# Towards a mix design model for the prediction of durability of hot-mix asphalt

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## Highlights

- Use of Probability Density Function to delineate sections based of propensity for permeability.
- Use of regression analysis of permeability control as a function of the micro level aggregate subset.
- Use of machine learning with the Gaussian Process Regression to predict porosity.
- The Bailey ratios and porosity correspond to permeability potential and field performances.
- Use of the binary aggregate ratio to predict the permeability of an asphalt mixture.

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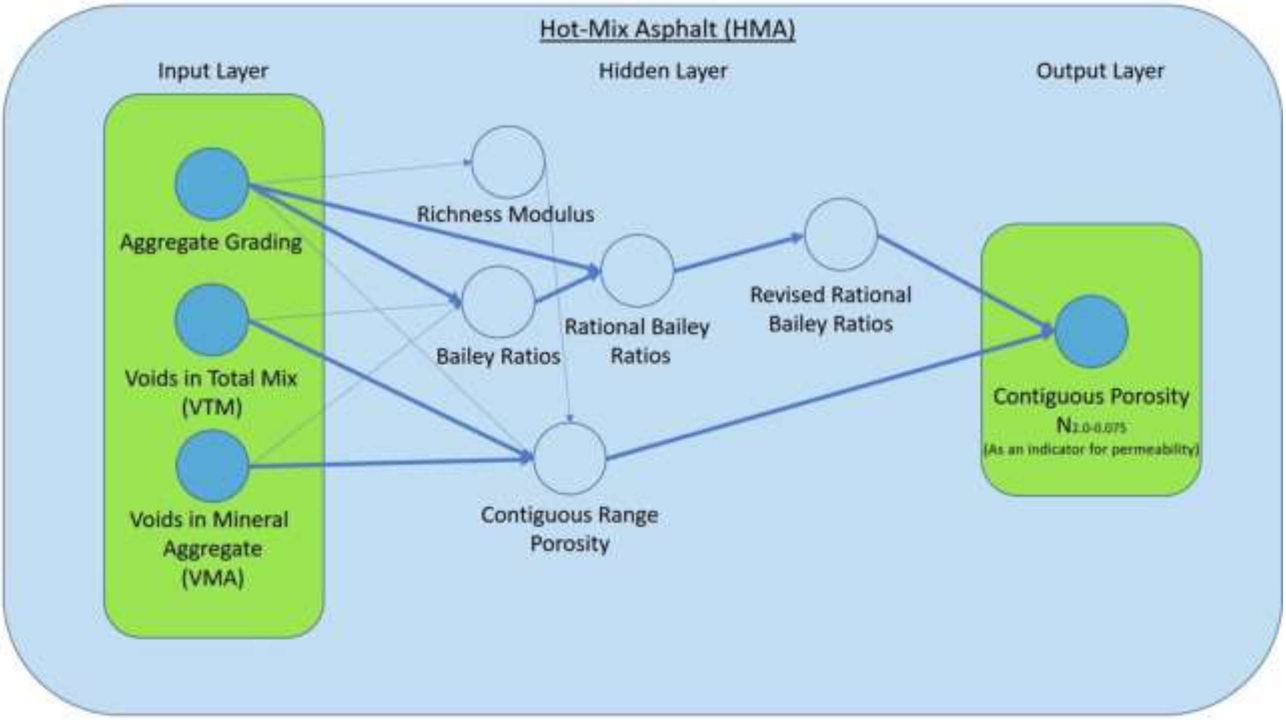
## Abstract

Hot-Mix Asphalt (HMA) is a designed pre-mix of graded aggregates and bituminous-based binder, hot applied on road pavements to provide a smooth and safe riding surface and protect the underlying layers. Current HMA mix design methods are focusing, mostly, on the strength of the mixture. However, the mixture permeability, which is an equally important performance parameter of an HMA layer - strongly influencing the durability of the HMA and underlying layers – is not always pertinently used as a mix design parameter. Exclusion of permeability is attributed to uncertainty on the accuracy of measured permeability, as well as poor correlation among predicted, field, and laboratory results. In this paper, it is hypothesised that practical and reliable methods are available to predict and measure the permeability of HMA in the field and laboratory as well as to successfully relate permeability parameters to long-term performance of HMA. The objective of the study is to establish these relationships and validate an HMA design model to predict durability. Numerous theoretical models were evaluated and the selected model is based on regression analysis of field data. Initially, predominant variables influencing layer permeability were found to be void proportion, binder content, aggregate grading and packing. Subsequently, regression analyses of data showed that within reasonable variation of the other variables, layer permeability is strongly correlated to aggregate grading and packing, as described by rational Bailey ratios, hence the focus of refining the model on the latter parameters. The research confirmed the hypothesis by showing an acceptable level of confidence in the relationships. The study objective was achieved to the extent that the predicted levels of permeability correlated well with field observations of durability performance. This was enhanced with machine learning modelling of the data sets available from recent as-built road sections with similar design and specifications and different permeability observations in the field. It is concluded that permeability can indeed be introduced as a primary design objective in HMA design practice. It is recommended that, while further machine learning refinement is being done, the model

be used by designers in enhancing the prediction of design life of HMA surfacing and structural pavement layers.

## Graphical abstract



**Keywords**

HMA; Mix; Design; Packing; Permeability; Durability; Bailey; DASR; Machine-learning; Model

## 1. OBJECTIVES

The objective of this study is to establish the relationship between aggregate grading and packing and porosity which acts as an indication of permeability potential, validating an HMA design model to predict durability.

## 2. INTRODUCTION

Asphalt mix design tend to primarily focus on strength and rut resistance. The grading and typical criteria even at the lowest level of asphalt mix design tend to focus on aspects that ensures binder content is at a level which ensures compaction is achieved and further deformation is limited with the stone or sand skeleton providing the main contribution towards strength [13]. At this design stage voids in the mix is specified at typically 4% to 6% and density at 93% minimum. This actually implies that the voids in the mix may already be close to the precipice where voids over 6% (eg 7% or 8%) may often be registered in practice in the constructed asphalt layer with known tendencies to become exponentially permeable [3]. This is not picked up by the prescribed permeability tests during the laboratory design phase which is done at lower air voids as per the design mix. In contrast the actual measurement of permeability in the field is fraught with practical problems [6] making for variable permeable, yet structurally strong asphalt mixes being laid.

An overview of recent research confirm it can be expected that the variables influencing layer permeability may include voids proportion (function of compaction, aggregate grading and packing, bitumen content), binder-aggregate cohesion (function of aggregate mineralogy, binder type, static loading, applied temperature), and layer thickness [4]. A study by Horak et al. [7] focused on the influence of aggregate grading and packing on permeability and aimed to rationalise Bailey ratios (which describe strength) with Dominant Aggregate Size Range (DASR) (which describe porosity) and link these parameters to permeability control of HMA. These latter relationships are the focus of this study.

## 3. PERMEABILITY CONTROL VIA BAILEY RATIOS - AN OVERVIEW

Permeability is dependent on the interconnectedness of percentage voids to permit flow of water. Horak et al. [7] attempted to correlate the Bailey ratios proposed by Al-Mosawe et al. [1] and the reworked DASR principles proposed by Denneman et al. [4] to provide improved criteria for permeability control, by means of reworking existing published data sets. The data sets considered, with Nominal Maximum Particle Size (NMPS) (often also named Nominal Maximum Aggregate Size) sizes respectively, were provided by Khosla and Sadasivam [10] (NMPS of 12.5 mm and 9.5 mm), Denneman et al. [4] (NMPS of 9.5 mm), and Al-Mosawe et al. [1] (NMPS of 16 mm). Due to the large NMPS value of the Al-Mosawe et al. [1] data set, it became problematic to consider it with the other data sets and was discarded for this reason. The data set provided by Denneman et al. [4] became the focus of the research due to its relevance in South Africa and can be used as a good first level control mechanism for permeability. Of the original Bailey ratios, Horak et al. [7] found that the Coarse Aggregate (CA) ratio showed sensitivity to permeability control, with the Coarse of Fine Aggregate (FAc) and Fine of Fine Aggregate (FAf) ratios showing poor sensitivity and control of permeability. Therefore, Horak et al. [7] states that permeability control tends to result from individual or combined aggregate fractions in the meso- and micro-level aggregate subsets.

Horak et al. [7] did a critical review of the Bailey and DASR methods and proposed rational Bailey ratios, which adhere to the DASR principles of porosity and contiguous aggregate fractions on the grading envelope. The rational Bailey ratios are shown in Table 1. It is seen that the FAc and FAf ratios are not included. This is because these ratios do not consider a contiguous aggregate range in the numerator and denominator. The ratios proposed by Al-Mosawe et al. [1] are included as they adhere to the contiguous aggregate range concept in the numerator and denominator of the ratio. The proposed ratios aim to 'deconstruct' the aggregate skeleton into macro, meso, and micro subsets, evaluating the contributions of various aggregate ranges individually and together, deliberately focusing on parameters which showed clear sensitivity to permeability control and can be used to better describe the aggregate skeleton packing efficiency.

**Table 1: Rational and revised Bailey ratios with good correlations with DASR porosity parameters (Horak et al. [7, 8])**

| Matrix Level | Original rational Bailey ratios | Proposed revised rational Bailey ratios | Explanation of new and proposed Bailey ratios and parameters |
|---|---|---|---|
| **Macro** | $\frac{P}{O}=\frac{(\%NMPS-\%HS)}{(100\%-\%NMPS)}=\frac{\%Interceptors}{\%Oversize}$ | $\frac{O}{P}=\frac{(100\%-\%NMPS)}{(\%NMPS-\%HS)}=\frac{\%Oversize}{\%Interceptors}$ | Proposed New Bailey Ratio (Extending the Al-Mosawe et al., 2015 approach). This can be called the Plugger to oversize (large) aggregate ratio. This is actually a ratio that bridges the macro and meso ranges. |
| | $CA=\frac{(\%HS-\%PCS)}{(100\%-\%HS)}=\frac{\%Interceptors}{\%All\ Plugges\ \&\ Oversized}$ | $CAr=\frac{1}{CA}=\frac{100\%-\%HS}{\%HS-\%PCS}=\frac{\%All\ Plugges\ \&\ Oversized}{\%Interceptors}$ | Original Bailey Coarse Aggregate ratio is describing the main or macro structural skeleton of large aggregates. It is the ratio of the Interceptors range over the Pluggers and large aggregate. |
| **Meso** | $\frac{Cf}{Fc}=\frac{(\%PCS-\%SCS)}{(\%HS-\%PCS)}=\frac{\%Coarse\ Portion\ of\ Fines}{\%Interceptors}$ | $\frac{Fc}{Cf}=\frac{(\%HS-\%PCS)}{(\%PCS-\%SCS)}=\frac{\%Interceptors}{\%Coarse\ Portion\ of\ Fines}$ | New Bailey Ratio (Al-Mosawe et al., 2015). Proposed name: Interceptor stability ratio. Was developed as standard Bailey ratios but does not describe packing and the matrix stability adequately on its own. |
| | $\frac{F}{C}=\frac{(\%PCS)}{(\%NMPS-\%PCS)}=\frac{\%Fines}{\%(Pluggers+Interceptors)}$ | $\frac{C}{F}=\frac{(\%NMPS-\%PCS)}{(\%PCS)}=\frac{\%(Pluggers+Interceptors)}{\%Fines}$ | New Bailey Ratio (Al-Mosawe et al., 2015). This ratio is a true meso range ratio as it is simply the fine portion relative to the medium coarse portion range (the pluggers plus the interceptors combined). |
| | $\frac{I}{P}=\frac{(\%HS-\%PCS)}{(\%NMPS-\%HS)}=\frac{\%Interceptors}{\%Pluggers}$ | $\frac{P}{I}=\frac{(\%NMPS-\%HS)}{(\%HS-\%PCS)}=\frac{\%Pluggers}{\%Interceptors}$ | This is the Interceptor to Plugger ratio. The Interceptors try to fill the Pluggers voids and therefore act as the main structural element of the middle (meso) portion of the aggregate matrix. |
| **Micro** | $FAcm=\frac{(\%SCS-\%TCS)}{(\%PCS-\%SCS)}=\frac{\%Medium\ Fine\ of\ Fines}{\%Coarse\ Fines}$ | $FArcm=\frac{(\%PCS-\%SCS)}{(\%SCS-\%TCS)}=\frac{\%Coarse\ Fines}{\%Medium\ Fine\ of\ Fines}$ | Suggested new ratio based on the logic promoted by Al-Mosawe et al. (2015). This ratio may provide an indication of the stability of the coarse range of the fine portion (typically fine sand range) in support of the whole fines range of the aggregate. |
| | $FAmf=\frac{(\%TCS-\%Filler)}{(\%SCS-\%TCS)}=\frac{\%Fine\ of\ Fines}{\%Medium\ Fine\ of\ Fines}$ | $FArmf=\frac{(\%SCS-\%TCS)}{(\%TCS-\%Filler)}=\frac{\%Fine\ of\ Fines}{\%Medium\ Fine\ of\ Fines}$ | Suggested new ratio. This portion may, in effect, give an indication of the finer portion of the fines (without the filler component) versus the overall fines portion. It is suggested to be referred as the Mastic Control Ratio. |

As previously mentioned, the data sets reworked by Horak et al. [7] led to the conclusion that, apart from the CA ratio, the remaining original Bailey ratios showed poor sensitivity to permeability control. It is known from more recent work done by Gogula et al. [6] that voids in the asphalt mix alone is not a good indicator of permeability due to various factors influencing the actual prerequisite for permeability, namely: interconnectedness of the voids. This led Horak et al. [7] to question the observed variability and consider it to be due to variance in interconnectedness of voids. This variability trend in the considered data sets narrowed the focus of Horak et al. [7] to the data which had either clear high or low permeability values in order to overcome the confusion regarding the interconnectedness of voids. The data sets were reworked in this manner and sensitivity criteria was developed. The sensitivity of the Bailey ratios was evaluated using a Red, Amber and Green (RAG) benchmark methodology. Ratios exhibiting high sensitivity implied a strong relationship to permeability. Horak et al. [7] found that the rational Bailey ratios which describe the fines portion of the aggregate skeleton show apparent sensitivity to permeability control. This led to a conclusion that the micro level range may have been overlooked in previous studies and that permeability control is not only governed by the CA ratio or other rational Bailey ratios, which consider the macro- and meso-level aggregate ranges. The research concluded by proposing suggested ranges (Table 2) for selected Bailey ratios that correlate with DASR descriptors.

**Table 2: Suggested permeability control criteria for various Bailey ratios (Horak et al. [7, 8])**

| Matrix Level | Rational Bailey Ratios | Suggested Range | Revised Rational Bailey Ratios | Suggested Range |
|---|---|---|---|---|
| Macro | CA | >0.5 | CAr | <2 |
| | P/O | >6 | O/P | <0.167 |
| Meso | I/P | >0.65 | P/I | 1.54 |
| | Cf/Fc | <1.05 | Fc/Cf | >0.95 |
| | F/C | <0.9 | C/F | >1.11 |
| Micro | FAcm | <0.37 | FArcm | >2.7 |
| | FAmf | >0.37 | FArmf | <2.7 |

### *3.1. Bailey Ratios in line with Binary Aggregate Packing Concept*

The use of the binary aggregate packing concept in pavement engineering stems from research in concrete aggregate packing technology. Originally, Furnas [5] developed ternary aggregate fraction combinations which were based on experimental work of beds of broken coarse and fine aggregates. His work formed the basis of further development and technology transfer aiming to optimise aggregate packing of concrete mixtures. Furnas determined that the size ratio of 0.20 to 0.23 of fine to coarse aggregate allowed for optimum packing density and low porosity. This ratio is also used in the Bailey method to differentiate between coarse and fine aggregate as per the primary coarse size definition and is agreed upon to be roughly 0.22.

Mota et al. [12] conducted further research regarding binary aggregate combinations for filter beds and determined that the coefficient of permeability is influenced by coarse/fine aggregate volume ratios. Mota et al. [12] concluded that a coarse/fine aggregate volume ratio value of 0.6 is seen to be the optimum value after which permeability increases.

Knop and Peled [11] conducted research, which showed that if coarse and fine aggregate fractions are combined, they might prevent porosity, and in turn permeability, from decreasing optimally when combined in a binary fashion. This decrease is linked to the ratios of both dimension and volume of fine to coarse. A dilation point, similar to the 0.6 threshold value determined by Mota et al. [12], defines the point where permeability is lowest and is predominantly influenced by the fine/coarse dimension ratio and the coarse volume fraction to fines. Moving away from this dilation point increases the potential for permeability.

While studying the porosity (related to permeability) of mixes in the late 1930s, Caquot [2] highlighted the importance of inter-particle interaction on the voids in the mix (VIM), namely the wall- and loosening-effect. The wall effect is defined as the interaction between the asphalt particles and any wall (formwork, pipe, etc.) which is in contact with the pavement. The wall effect can be described by considering an aggregate mixture of coarse and fine particles. When adding coarse particles into an infinite mixture of fines, the VIM is reduced, but the coarse particles disturb locally the arrangement of fines and increase the local porosity and VIM. This local porosity is increased proportionally to the surface area of the incorporated coarse aggregate [2]. The loosening effect can be illustrated by focusing on the effect induced by adding fines to an infinite mixture of coarse aggregate. As the fines increase to the point where the coarse aggregate particles are no longer in contact and forced apart, the interference (loosening) effect occurs and influences the VIM (the loosening effect is also known to influence rutting potential).

Horak and Cromhout [9] state that if the specific gravity of aggregate is equal for all aggregate fractions, the volumetric ratio of coarse to fine aggregate can be taken as equivalent to the proportion of mass percentage retained on the coarse and fine aggregate sieves, which forms the basis of this simplified concept. It should, therefore, be possible to benchmark various binary aggregate combinations to determine where they plot in reference to the dilation point defined by Mota et al.[12]. The dilation point may also be defined as the point where porosity reduction is altered by the combined effects of the wall- and loosening-effects. It shows the porosity variance of two aggregates combined in a binary fashion versus the varying proportions of the large aggregate in such a varying binary combination. Permeability can thus be controlled by adjusting the aggregate gradations of various fractions to ensure voids are filled and packing efficiency is achieved. Horak and Cromhout [9] suggested to align the rational Bailey ratios with the varying proportions of the large aggregate of the binary aggregate combinations and concluded that permeability is better described by the inverse of the rational Bailey ratios, i.e. the revised rational Bailey ratios, also shown in Table 1.

## 4. CRITICAL APPRAISAL OF PREVIOUS RESEARCH

### *4.1. Khosla and Sadasivam [10]*

Khosla and Sadasivam [10] conducted a lengthy study for the North Carolina Department of Transportation that aimed to evaluate gradation characteristics in relation to permeability and durability. The study used a reference mixture which was compacted using the Superpave Gyratory compactor and used for permeability tests and performance analyses. Four new mixtures were designed for both a 12.5 mm and 9.5 mm mixture in such a manner that two of the mixtures had low permeability properties and the other two mixtures having high permeability properties. The mixtures were centered on the percent fraction passing the 4.75 mm and 2.36 mm sieves, similar to the approach of Denneman et al. [4].

Performance tests were conducted on the mixtures and included the Frequency Sweep Test at Constant Height, the Repeated Shear test at Constant Height, and the Asphalt Pavement Analyser Test. These tests indicated that the permeability of the mixture affects its performance in terms of fatigue life, rutting potential, and moisture susceptibility. It too was found that the mixtures with low permeability properties had a higher fatigue life, rutting resistance, and lower susceptibility to moisture damage than the high permeable mixture.

Khosla and Sadasivam[10] concluded that the 4.75 mm sieve played the pivotal role in determining the permeability characteristics of both 12.5 mm and 9.5 mm mixtures, where a higher percent fraction retained on the 4.75 mm sieve typically led to more permeable mixtures.

### *4.2. Denneman et al. [4]*

The study focused on various sieve sizes and aimed to determine which sieve sizes affected the grading characteristics in such a way that the difference between good and bad field performing HMA mixtures could be identified. Denneman et al. [4] identified that the 4.75 mm and 2.36 mm sieve sizes best-described permeability and field performances of HMA mixtures, hence the refinement of the original DASR equation (Equation 1) to consider only these two sieve sizes.

$$\eta_{(4.75-2.36)} = \frac{\left(\frac{PP2.36}{100}\right)(VTM-VMA)+VMA}{\left(\frac{PP4.75}{100}\right)(VTM-VMA)+VMA} \qquad \text{Eq. 1}$$

Where:

$\eta_{(4.75\text{-}2.36)}$ = Porosity of a typical fraction passing 4.75 mm and retained on 2.36mm sieve,

$PP_{2.36}$ = Percentage particles passing 2.36 mm sieve,

$PP_{4.75}$ = Percentage particles passing 4.75 mm sieve,

VMA = Voids in Mineral Aggregate,

VIM = Total volume of mix.

### *4.3. Vardanega et al. [16]*

Research by Vardanega and Waters [14, 15] aimed to predict HMA permeability using a new parameter – representative pore size (RPS). The RPS is related to the air voids in the compacted mix and the $D_{75}$ of the asphalt mix grading curve. The study showed that collected Superpave permeability data correlated better with RPS than air voids and that by using RPS, the scatter in results was significantly reduced. Vardanega and Waters [14, 15] proposed a simple equation (Equation 2) that may be used to calculate HMA permeability of in-place pavements and based on the collected data, a permeability limit of <10µm/s was proposed.

$$k = \frac{46}{100}(\mathrm{Rp})^{3.70} \qquad \text{Eq. 2}$$

Where:

$k$ = permeability (mm/s)

$R_p = (2/3)[AV(\%)/100][D_{75}(mm)]$

AV(%) = percentage air voids

$D_{75}$ = the sieve aperture through which 75% of the granular material in the mix would pass

Subsequent research [16] expanded the database with data from an additional ten publications and modified Equation 2 to consider mixtures of both NMAS ≤ 12.5 mm (Equation 3) and NMAS > 12.5 mm (Equation 4).

$$k = \frac{26.9}{100}(\mathrm{Rp})^{3.67} \qquad \text{Eq. 3}$$

$$k = \frac{15.4}{100}(\mathrm{Rp})^{4.12} \qquad \text{Eq. 4}$$

### 4.4. Summary

The method of Vardanega et al. [16] shares similar traits with those proposed by Khosla and Sadasivam [10] and Denneman et al. [4] in that all methods have identified a particle or sieve size which best relates to permeability and the field performances of HMA, typically located within the meso range. These methods follow the principles of the Bailey and DASR methods which indicate that fine-graded mixtures tend to perform better than coarse-graded mixtures, as the coarser aggregates typically do not contribute to structural stability and increase the potential for the wall effect to dominate the permeability of the mixture.

There also seems to be a general focus on the 4.75 mm and 2.36 mm sieve sizes which may stem from the original CA Bailey ratio and is recalled to use both these sieve sizes. This may too be the reason for the overall lack of consideration for the micro level aggregate subset and its relation to permeability control, as highlighted by Horak et al. [7, 8].

## 5. RESEARCH APPROACH AND DATABASE

The research process of which this study forms part consists of six phases. The first phase (done by others) comprised the sampling of in-situ asphalt cores. The samples were taken from random locations across the width of the road surface from two uniform pavement sections. The second phase comprised laboratory testing (done by others) of the cores measuring, among others, aggregate grading, binder content, voids content, and density of the asphalt samples. The third phase comprised preparing, validating, analysing, and evaluating the data using statistical techniques. A new parameter - mass-porosity product ratio - was introduced to better explain sensitivity to permeability control.

The mass-porosity product ratio is defined in this study as the product of single revised rational Bailey ratios and their corresponding porosities of the ratios respective contiguous aggregate range. The fourth phase aimed to develop a beta model that defines relationships between various Bailey ratios and porosity as an indicator for permeability potential. The fifth phase focused on applying machine learning techniques to reduce and remain with the critical (most sensitive) parameters in order to gradually enhance the accuracy of the model. Matlab software was used to develop the machine learning model, and it was chosen based on the supposition that the algorithms are mature. An appropriate supervised learning technique, the Gaussian Process Regression (GPR), was utilised for the development of the machine learning model. The model was trained with 90%, validated with 5%, and tested with 5% of the data respectively. The sixth phase aimed to independently verify the binary aggregate ratio methodology using the principles proposed by Vardanega et al. [16], evaluating the permeability of the respective uniform sections and comparing the results to those of phases four and five.

### *5.1. Data Sets*

The data is from a real road project which, at the time of writing this report, is still part of a larger insurance claim and no permission has been granted to publish the data. The data sets from two uniform sections (USA and USB) of recently constructed road sections with the same mix design and specifications were obtained. These two uniform sections showed different field performance of which USA was non-permeable and USB had clear higher permeable field performance issues with clear durability-related distress development. The sample was predetermined based on the data obtained, with sample sizes of 222 for USA and 205 for USB.

## 6. MODEL DEVELOPMENT

Following preliminary statistical analyses, it was identified that USA showed both better homogeneity and parameter correlations than USB. The inverse of Rational Bailey ratios allows the use of Binary Aggregate packing principles to determine porosity [9]. It was identified that the inverted rational Bailey ratios which showed apparent sensitivity to permeability control are:

- Revised mastic control ratio ($FA_{rmf}$) Bailey ratio (This is in effect the invert of $FA_{mf}$),
- Revised stability of coarse fraction of fines ratio ($FA_{rcm}$) (This is the invert of $FA_{cm}$) mass-porosity product ratio, and
- $FA_{rmf}$ mass-porosity product ratio.

Using Matlab software and the above three variables, a machine learning model was developed based on the data of USA. The USB data set was used to validate the model. The success criterion was the ability of the model to conform to the USB data set as both data sets, even though having different permeability characteristics, had similar mix designs. The Binary Aggregate ratio methodology uses aggregate grading and packing to determine porosity, which is this study, is used as an indicator for permeability potential. The results of the developed model analysis are shown in Figure 1. Figure 2 shows the results of the model when applied to the data set of USB.

Good accuracy is noted for the GPR method, predicting the porosity of USA within ±1.5% for 98% of the time. However, when the model is applied to the data set of USB, it could only predict the porosity within ±1.5% for only 47% of the time. This confirms the accuracy of the model to predict permeability potential and shows that USB may be more prone to apparent permeability linked to pre-identified Binary Aggregate ratio parameters due to the inability of the model to conform to the data set. One of the strong points of a machine learning model is that it can be improved over time with the availability of more data, and the use of that additional data for further learning.

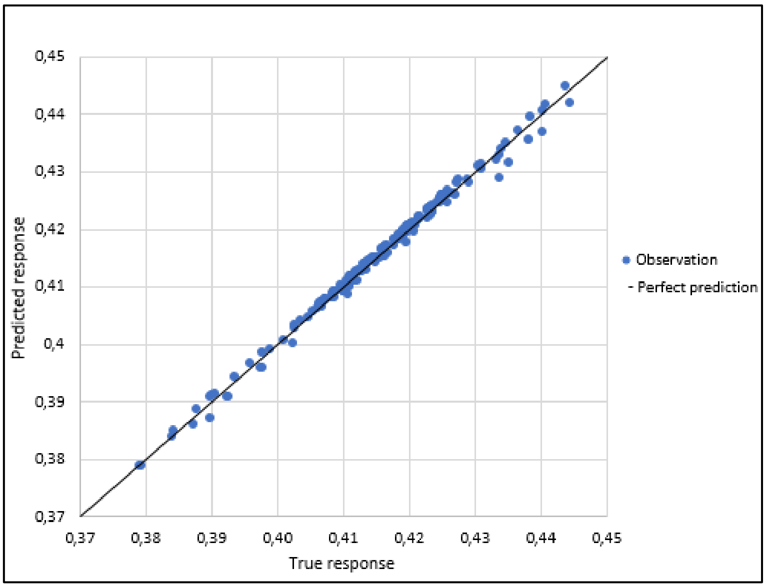


**Figure 1: USA - GPR (Squared Exponential) Observed and Predicted Porosity**

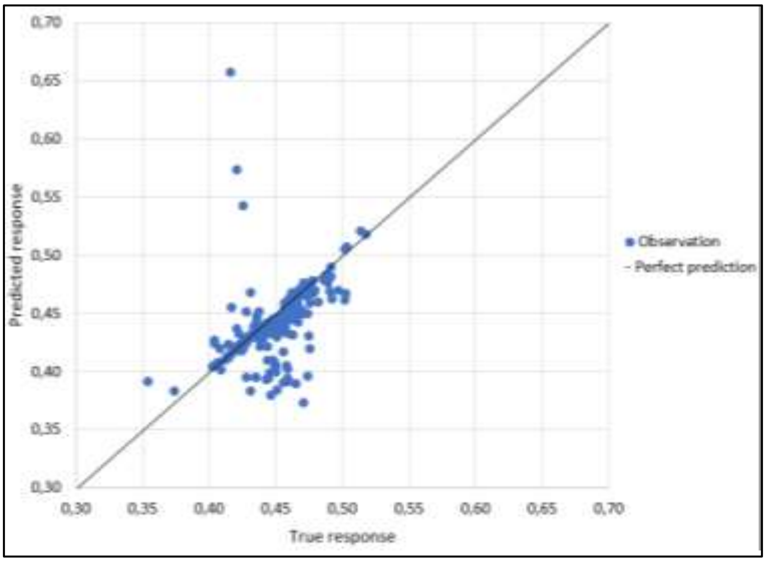


**Figure 2: USB - GPR (Squared Exponential) Observed and Predicted Porosity**

## 7. INDEPENDENT VERIFICATION

A separate analysis, using the formula proposed by Vardanega et al. [16], was conducted to evaluate and verify the permeability of USA and USB. A Probability Density Function (PDF) analysis was conducted, and the results are shown in Figure 3 below. From the PDF analysis, it is seen that there are distinct differences between the data sets with a similar trend to that seen from previous results. Furthermore, USA has a mean permeability of 3.01 µmm/s and USB has a mean permeability of roughly double that of the USA at 6.08 µmm/s. These results are in line with those of the binary aggregate ratio methodology and show that USB is potentially more permeable than the USA.

It is, however, understood that an asphalt pavement does not fail on average, but at random and isolated locations, largely due to construction related influences. This being said, the PDF analysis may be used to predict the overall performance of the data sets and confirms that homogeneity shares a relationship with field performance.

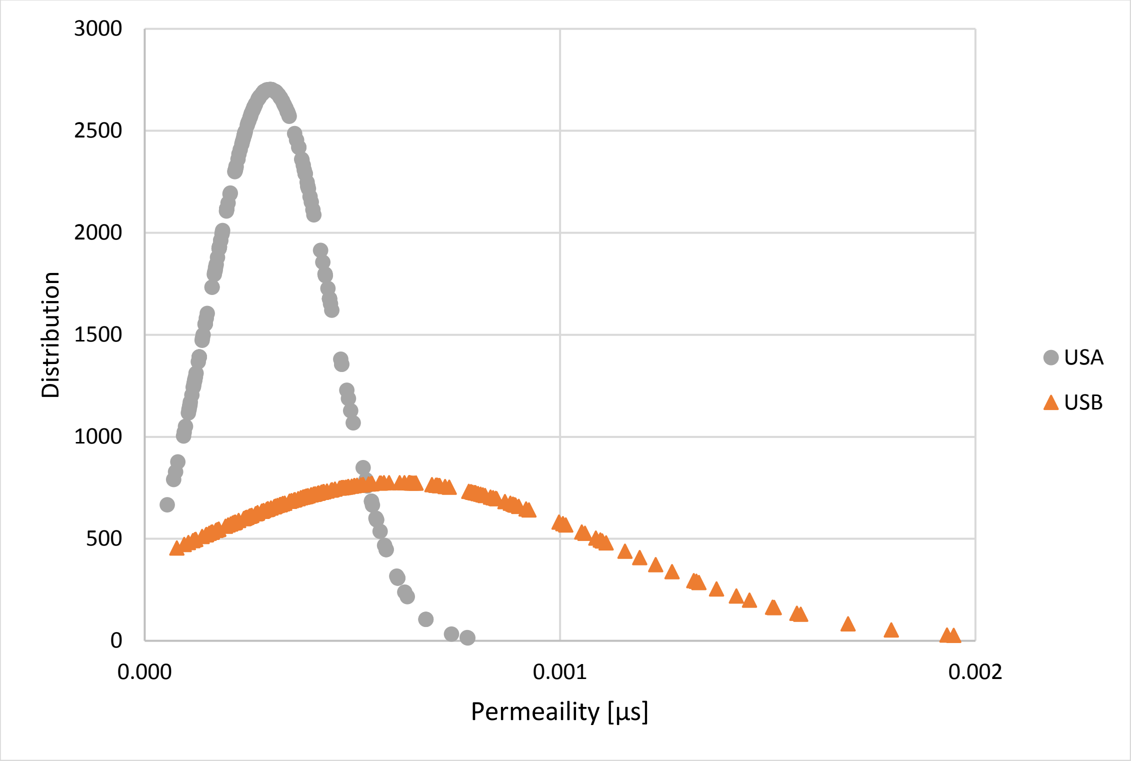


**Figure 3: PDF results – permeability**

Given the validation of the binary aggregate ratio methodology by both an independent analysis and field performances, it is, therefore, the author's opinion that the methodology may be used to predict with confidence the permeability of an asphalt mixture.

## 8. CONCLUSIONS

1. The mean of various revised or inverted rational Bailey ratios can be used to discern between the performances of uniform sections and indicate the permeability of those sections.
2. The PDF analysis shows a clear distinction between uniform sections in terms of propensity for permeability.
3. Regression results confirm the notion that permeability control is dependent on the micro level aggregate subset.

4. Results of analyses coincide with field performances confirming the micro level influence on permeability.
5. The relationship between Bailey ratios and porosity correspond to permeability potential.
6. The binary aggregate ratio methodology may be used with confidence to predict the permeability of an asphalt mixture.
7. Machine learning analyses with the GPR method show good accuracy for predicting porosity.
8. The machine learning model developed has only been calibrated to limited HMA data and should not be universally used.

From the above, the research confirmed the hypothesis by showing an acceptable level of confidence in the relationships. It is concluded that permeability can indeed be introduced as a primary design objective in HMA design practice.

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