RAG-colour background. The whole data set is in the green, or sound, (including the outlier) confirming this asphalt mix and aggregate grading showed no tendency to have interconnected voids if compacted to the correct density and void range as per the specifications. It confirms that the observed longitudinal joint permeability was therefore purely a construction density practice problem as originally identified. The emulsion enriched application over the joint appears to help to keep that area also impervious.

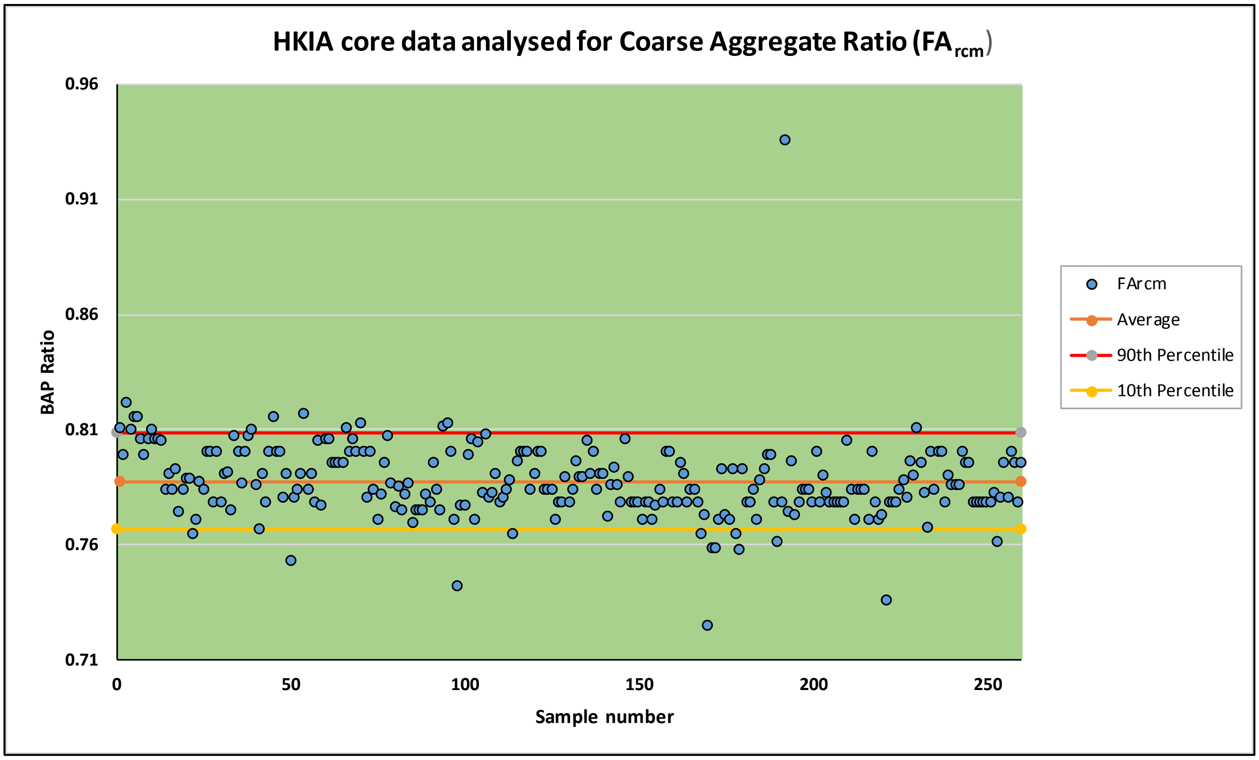


*Figure 10: $FA_{rcm}$ Values for HKIA Apron Cores Reworked.*

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