# SMA MIX DESIGN VIA BINARY PACKING TRIANGLE CONCEPTS

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## ABSTRACT

One of the principle requirements for stone mastic asphalt mix design is the provision of stone on stone packing for the aggregates and sands that will provide the intended rutting resistance for this mix.

This paper provides a rational mix design procedure for SMA based on particle packing triangle concept through a binary or two component design procedure with added consideration to the effect of fillers. The packing of materials is based in the classic work of Furnas, Powers and Lees, including the fixed binder work of Heukelom. The materials are combined in such a manner that it's interaction with the mastic ensure voids are at the required design level. Adjustments can be made to material combinations in an educated manner replacing the usual adhoc methods currently available.

A practical application of the packing theory is provided demonstrating the benefits of the method.

## 1 INTRODUCTION

Stone Mastic Asphalt is defined in AS2150 (2005) as 'a gap-graded wearing course mix with a high proportion of coarse aggregate, which interlocks to form a skeletal structure to resist deformation, and bound with a mastic mortar of fine aggregate, filler and binder.' It normally provides a negatively textured surface with good resistance to rutting and shoving. The mix features a high binder and filler content which provides a strong waterproof, flexible mastic. A small percentage of fibres are usually added to prevent drainage of the binder during transport and placing of the mix. It is assumed the presence of the mastic with a high binder/filler content makes SMA rut resistant and fatigue resistant, resulting in a long life surfacing.

In terms of mix design, largely a recipe approach has been taken in Europe but the US National Centre for Asphalt technology (NCAT) developed a 'rational' approach. This was modified by the Australian Road Research Board (ARRB Group) and incorporated in The Austroads Guide to Pavement Technology Part 4B (Austroads, 2007), formally known as Selection & Design of Asphalt Mixes: Australian Provisional Guide commonly referred to APRG 18 (Austroads, 1997) as an option to the recipe approach.

This paper is provided as a simple rational means to guide designers to:-

- Select materials to perform as SMA through size ratio considerations
- Provide interlock of the coarse and fine aggregate via binary combination considerations

- Determine the appropriate quantity of fine aggregate to provide sufficient void space for both filler and binder without destabilising the mix
- Determine the maximum quantity of filler

# 2 LITERATURE REVIEW

Johansen and Andersen (1970) describe the field of particle packing as "the problem of selecting appropriate sizes and proportions of particulate materials to fill larger voids with smaller particles, containing voids that again are filled with smaller particles, and so on".

## 2.1 US APPROACHES

### 2.1.1 VCA Concept

The Voids In Coarse Aggregate (VCA) concept was developed by the US National Centre of Asphalt Technology (Brown et al, 1994) with the original work and data funded by the National Cooperative Highway Research program (NCHRP) Project 9-8 "Designing Stone Matrix Asphalt Mixtures". This was further reported in the AAPT Journal (Brown et al, 1997) which subsequently became the reference source for the APRG18 dilation method.

In 1993 NCAT sought to determine a method to evaluate stone-on-stone contact in SMA mixes as previous work had been very subjective in this regard.

Stone-on-stone contact occurred when the density of the coarse aggregate in the SMA mixture is equal to or higher than that measured in the dry rodded test (material in excess of the 4.75mm sieve).

$$VCA_{MIX}(\%) < VCA_{drt}(\%) \tag{1}$$

The percentage Voids in Coarse Aggregate ($VCA_{MIX}$) of the asphalt mix is defined as:

$$VCA_{MIX}(\%) = 100 - \left( \frac{\rho_{mix} P_{coarseagg}}{\rho_{coarseagg}} \right) \tag{2}$$

where ρmix, Pcoarseagg and ρcoarseagg are the mix density, percentage and Bulk Density of the coarse aggregate respectively.

Emphasis was placed on the position at which the line deviates as the point 'at which stone-on-stone contact begins to develop'. The dry rodded test in the AAPT paper is used as a check to see if an adequate aggregate skeleton had developed and was suggested as being used as a limiting value.

### 2.1.2 Bailey Method

The following is extracted from the US Transportation Research Board Circular No. E-C044 (TRB, 2002):

*The Bailey Method for gradation selection considers the packing characteristics of aggregates. The parameters in the method are directly related to voids in the mineral aggregate (VMA), air voids, and compaction properties.*

*The Bailey Method is a means to design the aggregate interlock and aggregate structure in an asphalt mixture.*

*The Bailey Method is a systematic approach to blending aggregates that provides aggregate interlock as the backbone of the structure and a balanced continuous gradation to complete the mixture.*
Further information can be found in AAPT Journal (Vavrik et al, 2001), and a good summary of the Bailey Method and its application to SMA is contained in Appendix F of the Group Report of the 2004 AAPA Study Tour USA June 6-19 (AAPA, 2004).

## 2.2 BINARY PACKING

### 2.2.1 Specific Volume (Furnas)

Furnas (1928) presented the voids relationships between the densities of two (binary) components when they are packed together by allowing one component to fall onto a bed of the other from a short distance above. His Figure 3 of the relation between voids and size composition in two-component systems of broken solids is reproduced here as Figure 1. The figure used materials of varying diameter ratios between the two components where each component had an individual voids value of 0.50. Other figures in his work were for individual values of 0.4 and 0.6 voids.

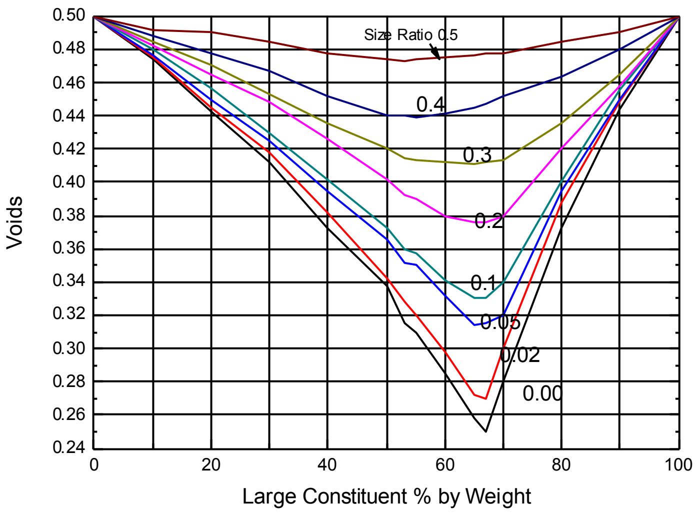



**Figure 1. Furnas's Packing Diagram for Different Size Ratios**

The work was transformed into the form of a 'Specific Volume' diagram as shown in Figure 2 where a bulk density of 2.6 t/m3 was used for each component. In the Furnas two component diagrams the vertical axis is in terms of specific volume and the proportion of each component is by weight.

Knowledge that the effect of component diameter size ratios is not linearly related to compaction allows the minimum voids position (dilation point) to be reasonably estimated for other more realistic diameter size ratios as long as the zero diameter size ratio minimum point is known.

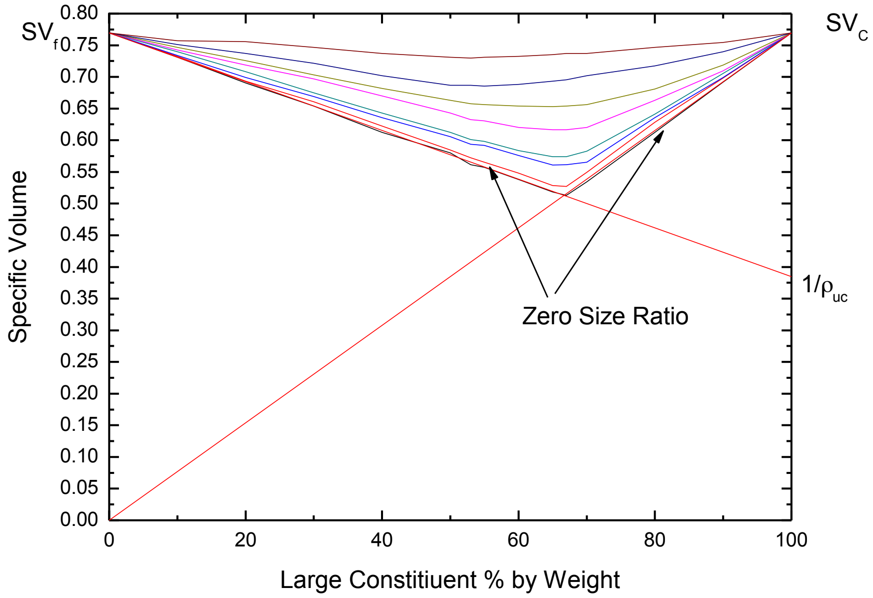



**Figure 2. Furnas Specific Volume Diagram**

### 2.2.2 Specific Voids (Powers)

Powers (1964) in examining aspects of fresh concrete technology converted the Furnas type diagrams using Specific Volume to ones using Specific Voids ($v_S$). Specific voids in effect is the ratio of voids over the solid volume of aggregate. In this way the use of bulk density (specific gravity) was eliminated for the vertical axis values.

It is interesting to note that the work of Powers '*resulted in empiric analytical relationships for the estimation of the void ratio of concrete aggregates. The work by Powers contains the roots of the widely accepted American mix design practice known as "The American Concrete Institute Standard Recommended Practice for Selecting Proportions for Concrete"'* (Marais, 1974).

In the Powers two component diagrams the vertical axis is in terms of Specific Voids whereas the proportion of each component is in terms of volume. When the Bulk Densityis the same there would be no change in converting from weight to volume but, for example, when using a filler where the bulk density is significantly different, the volumes would have to be calculated. An illustrative Specific Voids diagram is presented as Figure 3.

The calculation of the position of dilation point for the zero diameter size ratio allows the locus of this position for different individual component packing specific voids to also be calculated and this is shown overlaid on the previous data for the specific case when the individual component Specific Voids are the same.

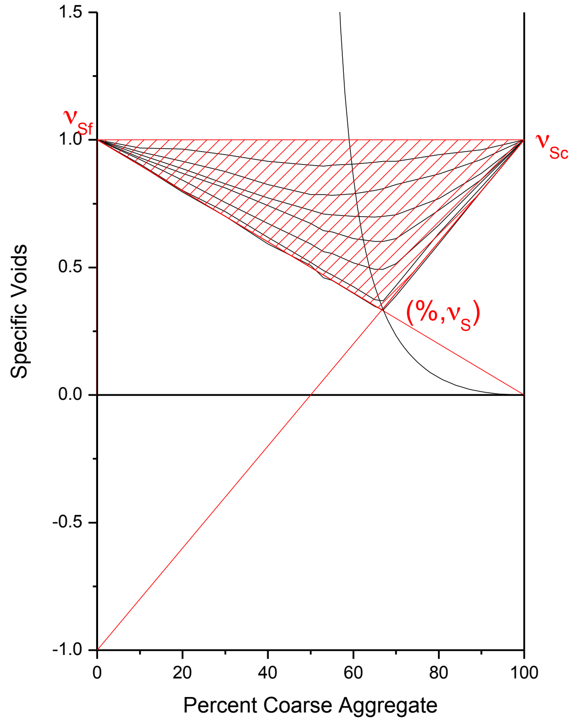



**Figure 3. Basic Specific Voids Diagram**

### 2.2.3 Lees

Lees (1970) in building on the work of Furnas and Powers introduced the concept of Porosity. In the work by Lees, porosity is equivalent to the common use of percent voids (specific voids is determined on voids expressed as a decimal). Lees carried out 'a full series of experiments with a variety of aggregate combinations over a wide range of size ratios' resulting in his conclusion that the percent fines to generate the minimum voids was a function of the average voids of the two components, their voids difference and the size ratio.

From the results of over 80 experiments it was concluded that the relationships between voids average, difference and size ratio encompass the effects of particle shape, surface texture, surface charge, lubricating and adhesive coatings, boundary effects, compactive effort and size ratio. These effects are, of course, important ones in considering the volumetric changes that occur in an SMA mix design.

The fact that Lees obviously found voids to be more valuable than specific voids in developing mix design charts points to the conclusion that a return to a voids chart for mix design work is warranted. Specific volume/voids concept is useful only to find a mathematical position for the minimum voids (dilation point for the zero size ratio case).

To reinforce this point the coordinate for minimum voids has been converted from specific voids to percent voids as follows:

$$\frac{100-\nu_c}{1-\frac{\nu_f \nu_c}{100^2}}, \frac{\nu_f \nu_c}{100} \qquad (3)$$

The important Triangle of Packing can then easily be constructed on a voids/percent component diagram as shown in Figure 4 when the individual component voids are 20 ($v_F$) and 30% ($v_C$) respectively.

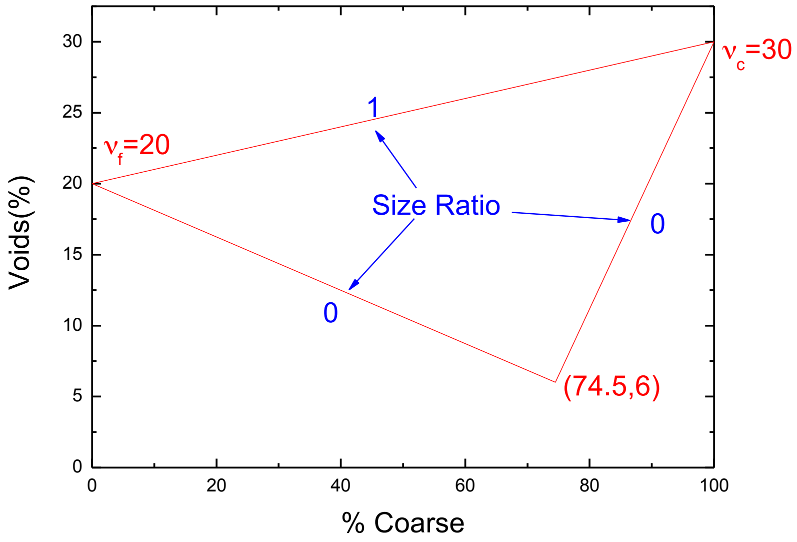



**Figure 4 Triangle of Packing**

Examination of the Lees (1970) voids charts, points to the fact that the packing of equal voids material is a special case that divides packing behaviour. Equal individual voids material, it is assumed, from the Lees charts progress from the zero size ratio position (minimum voids) for increasing size ratio, to the 50% component position on the size ratio one line. The charts also indicate that when there is either a positive or negative voids difference between the components, and this probably more the norm in reality, the progress, for increasing size ratio, is from the minimum voids position to the lowest individual component value at size ratio one (as indicated in Figure 4).

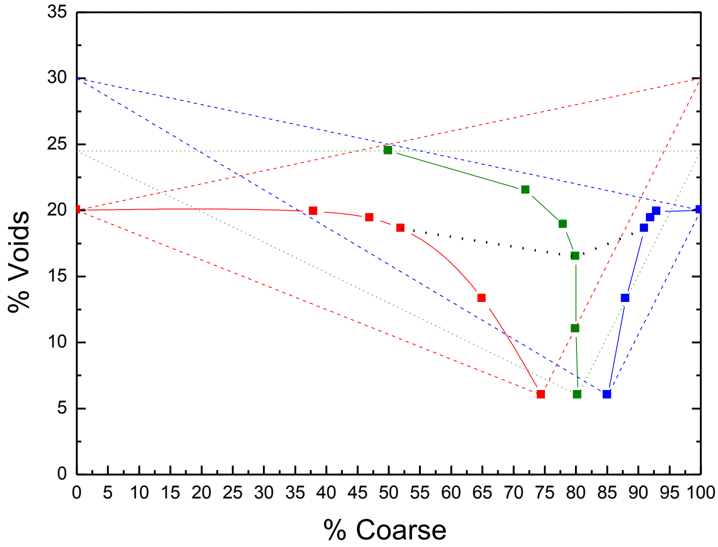



**Figure 5. Positive, Negative and Equal Triangles of Compaction**

The Lees 0.23 positions for the three types of Triangles of Compaction, as shown connected by the dashed line in Figure 5, also reinforce the concept that the size ratio 0.23 represents a 'hinge point' in behaviour. Significant void reduction to the absolute minimum value occurs for size ratio 0.23 or less, but significant variation in proportions of the two components can occur for size ratios above 0.23 with little change to the minimum voids.

## 2.3 SIZE RATIO

### 2.3.1 Aggregate size representation.

Size ratio is a key feature with the packing of particles. To determine a size ratio, firstly a size needs to be attributed to the particles contained between limiting sieve sizes. A limiting sieve size indicates the range of sizes between which the material is identified. For example, 26.5 – 13.2 indicates material retained on the 13.2 mm sieve but passing the 26.5 mm one. Lees measured the Equivalent Spherical Diameter (ESD) between limiting sieves by counting at least 500 particles contained between these sieves. By knowing the mass and Bulk Density he determined the diameter assuming a spherical volume of the particles. His mix design porosity charts are therefore constructed on the basis of a size ratio between these ESDs.

Using the average of the limiting sieve sizes, it was found for the coarse sieve sizes that a good one to one fit with the ESD was found but that for the fine aggregate sieve sizes, eighty percent of the difference between the limiting sieves gave a very good one to one fit. Application of this approach to both the Dickenson (1976) and Oliver (1975) and the Lees data is illustrated in Figure 6. It shows that an equivalent Lees ESD with reasonable accuracy can be obtained by use of the simplest method of using an average sieve size.

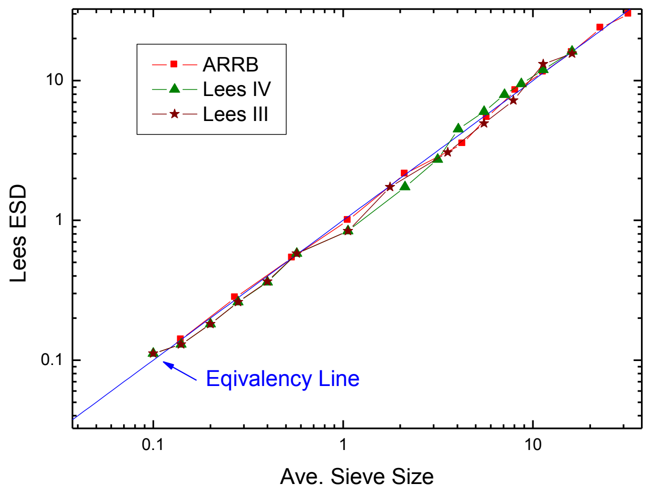



**Figure 6. Average Sieve Size v's Lees ESD**

Powers appears to support the view of using two thirds the maximum diameter as being the ESD.

Lees charts are for single sieve sized materials. To make use of these charts in the experimental work reported in this paper an ESD equivalent was required for a graded material so that the coordinate for the maximum compaction position could be estimated.

Following the work of Johansen and Andersen (1970) in making use of the Rosin-Rammler-Sperling-Bennett (RRSB) relation to represent a grading it was found that 35% passing for the graded aggregate gave a reasonable estimate for $ESD_E$. The $ESD_E$ used in this paper are therefore the 35% passing for the particular aggregate.

The experimental work carried out here has therefore used the Lees charts to overlay the experimental work but used the $ESD_E$ and the associated size ratios.

#### 2.3.2 Critical Size Ratio

An important feature of Lees work in relation to aggregate interlock is his introduction of the concept of Critical Ratio of Dilation. This term was developed to be analogous to the terms Critical Ratio of Occupation and Critical Ratio of Entrance which are used in the theory of combination of mono-spheres arranged in either square or rhombic packing. The Critical Ratio of Occupation is for the diameter of a small sphere which is too large to enter the void between large spheres but can exist inside the void between them without disturbing their packing. The Critical Ratio of Entrance is the diameter of the largest small sphere which can just pass through the pore existing between the large spheres. The terms can relate to either the loosest or tightest packing possible.

As with most things statistical chance plays a part and Lees refers to '*apparently it requires at least 4 times as many particles of the smallest size to provide enough chances for 'all' voids to receive a minimum of one occupant particle'* with the extra particles obviously contributing to dilation and loss of interlock. Though some authors looked at Critical Ratio of Occupation as a means for Gap Graded mix designing, Lees dismissed it as a viable option.
His experimental data showed there is a critical size ratio or '*a Critical Ratio of Dilation above which the coarse aggregate is dilated to a porosity greater than that of its loosest packing and below which the coarse aggregate is dilated to a porosity intermediate between that of its closest and that of its loosest packings – the Critical Ratio of Dilation lay in the region of 0.23 for a wide variety of aggregate shapes'*.

The Bailey Method, also, uses the maximum nominal sieve size as the basis for size ratio and draws on the work of Johansen and Andresen to apply the limiting size ratio of 0.22. This should be compared to the size ratio of 0.23 estimated by Lees to be the Critical Ratio of Dilation.

## 3. FILLER PROPERTIES

A number of fillers in the experimental work were examined for their properties in relation to optimum mix design proportions These were:

- Baghouse fines
- Lime
- Cement
- NSW Flyash
- Pt Augusta Flyash
- Kiln Dust (Calfines)

### 3.1 Basic Properties

The pertinent physical properties of these fillers are shown in Table 1. Rigden Voids ($V_R$) or Voids in Dry Compacted Filler (AS 1141.17) is the percentage of voids based on the compaction of a very small mass (approximately 10 g) by a plunger raised 100 times and dropped onto the filler contained in a small cylinder. It has been shown by Heukelom and others that a 'filler' locks in a certain quantity of bitumen around the filler and this bitumen quantity is referred to as 'fixed' bitumen, ie, it is not available to

$V_R$

00%

$V_F$

coat or lubricate the other mix components. The quantity of fixed binder, i.e., binder locked around a filler particle, has been correlated on an almost one to one basis shown to approximate the Rigden Voids associated with a filler.

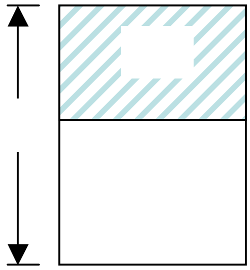


**Figure. 7 Rigden Voids (VR)**

**TABLE 1: Filler Physical Property**

| Filler | Bulk Density ($t/m^3$) | Rigden Voids (%) | Fixed Binder (%) 10% Filler |
|---|---|---|---|
| **Baghouse Fines** | 2.737 | 63.1 | 17.1 |
| **Lime** | 2.24 | 60.5 | 15.3 |
| **Cement** | 3.0 | 52.5 | 11.1 |
| **NSW Flyash** | 2.4 | 57.0 | 13.2 |
| **Pt Augusta Flyash** | 2.42 | 46.8 | 8.8 |
| **Kiln Dust** | 2.7 | 57.2 | 13.4 |

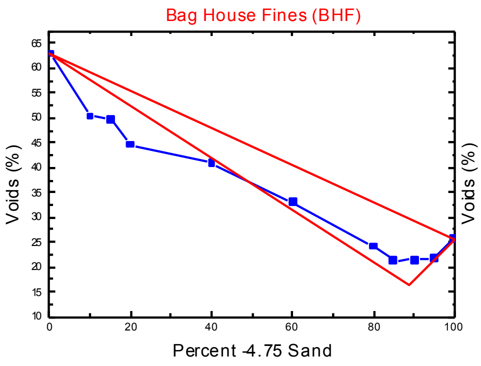
Using Figure 7 as a schematic diagram, an example of 10% by volume of filler ($V_F$) would indicate, if the Rigden Voids was 60%, that there would be (60/(100-60))x10 by volume of fixed bitumen attributed to it, ie 15%.

An excellent visual illustration of the significant change in filler densities causing large volume changes is the figure prepared by Peter Bryant (2005) of TMR Q'ld for his presentation at the 2005 AAPA Industry Conference. This clearly shows the "wet and dry" mastics with theoretical proportions of fixed bitumen. Table 1 also clearly illustrates that the quantity of 'free' binder available changes significantly with the same quantity but different filler type.

### 3.2 Filler Packing Behaviour

In the initial experimental work with fillers, hydrated lime and bag house fines (bhf) were combined with sand which had been scalped on the 4.75 mm sieve. The hydrated lime and bhf were also combined in a 50/50 blend and again combined with the sand. It should be noted that this work with fillers was carried out in the dry state (no binder involved) and this review of fillers after examining the fixed binder aspect has shown that this could produce a different result than if it were used in the wet state. The VCA, after compaction in a standard gyratory mould using the Servopac, of the blended sand, bag house fines and hydrated lime was 27%. The compaction method adopted, to represent field effects, was gyratory compaction at 80 cycles rather than, say, rodded density or even Marshall density. The consequent data did not suggest this needed to be modified.

The Servopac voids against the percent sand together with the appropriate packing triangle are shown in Figures 8a and 8b. The 50/50 filler blend is shown in Figure 9.



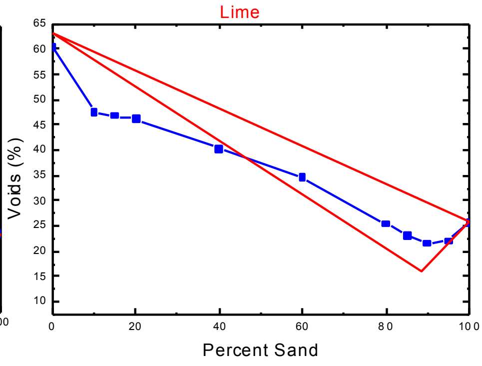



**Figure 8a. Bag House Fines** **Figure 8b. Hydrated Lime**

As the percentage of filler increases, operator problems in combining high percentages of filler with the sand in a homogeneous fashion are reflected in a divergence of data from the packing triangle. In reality the area of interest is around the position of minimum voids and fortunately the compaction behaviour is fairly regular in this area. For Packing Triangle purposes, however, the Rigden Voids appeared to match the Servopac compaction approach and therefore it was decided to use the Rigden Voids as the 100% fines component of the Packing Triangle in future work.

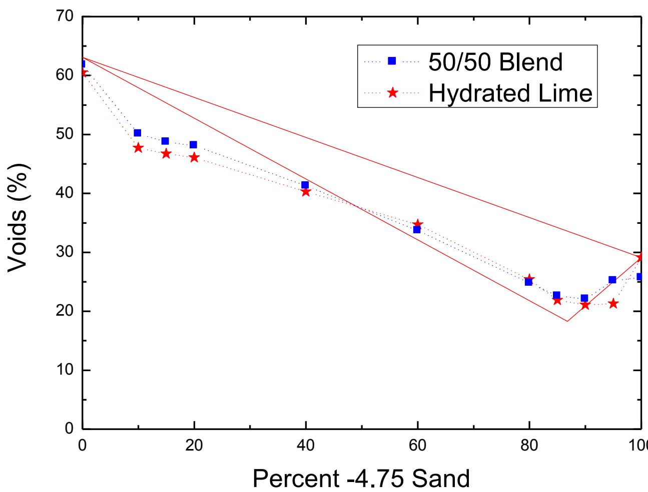



**Figure 9. 50/50 Blend and Lime Comparison**

### 3.3 Packing Triangle - Fixed Binder Effect

A number of authors have investigated the properties of fillers/mastics over the years with the concept of fixed binder being now well recognised. For example Heukelom was able, to a certain extent, unify the effect of fillers through his concept of 'Effective Volume'. Essentially Effective Volume is the filler volume together with its fixed binder volume with the fixed binder represented by the relevant Rigden Voids. VSP effectively is VMA minus the fixed binder volume (Rigden Voids). The work by

Heukelom has been further investigated in an attempt to relate it to the Packing Triangle concept.

The Heukelom (1965) unifying relationship was stated as:

$$VSP = VMA - \alpha Eff.Volume \tag{4}$$

where α is the slope of the linear relationship and (1-α) is interpreted as a dilation factor.

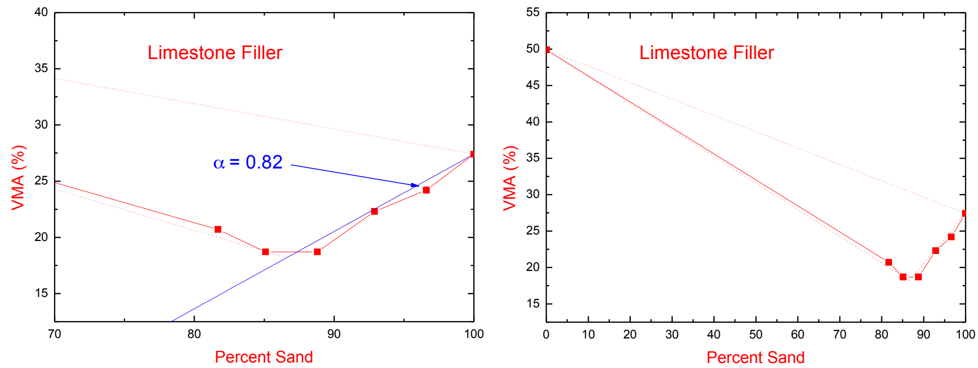



**Figure 10. Close up and full view of Limestone filler packing triangle**

An analysis of the VSP/Effective Volume 'Heukelom' unification view suggests that filler together with its fixed bitumen act as uniform monotonic spheres to fill the void space. Using the information contained in powder technology monotonic spheres are only able to fill approximately 65% of the volume and explains the Heukelom relationship. Working through the mathematics shows that the VMA associated with a filler/mix combination equates to VMA – $V_F$ + $35V_F/(100-V_R)$. This shows that when a volume of filler ($V_F$) is added, it fills the void space by this volume (VF) but is balanced by an additional space associated with the void space created by the packing of monotonic spheres ($35V_F/(100-V_R)$). This can be thought of as a dilation term attributed to electrostatic and other surface energy forces as described by Hefer et al (2005) or an alternative view is that the filler plus fixed binder forms a new particle which has a new packing regime.

The VMA relationship has been found to provide the best method to determine the dilation component 1-α, by plotting VMA with a chosen α until a close fit is obtained. The dilation point coordinates are then obtained through a spreadsheet process. An example of the fit together with the associated dilation coordinate is shown in Figure 10. The VMA for the zero percent sand or 100% filler is obtained by adding the dilation percentage to a reduced percentage of the Rigden voids as follows:

$$100(1-\alpha)+\alpha v_R \tag{5}$$

# 4. EXPERIMENTAL DATA

## 4.1 Survey of Local Aggregates

As resilient modulus was favoured as the design tool at the time its change with filler was looked at in terms local materials. Filler contents chosen were 8, 10 and 12%. The particle size distribution of the coarse aggregates used, ie, 10-5 and 7-2

Linwood, 10-5 and 7-2 Riverview, and 10-7 and 7-5 Lobethal aggregates are shown in Table 2. The equivalent size diameter ($ESD_E$) of the aggregate has been determined by estimating the sieve size equivalent to the position at which 35% of the material would pass. The $ESD_E$s are shown at the bottom of the table.

The same ingredient factors as a blended sand, bag house fines plus 2% hydrated lime, 0.3% Arbocell fibres and 6.5% Class 320 bitumen were used to combine with the coarse aggregates to provide the asphalt mixture. The particle size distribution of the blended sand and the associated $ESD_E$ is as shown in Table 3.

**TABLE 2: Coarse Aggregate PSDs**

| Sieve Size (mm) | Linwood 10-5 | Linwood 7-2 | Riverview 10-5 | Riverview 7-2 | Lobethal 10-7 | Lobethal 7-5 |
|---|---|---|---|---|---|---|
| | Percent Passing | | | | | |
| **13.2** | 100 | | 100 | | 100 | |
| **9.5** | 90 | 100 | 67 | 100 | 83 | 100 |
| **6.7** | 19 | 95 | 9 | 81 | 6 | 78 |
| **4.75** | 3 | 37 | 1.5 | 28 | 0.5 | 12 |
| **2.36** | 0.4 | 0.8 | 0.9 | 1.3 | 0.3 | 0.5 |
| **1.18** | 0.3 | 0.5 | 0.9 | 1.1 | 0.3 | 0.5 |
| **0.6** | 0.3 | 0.5 | 0.9 | 1.0 | 0.3 | 0.5 |
| **0.3** | 0.3 | 0.5 | 0.9 | 1.0 | 0.3 | 0.5 |
| **0.15** | 0.3 | 0.5 | 0.8 | 1.0 | 0.3 | 0.5 |
| **0.075** | 0.3 | 0.5 | 0.7 | 0.9 | 0.3 | 0.5 |
| **$ESD_E$** | 8.1 | 4.6 | 8.9 | 5.8 | 9.4 | 5.9 |

**TABLE 3: Fine Aggregate PSDs**

| Sieve Size (mm) | Blended Sand |
|---|---|
| | Percent Passing |
| **6.7** | 100 |
| **4.75** | 100 |
| **2.36** | 68 |
| **1.18** | 53 |
| **0.6** | 41 |
| **0.3** | 26 |
| **0.15** | 10 |
| **0.075** | 4.6 |
| **$ESD_E$** | 0.8 |

This sand was scalped on the 4.75mm sieve before being combined with the aggregates to provide the 8, 10 and 12% filler content (the baghouse fines percentage was adjusted to provide the variation). At each filler content, in order to assess the change in material passing at the 'hinge point', the coarse grading was also adjusted to give 35, 30 or 25% passing the 4.75mm sieve. The size ratios for the mixes based on the $ESD_E$ of the fine aggregate and the appropriate coarse aggregate are as shown in Table 4.

**TABLE 4: Size Ratios**

| % Filler | Linwood 10-5 | Linwood 7-2 | Riverview 10-5 | Riverview 7-2 | Lobethal 10-5 | Lobethal 7-2 |
|---|---|---|---|---|---|---|
| 8 -12 | 0.099 | 0.174 | 0.09 | 0.138 | 0.085 | 0.136 |

The packing triangle plots below reflect single data points with compactions only repeated if a data point appeared to be 'out of step' and were all carried out in the dry state as other work has shown the lubricating effect of binder to be minimal. The two aggregates were simply mixed in a bowl until they look homogeneous.

Figure 11 shows the combination of Linwood 10-5 and Linwood 7-2 coarse aggregate material with the fine aggregate for varying percentages of total filler. The packing triangle and the locus of the minimum void position determined from Lees charts are also provided in Figure 11. The Linwood 10-5 data appears to match the Lees minimum position reasonably well whereas the Linwood 7-2 appears to be a little indeterminate in that the minimum position has not been reached but even so the position would probably be in slightly in excess of Lees size ratio 0.2 location.

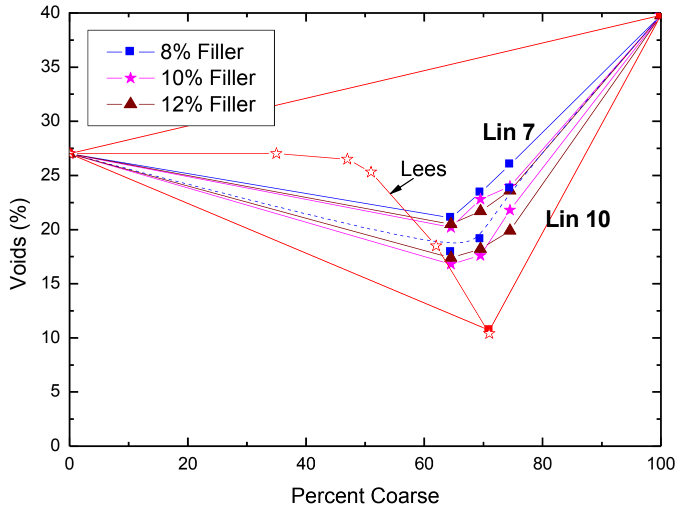



**Figure 11. Packing Triangle for Linwood Material**

Figure 12 shows the combination of Lobethal 10-5 and Lobethal 7-2 coarse aggregate material with the fine aggregate for varying percentages of total filler. The packing triangle and the locus of the minimum void position determined from Lees charts are also provided in Figure 12. Both the Lobethal 10-5 and the Lobethal 7-2 data appears to match the Lees minimum position reasonably well.

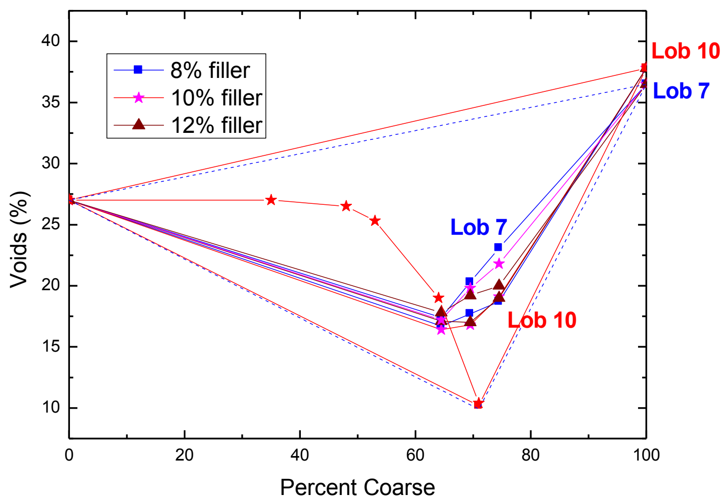



**Figure 12. Packing Triangle for Lobethal Material**

Figure 13 shows the combination of Riverview 10-5 and Riverview 7-2 coarse aggregate material with the fine aggregate for varying percentages of total filler. The packing triangle and the locus of the minimum void position determined from Lees charts are also provided in Figure 13. Both the Riverview 10-5 and the Riverview 7-2 data appears to match the Lees minimum position reasonably well.

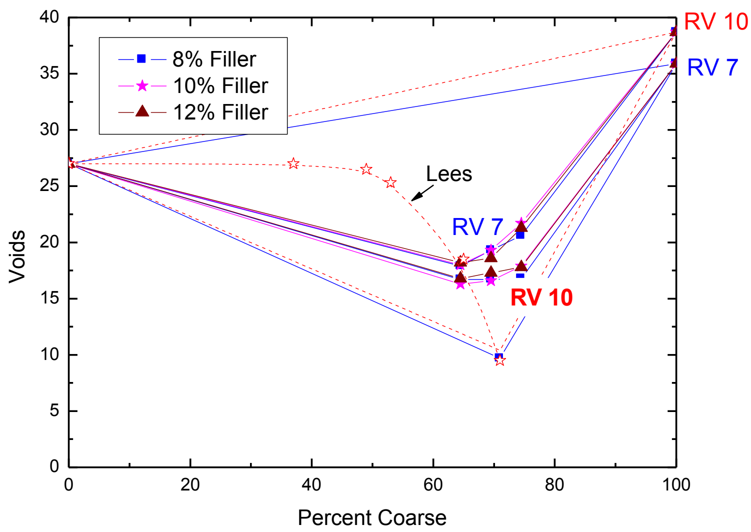



**Figure 13. Packing Triangle for Riverview Material**

The raw materials, excluding the bitumen and fibres, were compacted by the IPC Servopac gyratory compactor to 80 cycles where the final height was recorded so that the mensuration density could be calculated. Two percent binder was included with the coarse aggregates to mimic lubrication effects of the binder in the final compacted mix. The voids in the compacted aggregate (VCA) was calculated from these measurements.

Loose and rodded bulk densities (AS 1141.4) were also performed on the coarse aggregates to compare these values to the VCAs of the coarse aggregates. The density values are shown in Table 5 together with the Bulk Density (AS 1141.6).

**TABLE 5: Coarse Aggregate Densities**

| Densities ($t/m^3$) | Linwood 10-5 | Linwood 7-2 | Riverview 10-5 | Riverview 7-2 | Lobethal 10-5 | Lobethal 7-2 |
|---|---|---|---|---|---|---|
| **Bulk Density** | 2.690 | 2.690 | 2.737 | 2.737 | 2.700 | 2.700 |
| **Loose** | 1.342 | 1.326 | 1.378 | 1.440 | 1.404 | 1.381 |
| **Rodded** | 1.484 | 1.481 | 1.595 | 1.529 | 1.550 | 1.514 |

The comparison of VCAs for the coarse aggregates is shown in Table 6. A further sampling exercise was carried out a substantial time later and the VCAs recalculated providing a second set of comparison data. This set is also shown in the Table 6 and both sets have been compared graphically as shown in Figure 14. There appears to be a linear relationship between the Servopac gyratory compaction, with the approximate relationship being that rodded and loose densities result in 5% and 10% more voids than when compared to the Servopac for the 80 and 30 cycles gyration compaction respectively.

**TABLE 6: Voids in Coarse Aggregates (VCA)**

| VCA (%) | Linwood 10-5 | Linwood 7-2 | Riverview 10-5 | Riverview 7-2 | Lobethal 10-5 | Lobethal 7-2 |
|---|---|---|---|---|---|---|
| **Loose** | 50.1 | 50.7 | 47.4 | 49.7 | 48.0 | 48.9 |
| **Rodded** | 44.8 | 44.9 | 41.7 | 44.1 | 42.6 | 43.9 |
| **30 cycle** | 40.2 | 40.7 | 39.2 | 38.7 | 39.4 | 37.8 |
| **80 cycle** | 38.7 | 38.7 | 35.9 | 35.3 | 37.8 | 35.6 |
| **Loose** | 39.9 | 40.7 | 36.6 | 39.4 | 37.4 | 38.4 |
| **Rodded** | 33.5 | 33.6 | 29.8 | 32.7 | 30.8 | 32.4 |
| **30 cycle** | 30.5 | 31.0 | 29.3 | 28.7 | 29.5 | 27.7 |
| **80 cycle** | 28.7 | 28.6 | 25.4 | 24.8 | 27.7 | 25.1 |

**TABLE 7: Modulus(Voids) – Mpa (%)**

| % filler & % 4.75 | | Linwood 10-5 | Linwood 7-2 | Riverview 10-5 | Riverview 7-2 | Lobethal 10-5 | Lobethal 7-2 |
|---|---|---|---|---|---|---|---|
| | **35** | 2645(2.7) | 1975(6.3) | 4057(0.7) | 2670(2.2) | 3216(1.0) | 3357(1.9) |
| **8%** | **30** | 2415(4.1) | 2034(9.0) | 3607(0.7) | 2384(3.8) | 2348(2.2) | 2629(5.3) |
| | **25** | 1672(9.1) | 1966(12.1) | 4315(0.8) | 2345(5.4) | 2508(3.4) | 2038(8.6) |
| | **35** | 3431(1.4) | 2536(5.2) | 3761(0.2) | 2638(2.2) | 2738 (0.7) | 2802(1.6) |
| **10%** | **30** | 3030(2.3) | 2374(7.5) | 4001(0.6) | 2405(3.9) | 2742(1.2) | 2477(4.7) |
| | **25** | 1978(7.3) | 2167(9.7) | 3134(2.2) | 2503(6.6) | 2909(3.9) | 2121(7.1) |
| | **35** | 3283(2.1) | 2258(5.5) | 4004(0.8) | 2589(2.5) | 2698(1.4) | 3191(2.4) |
| **12%** | **30** | 3344(3.1) | 2229(7.0) | 4043(1.5) | 2478(3.0) | 2516(1.4) | 2038(4.0) |
| | **25** | 2470(5.1) | 2342(9.2) | 2955(2.0) | 2571(6.2) | 2516(3.8) | 2068(4.9) |

The dilation position estimated by resilient modulus as advocated by Stephenson (Austroads, 2007) was also examined using the available experimental data for the Linwood, Lobethal and Riverview coarse aggregates. The resilient modulus determined to AS 1289.13.1 together with the mix pat voids are shown in Table 7.

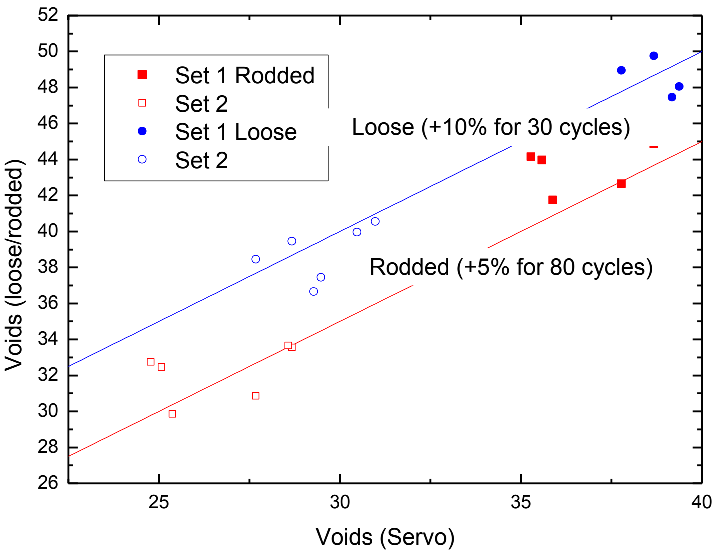



**Figure 14. VCA Coarse Aggregate Comparisons**

A plot of the resilient modulus against the associated voids for each filler percentage, as in Figure 15, indicates that there is no distinguishable difference between the data sets and that the main influence on modulus is the percentage voids (rather than any precise relationship to filler percentage).

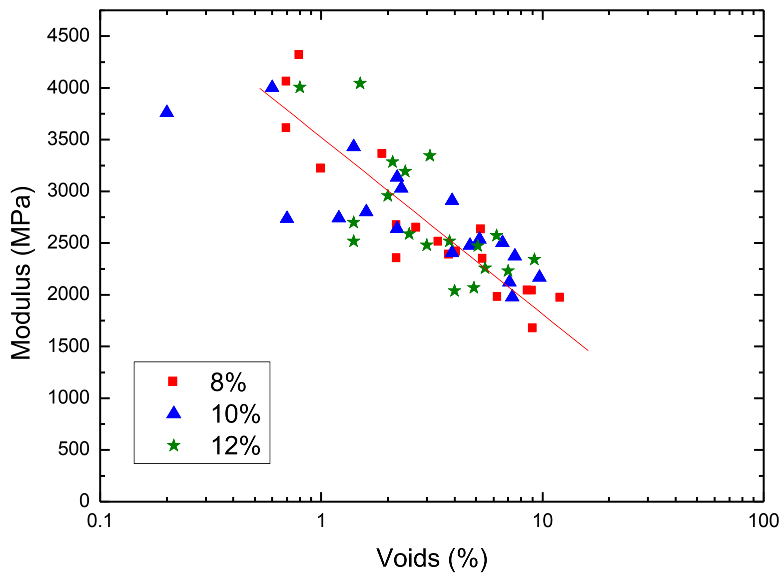



**Figure 15. Effect of Voids/Filler on Modulus**

As distinct from previously experienced behaviour for dense mixes, however, the relationship of modulus with increasing voids appears not to terminate at zero at 21% voids (Austroads Pavement Design Guide, 2004) but appears to terminate at 100% voids. A reason suggested for this phenomenon is that previous relationships would have been based on varying compaction whereas this data set is based on the same compactive effort. It is therefore assumed that a percentage reduction in the adhesive bonds in the mixes is producing a percentage reduction in modulus.

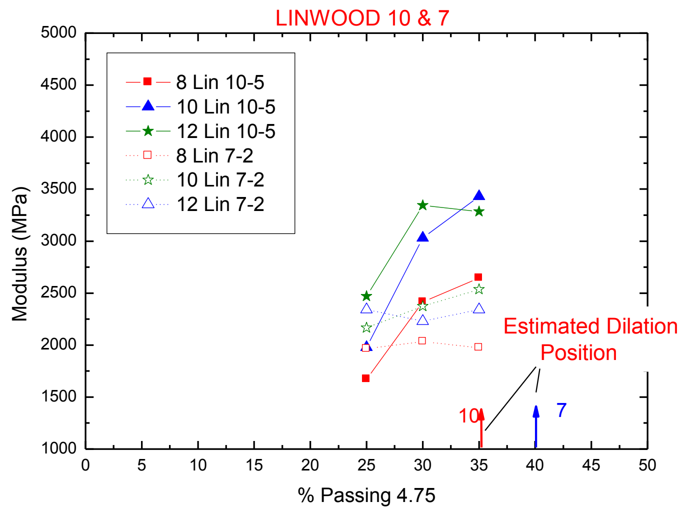



**Figure 16. Linwood 10-7 and 7-2 Modulus Change with Percent Passing 4.75**

Figure 16 shows the combination of Linwood 10-5 and Linwood 7-2 coarse aggregate material with the fine aggregate for varying percentages of total filler. The Linwood 10-5 data appears to be increasing for increasing percentage passing the 4.75 mm but the 7-2 Linwood material appears to have generally a flat response. The dilation positions derived from the packing triangle approach are also shown on

Figure 16 but more data at higher percentages passing 4.75 would be required to ascertain any positive conclusions. It is doubtful, however, that the definite point indicated in the Stephenson graph A23 (Austroads, 2007) would be attained.

Figure 17 shows the combination of Lobethal 10-5 and Lobethal 7-2 coarse aggregate material with the fine aggregate for varying percentages of total filler. As compared to the Linwood material the data here is a lot less regular. Once again, it is doubtful whether the definite point indicated in the Stephenson graph A23 (Austroads, 2007) would be attained.

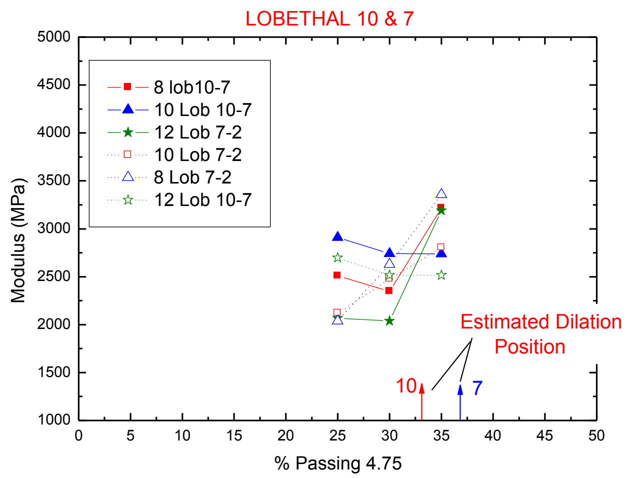



**Figure 17. Lobethal 10-7 and 7-2 Modulus Change with Percent Passing 4.75**

Figure 18 shows the combination of Riverview 10-5 and Riverview 7-2 coarse aggregate material with the fine aggregate for varying percentages of total filler. The Riverview 10-5 data is variable for increasing percentage passing the 4.75 mm but the 7-2 Riverview material appears to have generally a flat response.

The dilation positions derived from the packing triangle approach are also shown on Figure 18 but more data at higher percentages passing 4.75 would be required to ascertain any positive conclusions. It is doubtful that the definite point indicated in the Stephenson graph A23 (Austroads, 2007) would be attained.

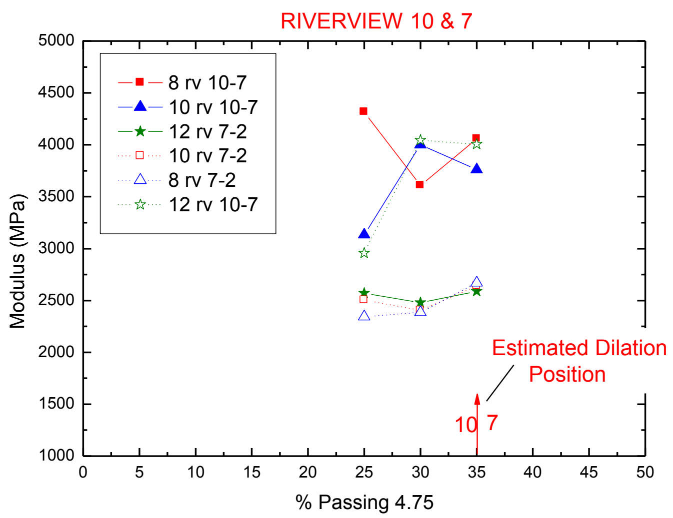



**Figure 18. Riverview 10-7 and 7-2 Modulus Change with Percent Passing 4.75**

## 4.2 SMA7 DESIGN EXPERIMENTS

A number of experiments were carried out on varying percentage blends of aggregates prior to settling on a mix design for field trial purposes. An asphalt coarse aggregate (Linwood 7-2) and a spray sealing aggregate (Linwood 7-5) as shown in Table 8 were used as the coarse aggregates. Linwood Quarry sand and Stoneyfell pit sand were used as the fine aggregates with flyash being the filler component.

**TABLE 8: Coarse & Fine Aggregates**

| Sieve Size (mm) | Linwood 7-5 | Linwood 7-2 | Linwood Quarry Sand | Stoneyfell Pit Sand |
|---|---|---|---|---|
| | Percent Passing | | | |
| **9.5** | 100 | 100 | | |
| **6.7** | 86 | 95 | | |
| **4.75** | 15 | 37 | 100 | 100 |
| **2.36** | 0.5 | 0.8 | 96 | 98 |
| **1.18** | 0.5 | 0.5 | 62 | 85 |
| **0.6** | 0.5 | 0.5 | 41 | 62 |
| **0.3** | 0.5 | 0.5 | 30 | 32 |
| **0.15** | 0.4 | 0.5 | 23 | 12 |
| **0.075** | 0.4 | 0.5 | 18.8 | 2.4 |
| **$ESD_E$** | 5.7 | 5.06 | 0.44 | 0.25 |

While there has been strong promotion from Europe on the concept of a 'true SMA' where a single size aggregate such as used in spray sealing is used as the coarse aggregate there is also a strong desire of the asphalt companies (and quarry companies to avoid excess waste material) to use the more graded asphalt coarse aggregates. The packing performance of the Linwood 7-2 and 7-5 have therefore being comparatively examined as shown in Figure 19 by combining these with the Linwood Quarry and Stoneyfell pit sands.

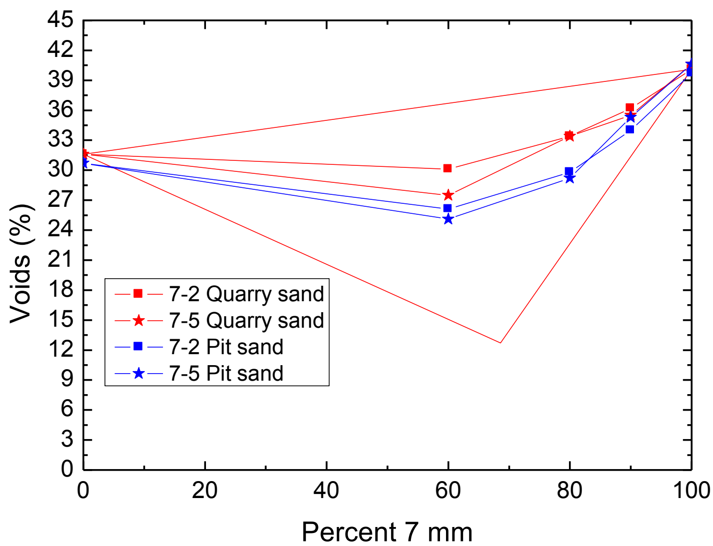



**Figure 19. Comparison between 7-5 and 7-2 Aggregates**

It can be seen that there appears to be only a little difference between the Linwood 7-5 and 7-2 when combined with the sands. The biggest difference is between the quarry and pit sands and this probably a reflection of the $ESD_E$ difference between the two resulting different size ratios.

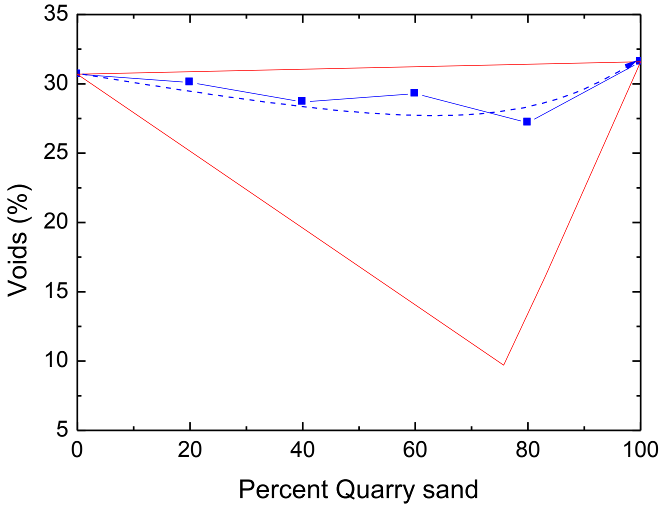



**Figure 20. Quarry and Pit Sand Combination**

The packing characteristics of the sand combination was also looked at and is shown in Figure 20. As there is a high size ratio between the two (0.7) there is little packing and a wide choice of combination ratio is therefore available. Of course 100% of either component is not advisable owing to the high rutting potential (100% pit sand) or difficult compaction (100% quarry sand) aspects. The sands were combined as two parts quarry to one part pit in further experimental work.

Figure 21 shows the packing characteristics of using the two coarse aggregates when the quarry and pit sand are combined in a two to one ratio and used as the fine aggregate. The size ratio of approximately 0.19 of these combinations is reflected in the shallow shape to the packing curves. While this indicates a dilation 'plateau' rather than an actual point, the safe position appears to be in excess of 50% coarse aggregate. The other factor to consider is the quantity of voids required to provide sufficient space to take the other components of the SMA7 mix, ie, fibre, binder and filler. A good balance is also required between the percentage of free and fixed binder.

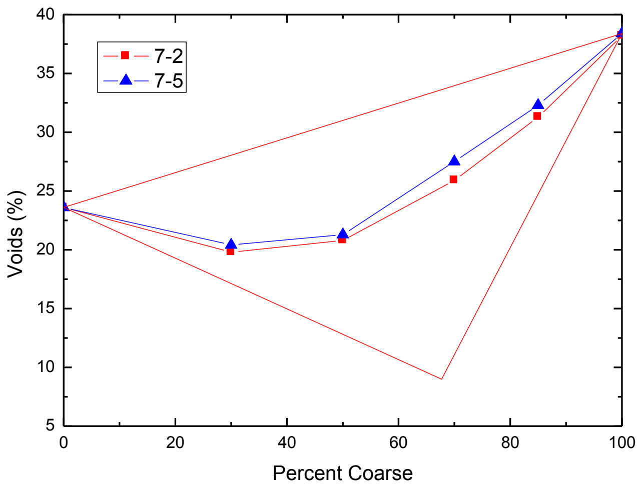



**Figure 21. Packing Characteristics Using the Sand Blend**

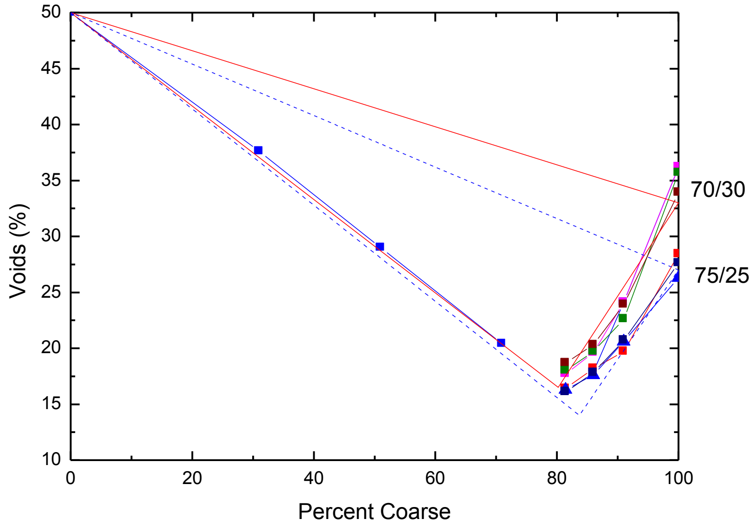



**Figure 22. SMA7 Mix Variations**

Figure 22 shows the packing triangles (filler in the dry state) of two mixes prepared with the 7-5 Linwood aggregate and differing by two percentages of the blended sands. Each of these had varying percentages of filler as shown. As filler to aggregate size ratio is very small it is no surprise to see the plots match fairly closely to the zero size ratio lines.

## 4.3 TRIAL MIXES

Following the experimental work and the desire at that time from project personnel for an SMA7 mix, two trials of SMA7 proceeded. The first used the 7mm asphalt aggregate (7-2) with a mix approval number SMA7M35PL-PM1-T308 and the second used a 7mm spray seal aggregate (7-5) with mix approval number SMA7M35PL-PM1-T332. The mixes used White Rock Quarry sand, Stoneyfell pit sand, 1% hydrated lime, baghouse fines, 0.3% Arbocell cellulose fibres and 6.7% A35P (EVA) modified binder as common components. The component particle size distributions are shown in Table 9. While flyash was used in the experimental work the asphalt company opted to use baghouse fines as additional filler in this instance.

The combined aggregate grading for these mix designs are shown in Table 10 and compared against the recent revision of AS2150 SMA7 specification in Figure 23.

**TABLE 9: Trial Mix Component Gradings**

| Sieve Size (mm) | Linwood 7-5 | Linwood 7-2 | White Rock Quarry Sand | Stoneyfell Pit Sand |
|---|---|---|---|---|
| | Percent Passing | | | |
| **9.5** | 100 | 100 | | |
| **6.7** | 86 | 97 | 100 | 100 |
| **4.75** | 15 | 46 | 99 | 99 |
| **2.36** | 0.5 | 1.0 | 96 | 89 |
| **1.18** | 0.5 | 0.7 | 63 | 75 |
| **0.6** | 0.5 | 0.5 | 42 | 57 |
| **0.3** | 0.5 | 0.4 | 30 | 31 |
| **0.15** | 0.4 | 0.3 | 22 | 6 |
| **0.075** | 0.4 | 0.3 | 16 | 2 |
| **$ESD_E$** | 5.7 | 4.1 | 0.44 | 1.03 |

Examination of the two mix designs as against the AS2150 envelope indicates that the envelope can encompass both types of coarse aggregate with a natural hinge point moving from 4.75mm for the coarse spray seal aggregate to 2.36mm for the asphalt aggregate.

**TABLE 10: Approved Trial Mix Gradings**

| Sieve Size (mm) | T308 (7-2) | T332 (7-5) |
|---|---|---|
| | Percent Passing | |
| **9.5** | 100 | 100 |
| **6.7** | 96 | 90 |
| **4.75** | 58 | 40 |
| **2.36** | 30 | 29 |
| **1.18** | 25 | 22 |
| **0.6** | 19 | 18 |
| **0.3** | 15 | 14 |
| **0.15** | 12 | 10 |
| **0.075** | 9.4 | 8.2 |

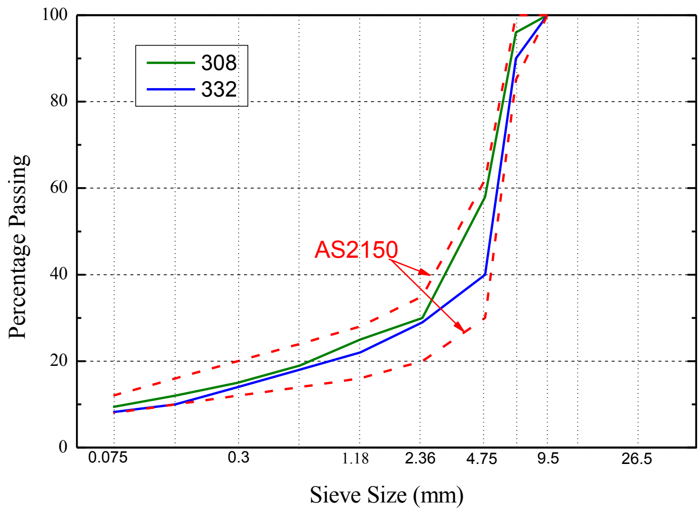



**Figure 23. Comparison of Trial Mixes to AS2150**

Production data for both mixes is compared to the mix designs in Table 11 and shows that a good replication of the design occurred in both cases.

**TABLE 11: Trial Mix Production Data**

| Sieve Size (mm) | T308 | Difference From design | T332 | Difference From design |
|---|---|---|---|---|
| | Percent Passing | | | |
| **9.5** | 100 | 0 | 100 | 0 |
| **6.7** | 97 | +1 | 96 | +6 |
| **4.75** | 60 | +2 | 42 | +2 |
| **2.36** | 30 | 0 | 30 | +1 |
| **1.18** | 24 | -1 | 23 | +1 |
| **0.6** | 18 | -1 | 18 | 0 |
| **0.3** | 15 | 0 | 14 | 0 |
| **0.15** | 11 | -1 | 11 | +1 |
| **0.075** | 9.2 | -0.2 | 8.6 | +0.4 |
| **bc (%)** | 6.62 | -0.08 | 6.65 | -0.05 |
| **voids (%)** | 4.1 | -0.4 | 4.1 | -0.4 |

# 5. MIX DESIGN APPROACH

## 5.1 Schematic

The proposed mix design approach or procedure is schematically indicated in the flow diagram of Figure 24. The normal mix design elements of material quality and selection are assumed as given and would match most material specifications for SMA as they stand at the present. An addition is the calculation of the $ESD_E$s of the raw aggregate materials so that an equivalent size ratio can be determined and the compaction of the aggregates in their dry state at 80 gyratory cycles.

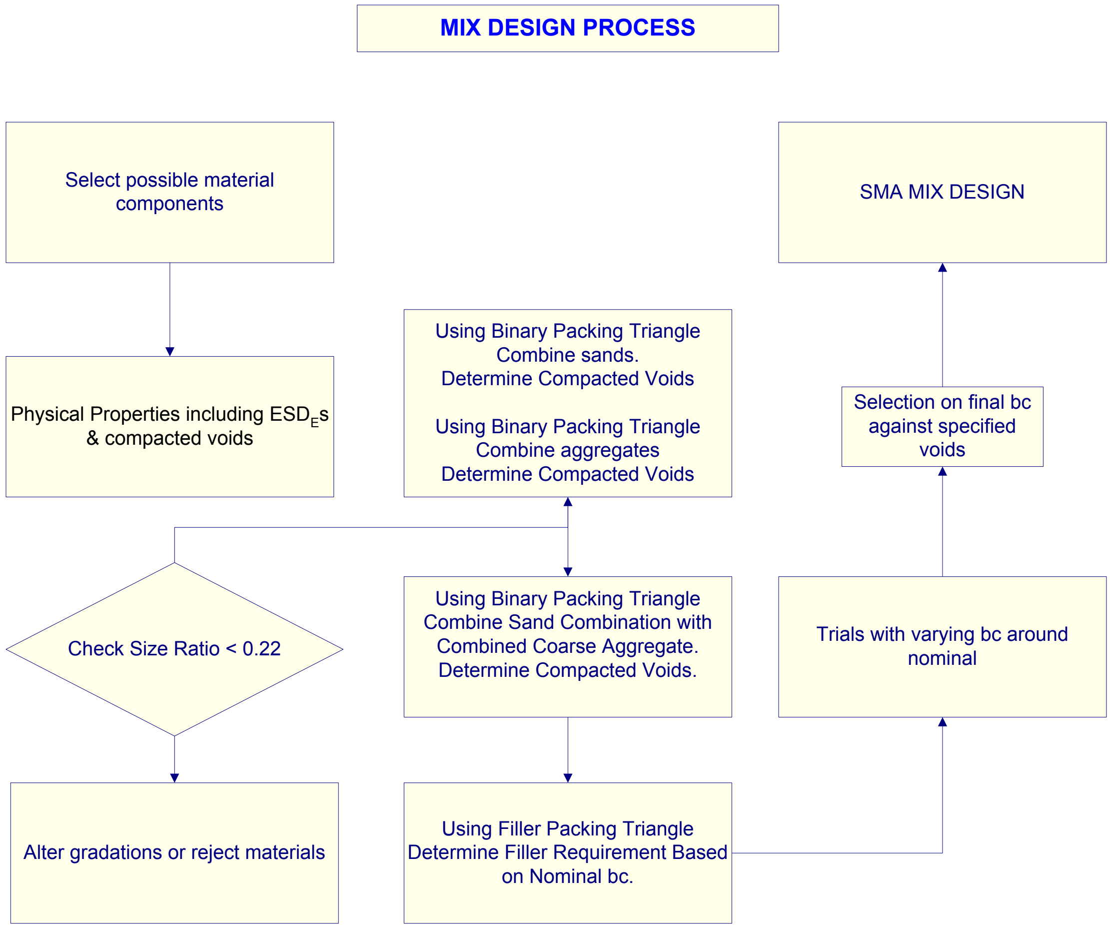



**Figure 24. SMA Mix Design Flow Chart**

As stated, the high size ratio involved with blending sands indicates that a combination is one more of convenience rather than a functional requirement.

Construction of the Binary Packing Triangle when combining the blended sand with the coarse aggregate gives a good pointer to the position of the dilation point. Lees charts using his required input data, enable a locus of the position of minimum voids from the theoretical zero size ratio to one to be constructed if additional guidance to selecting the percent combination is required. A safety margin of 5% away from the dilation point is recommended to overcome production variation issues.

Construction of the Filler Packing Triangle enables the percent filler to be selected based on having sufficient voids or space remaining to give the final mix air voids, space for fibre and volume of binder. If there is sufficient free binder then the final job mix formula can be determined by the normal exercise of varying the binder content around the nominal used in the preliminary volumetric design exercise and measuring voids.

A mix design spreadsheet as shown in Figure 25 can be created so that some of the more complex calculations can be automated.

If the free binder is insufficient the coarse aggregate/sand combination would need to be modified accordingly and this part of the exercise repeated.

| | | | | | | SMA Design | | |
|---|---|---|---|---|---|---|---|---|
| | x | y | | x | y | | x | y |
| | | | | | | alpha | 0.62 | |
| Washed S | 0 | 35.8 | Comb'n Sand 60/40 | 0 | 28.8 | Filler | 0 | 47.5 |
| Quarry Sa | 100 | 30 | Coarse Ag | 100 | 41 | Comb'n Agg/Sand 76/24 | 100 | 32.2 |
| PT Co-ord | 78.42259 | 10.74 | PT Co-ord | 66.89949 | 11.808 | PT Co-ord | 87.75 | 28.81667 |
| | 0 | 35.8 | | 0 | 28.8 | | 0 | 67.45 |
| Inter Pt1 | 40 | 29.7 | Inter Pt1 | 20 | 26 | Inter Pt1 | 88 | 28.8 |
| Inter Pt 2 | 60 | 28.8 | Inter Pt 2 | 40 | 25.2 | Inter Pt 2 | 90 | 29.2 |
| Inter Pt3 | 80 | 29 | Inter Pt3 | 60 | 25.4 | Inter Pt3 | 92 | 30.2 |
| | 100 | 30 | | 83 | 32.2 | | 100 | 32.2 |
| | 100 | 30 | | 100 | 41 | | 100 | 32.2 |

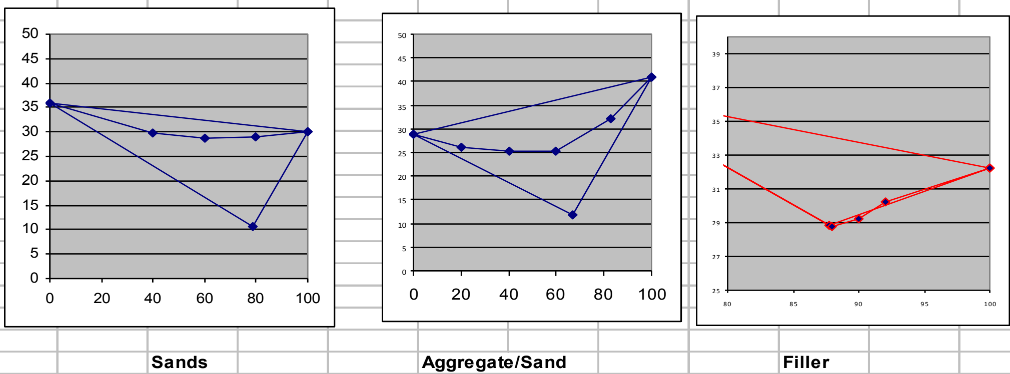



**Figure 25 Mix Design Packing Triangle Spreadsheet**

Level 2&3 checks on performance properties may be required depending on importance of mix application.

## 5.2 STEP BY STEP APPROACH

**Basic component stage**

Determine the estimated Equivalent Spherical Diameters ESDEs. (ESDE is estimated from the particle size distribution of the component at the theoretical sieve size where 35% of the material would be expected to pass.)

The filler component should be separated from the sands

Compact the sands (less filler component) to 80 cycles in the Gyropac machine and determine the mensuration voids referred to here as Packing Triangle Voids (PTV). The SSD Bulk Density of the sand/s will be required in this calculation.

Compact the coarse aggregates to 80 cycles in the Gyropac machine and determine the PTV. The SSD Bulk Density of the aggregate/s will be required in this calculation.

Determine the Rigden voids (again PTV) of the separated filler together with any proposed added filler.

As these PTV determinations govern the remaining procedures they should be the average of two determinations to form the basic Packing Triangle coordinates. Any compactions leading to internal Packing Triangle data points need only be individual results and only be repeated if any 'out of step' behaviour is shown

**<u>Two component combination stage</u>**

**Base understanding:**

1) The minimum voids (Vmin) co-ordinate for a two component combination is

$$\frac{100 - V_C}{1 - \frac{V_F V_C}{100^2}}, \frac{V_F V_C}{100} \qquad (6)$$

where VC is the PTV for the coarse component and VF is the PTV for the fine component.

2) Size ratio here is defined as the ratio of the two estimated Equivalent Spherical Diameters (ESDE) of the component materials.

3) The Packing Triangle is formed by the component PTVs and the Vmin.

**Sand combination**

Determine Vmin component for the two sands and create the packing triangle. Determine intermediate Packing Triangle Voids (PTVs) for the sand combinations of 40/60, 60/40 and 80/20 where the first part of the combination is the fine percentage. Plot the PTVs on the Packing Triangle. Select the combined ratio and estimate the combined sand PTV from the plot.

Combined the fillers separated from the sands in the same ratio as determined from the sand combination and determine the rigden voids so that the new PTV for the combined filler is known.

Aggregate Combination

When two or more coarse aggregates are to be used the combined aggregate PTV should be determined before combining with the sand combination and should follow the binary combination procedure as outlined in the sand combination phase.

**Aggregate/Sand Combination**

Check that the size ratio of the aggregate and sand/s components are less than 0.22. Use the combined sand PTV as the fine PTV to use when combining with the coarse aggregate. Calculate the Vmin co-ordinate and create the aggregate/sand Packing Triangle. Determine intermediate PTVs for the combinations of 60/40, 80/20 and 90/10 combination. Plot the PTVs on the Packing Triangle. Select a ratio from the plot such that the combined PTV has sufficient volume space for binder, filler, voids and fibre.

**Filler aspect**

**Base understanding:**

(1) When binder is mixed with filler a quantity of binder fixes itself to the filler and filler packing estimates therefore need to be carried out in association with a binder. The fixed binder quantity has been assumed to equal the Rigden Voids value for the filler.

(2) The filler and fixed binder appear to form a new particle that has its own packing associated with it and this dilates the previous Rigden Voids packing of the filler. As this packing may vary between various materials it is necessary to estimate the quantity of dilation by preparing three mixes at different filler percentages.

The volume of filler Volf associated with the point of dilation for the sand aggregate combination is estimated from:

$$\frac{PTV_C(100-\nu_R)}{100(2-\alpha)} \tag{7}$$

where α is a the dilation factor for the filler when fixed binder is present and vR is the Rigden voids for the filler.

The PTVF for the filler becomes $100(1-\alpha)+\alpha\nu_R$ to allow for the dilation in the filler.

The minimum coordinate point for the Packing Triangle is 100-VOLf for the x coordinate and $PTV_C\left[1-\frac{100\alpha-\nu_R}{100(2-\alpha)}\right]$ for the y coordinate.

(3) Filler Bulk Density tend to vary significantly and all packing estimates should be carried out on a volume rather than a weight basis.

When the percentage filler Pfill, the percentage binder content Pb and bulk density ρbulk together with the filler Bulk Density ρfill are known, the percentage filler by volume would be:

$$\frac{P_{fill}\,\rho_{bulk}(100-P_b)}{100\rho_{fill}} \tag{8}$$

The resultant from the aggregate /sand packing combination represents the coarse PTVC for combination with the filler/s. Initially use 0.8 as an estimate for the filler dilation factor and calculate the estimated volume of filler that would be the dilation point for the aggregate/sand filler combination. Step back from this point by 1% and prepare three mixes with 6% nominal C320 binder using this combination and two others at 2% by volume of filler in increments less than the first point. Fibre may be needed to be added to prevent drainage. (Note: A 6% nominal value of binder is very close to the midpoint values of the Queensland specification (DMR, 2009) of 0.45 for fixed binder ratio and 8% free binder for many mixes.)

The VMAs of the mixes need to be determined and plotted against the volume percentage of aggregate. The dilation factor α is then determined by fitting the line equation to the data:

$$VMA = PTV_C - \left(100 - V_f\right) + \frac{100(1-\alpha)}{\left(100 - \nu_R\right)}\left(100 - V_f\right) \qquad (9)$$

On a settled value of the dilation factor α the aggregate/sand filler dilation coordinate point can be fixed and the packing triangle created. On selection of a safe filler volume refinement of the binder content can be achieved by further mixes at varying binder content.

The volume of both the free and fixed binder are important in the mix behaviour in that too much fixed binder can produce a 'dry' mix severely affecting mix performance. Too little free binder has a similar affect.

The volume of fixed binder is equivalent to the filler volume times

$$\frac{\nu_R}{\left(100 - \nu_R\right)}. \qquad (10)$$

TMR Q'ld in their latest specification for SMA have the following limits in place for these aspects:

Free binder volume should be between 7 and 9.5% of the mix and fixed binder should be between 35 and 55% of the total binder.

## 6. DISCUSSION

SMA is defined as a coarse gap graded asphalt mix. Grading envelopes reflecting this definition and void criteria have attempted to control the long term behaviour (recipe design) but a number of authorities have experienced difficulties with either supply of aggregates or with field problems resulting in a multiplicity of criteria (mainly with grading envelopes).

The aim of a mix design is firstly to give structural strength and then to guard against mix distress. With SMA, fatigue is guarded against by a larger volume of binder, mix stability is assumed to be achieved by designing on the correct side of any dilation points (stone on stone contact) and moisture damage by adopting a suitable void criteria.

Rational design to date has been related to identifying the dilation point or region with the aggregate combinations. The current recommended approach has a vagueness or poor identification of the dilation point and the associated relatively complicated procedure has seen little adoption of it.

The packing of two components has been researched by a number of authors in the concrete, asphalt and powder technology area. Adopting the concepts from this research allows the creation of a triangle within which all possible compaction scenarios occur. This is referred to here as the Packing Triangle. In a voids/volume plane a zero (first triangle coordinate) to one hundred percent (second triangle coordinate) volume combination of a component lies the maximum compaction position (third triangle coordinate) for a theoretical zero size ratio combination. This coordinate is determined from the other two coordinates and allows judgements to be made on the dilation positions of compaction scenarios within the triangle, i.e. real size ratios.

Most of research work on binary combinations has been carried out on single sieve size components, with Lees producing combination charts for different size ratios when using asphalt aggregates. Using Lees charts and his procedures with a graded aggregate tends to produce data not consistent with practice and to take advantage of the Lees charts an equivalent size (size equivalent to 35% passing) for a graded aggregate has been devised here so that an equivalent size ratio can be determined.

By examination of the experimental data of Heukelom and Ishai et al (1980) in their investigations into fillers the concept of Fixed Binder was seen as a significant factor in compaction behaviour. It would appear filler 'fixes' binder to it and it is assumed here that a new spherical like particle is formed and the compaction of monotonic or substantially monotonic spheres also appears to control the compaction of the mix. By using the associated relationships a Packing Triangle is still able to be formed and was incorporated into a proposed mix design procedure.

The literature on free and fixed binder and their relationship to performance behaviour is very small but on the evidence to date a minimum criteria of 7% free binder by volume is suggested as a criteria in mix design.

While early experimental work on fillers carried out here was in the dry state the understanding now of the nature of fixed binder and its effect on compaction has resulted in current work being carried out in association with C320 binder.

Experiments have been described showing the value of the Packing Triangle concept in identifying the dilation point and also the general compaction behaviour of aggregate combination using local aggregates.

Modulus as a tool for determining the dilation position was suggested by Stephenson. While more work needs to be carried out on performance criteria associated with a Packing Triangle approach to volumetric design, the modulus changes observed in the experimental data here appeared to be more void related than any other obvious variable.

## 7. CONCLUSIONS

A mix design flow chart reflecting a mix design procedure has been produced together with an associated spread sheet to produce any compaction data plots with the relevant Binary Packing Triangles.

Size ratio determinations either by estimation or by actual plot comparisons to Lees charts enable the correct selection of materials to enable sufficient particle interlock.

Binary Packing Triangle plots enable correct selection of proportions so mix instability is avoided.

A technical base to the understanding of the filler behaviour has also been provided around the concept of the formation of a new spherical like particle and the compaction of monotonic or substantially monotonic spheres. By using the associated relationships a Packing Triangle is still able to be formed and was incorporated into a proposed mix design procedure.

The literature on free and fixed binder and their relationship to performance behaviour is very small but on the evidence to date a minimum criteria of 7% free binder by volume is suggested as a criteria in mix design.

The value of using the Binary Packing Triangle, Lees charts and an equivalent size ratio was tested by comparison with experimental data created in investigations into an SMA7 design. Two SMA7 trials have been laid based on the experimental work carried out, one with a 7-2 asphalt aggregate and the other with a 7-5 spray seal aggregate.

## ACKNOWLEDGMENT

The authors would like to thank Mr Andrew Milazzo, Executive Director, Transport Services Division, Department for Planning, Transport, and Infrastructure (DPTI), for permission to publish this paper. The views expressed are those of the authors and not necessarily those of DPTI.

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