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VOIDS IN UNI-LAYER CHIP SEAL AGGREGATE MATS

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ABSTRACT

In the design of chip seals, the expected voids content of the aggregate mat provides an indication of the quantity of bituminous binder to apply on the base course. Over application will result in bleeding and loss of skid resistance; under application will result in insufficient aggregate embedment and weak binder-aggregate bonds in the chip seal mat. It is generally assumed, irrespective of the dimensional or shape characteristics of the component aggregates, that chip seal mats have a voids content of the order of 50% when initially laid with the aggregates in loose random orientation. This value reduces to about 30% following initial compaction and finally to 20%, after long-term traffic compaction. This study investigated the voids content in uni-layer cheap seal mats for two aggregate packing orientations; random packing and flat side packing, using a laboratory model in which aggregates were packed in shoulder-to-shoulder contact to form an aggregate mat one-stone thick. The results indicated a dependence of the initial voids content on aggregate size and packing orientation.

***Keywords*:** Aggregate mat, chip seal, random packing, flat side parking, voids content, bituminous binder content

1. INTRODUCTION

A chip seal is a non-structural bituminous surfacing in which a thin layer of bituminous binder is applied to a base course and overlain with a mat of single-size aggregates. This type of bituminous construction, which is also known as surface dressing, is meant to waterproof the pavement surface and not to provide structural strength. The aggregate mat is essential for providing protection for the binder layer from damage by vehicular tyres and for maintaining a surface texture that will ensure adequate skid resistance for vehicular movement.

Stability of the surfacing is achieved when the aggregates firmly embed in the binder layer and assume an interlocking mosaic. The depth of aggregate embedment is dependent on the quantity of binder applied, which in turn depends on the voids content estimated of the mat. When there is over application of binder, bleeding and loss of skid resistance are likely to result; under application, on the other hand, will result in insufficient aggregate embedment and weak binder-aggregate bonds in the chip seal mat. In either case, surface deterioration of one type or the other may result and reduce the performance and durability of the chip seal. Thus, the success of a chip seal design is dependent on the accurate determination of the voids space expected in the aggregate mat (Estakhri and Gonzalez, 1990).

The mode of packing of aggregates in chip seals affects the available voids space. According to Hanson (1934), when initially spread, chip seal aggregates pack in random orientation but re-orient after some initial compaction by traffic to lie on their flat side with their least dimension vertical. When the aggregates are in loose random packing orientation, the mat's voids content is believed to be of the order of 50%; this reduces to about 30% after initial rolling and finally to 20% after long-term compaction by traffic. To ensure adequate chip embedment to minimize the potential of the aggregate to be dislodged from the road surface by traffic, seals must be designed to have about 60-70% of the terminal voids space filled with binder (NAPA, 1991). This consideration dictates the rate of binder application on the base course during construction.

The mode of aggregate packing in chip seals put forward by Hanson (1934) appears to suggest that the voids content of the mat would be affected by the dimensional characteristics of the aggregates forming the mat and, therefore, the generally assumed initial mat voids content of 50%, irrespective of aggregate size and shape, appears to be contentious. Indeed, the voids content of chip seal mats and hence the binder application rate, is a subject that has engaged the attention of many researchers in the past. For example, a study by Saner and Herrin (1965) established that a curvilinear relationship exists between the percentage of voids and the aggregate size for a given shape. It also established that the voids content in chip seal layers change with changes in aggregate shape. McLeod (1969) proposed a chip seal design approach in which the amount of bituminous binder required was determined according to the type of aggregate to be used.

The TRRL (1993) method of chip seal design uses aggregate shape as a factor in the determination of the binder application rates through the shape and size parameter known as the average least dimension. Kerby (1953), and Benson and Gallaway (1953) determined the voids in a layer of chip seal aggregates by computing the percentage of voids in the loose unit weight of the aggregates and then assumed that the aggregate in the one-stone-thick layer will have the same arrangement and voids. More recently, the work by Estakhri and Gonzalez (1990) has provided a more positive direction and impetus for the estimation of chip seal voids, though, it did not explore the effect of aggregate size on voids. In this paper, the packing of aggregates in a single layer chip seal mat is modeled in the laboratory. The model is then used to estimate the voids content in uni-layer chip seal mats and to investigate the relationship between voids content and aggregate size and packing in such layers.

2. THEORY

The volume of a chip seal mat without binder in-fills may be defined in terms of the component volumes as

$$V_m = V_a + V_V \qquad (1)$$

where, V_m=volume of mat

V_a=volume of aggregates in the mat

V_v=volume of inter-granular voids in the mat

The voids content of the mat is defined as the ratio of the inter-granular voids volume to the mat volume. By definition, therefore,

$$e = \frac{V_v}{V_m} \qquad (2)$$

where, e=voids content.

By using the parameter, e, as defined by Equation 2, the relationship expressed by Equation 1 may be re-written as;

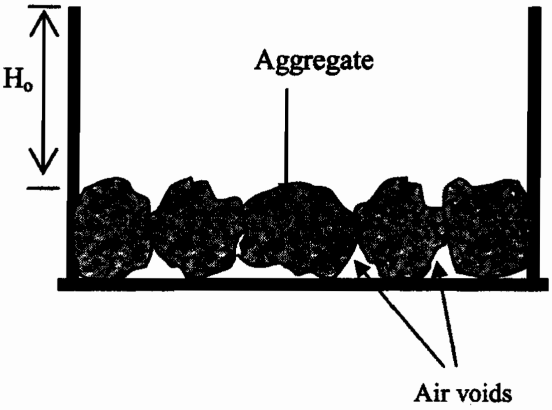
$$V_a = (1 - e)V_m \qquad (3)$$

Thus, knowing the mat and aggregate volumes, the voids content of the mat may be evaluated using Equation 3.

3. MODEL OF A UNI-LAYER CHIP SEAL MAT

By working along the lines of the studies conducted by Estakhri and Gonzalez (1990) a chip seal mat may be modeled in the laboratory by manually packing aggregates of a given size such that the aggregates are in shoulder-to-shoulder contact. If the packing is done within a confined area such as in a box, it makes it possible for volume determinations to be made. Figure 1 is a section through a rectangular box with such a packing arrangement. The packing arrangement can be said to replicate that characterizing uni-layer chip seal mats existing in the field and, therefore, the assumption may be made that the aggregate-voids relationship characterizing the laboratory model is similar to that which would characterise a similar layer in the field. Hence Equation 3 can be applied to the laboratory model for voids determination. The volume of the aggregate mat formed at the base of the box is given by the following expression;

Figure 1. A section through a uni-layer chip seal mat



$$V_m = V_{box} - AH_O \qquad (4)$$

Where, A is the internal base area of the box and, H_o the depth of the box space above the aggregate mat (see Figure 1).

Hence the quantity AH_o is the box volume above the layer of aggregates. This quantity can be determined by covering the aggregate layer with an impermeable flexible membrane (such as tissue paper) and filling the box space above the aggregate mat with calibrated sand. The volume of the aggregates forming the mat may be determined by water displacement method. Packing of aggregates of a given size in boxes with different base areas will result in different V_m and corresponding V_a values but the voids content will be the same. Because the two parameters are related in accordance with the expression in Equation 3, for a given aggregate size, a plot of V_a versus V_m will result in a linear relationship with a slope (S) related to the voids content of the aggregate mat through the expression;

$$S = 1 - e \qquad (5)$$

4. MATERIALS AND METHOD

4.1 Materials

The materials used in the laboratory study were calibrated quartz sand, rectangular wooden boxes, tissue paper and single-size granite aggregates with the following nominal sizes; 10mm (3/8 in), 12mm (½ in), 14mm, 19mm (¾ in), and 25 mm (1in). The aggregates were washed and oven-dried before use. The wooden boxes had the dimensions detailed in Table 1.

4.2 Test methodology

A uni-layer aggregate mat was modeled by manually packing single-size aggregates in shoulder-to-shoulder contact to cover the entire base area of the rectangular boxes. Two packing arrangements were investigated; random packing and flat-side packing with the aggregates having their least dimension vertical. Thus, using the boxes, five separate same-thickness layers differing only in surface area were constructed for each aggregate size and a given packing orientation. After packing the aggregates in a box, a tissue paper cut to fit the internal dimensions of the box was placed on top of the layer of aggregates formed and the mass of the box and its contents determined and recorded as M_1. Care was taken to ensure that the aggregate packing was not disturbed.

Table 1. Internal dimensions of rectangular boxes

Box	Length (cm)	Width (cm)	Depth (cm)	Base area (cm^2)	Volume (cm^3)
1	15	10	15	150	2250
2	15	15	15	225	3375
3	20	10	15	200	3000
4	15	20	15	300	4500
5	20	20	15	400	6000

The space above the aggregate layer was then filled with calibrated sand in one smooth pour until the box overfilled and the excess sand scrapped off with a straight edge. The mass of the filled box was then determined and recorded as M_2. The purpose of the paper membrane was to prevent the sand from entering the voids in the aggregate mat when the box space above the aggregate layer was being filled.

The content of the box was then emptied into a pan and the aggregates used in forming the mat picked, their volume V_a, then determined by water displacement method.

The volume of the aggregate mat formed in the box was then determined as follows:

$$V_{sand} = \frac{M_2 - M_1}{\rho} \qquad (6)$$

$$V_m = V_{box} - V_{sand} \qquad (7)$$

where, p = density of sand=1,440 kg/m^3 (from calibration)

V_m = volume of aggregate mat

V_{sand} = volume of sand filling box space above aggregate mat

V_{box} = volume of box

5. RESULTS

5.1 Mat voids content

The aggregate and mat volumes for a given nominal aggregate size and packing orientation were used in establishing the aggregate-mat volume relationship expressed by Equation 3. The best fit linear relationship between aggregate volume and mat voids content was obtained by regression for each set of test results. Figures 2 to 6 show the plots of the linear relationship for the different aggregate sizes for flat-side and random aggregate packing.

Associated with each graph is the equation of the line of best fit obtained by linear regression of the experimental points. It is seen from the graphs that the coefficient of determination (r^2) values are essentially equal to unity for each of the regression lines suggesting a high degree of accuracy of the experimental work.

The slope of each straight line was obtained directly from the regression equation thus enabling, for each nominal aggregate size and packing orientation, the voids content of the aggregate mat to be obtained from the corresponding graph in accordance with Equation 5. Table 2 is a summary of the voids content corresponding to the different nominal aggregate sizes and packing modes investigated in this study.

Table 2. Mat voids content for aggregates in random and flat-side packing orientations

Aggregate Size (mm)	Mat Voids Content (%)	
	Flat-side packing	Random packing
10	61	73
13	54	67
14	53	68
19	52	62
25	46	53

5.2 Voids content, nominal aggregate size and aggregate packing

The data in Table 2 were transformed into a graph to provide a visual presentation of the relationship between nominal aggregate size and mat voids content corresponding to the two packing orientations investigated. Figure 7 depicts the relationship between the three parameters.

6. DISCUSSION

Figure 7 shows a decreasing linear relationship between the nominal size and voids content for each aggregate packing orientation; the voids content decreases with increasing aggregate size. The lines of best fit obtained by linear regression for the relationship between aggregate size and mat voids content of newly-placed single layer mats for the two packing orientations are;

$$e = 66.879 - 0.844d$$

r^2=0.86 (flat-side packing) (9)

$$e = 84.343 - 1.238\,d$$

r^2=0.97 (random packing) (10)

Where, e=voids content in %,

d=nominal aggregate size (mm)

The high values of the coefficient of determination (r^2) for the above relationships are indicative of the high predictive power of the models and, therefore, the equations may be used to predict, to a satisfactorily high degree of accuracy, the voids content in unilayer chip seal mats from a knowledge of the nominal size of the single-size aggregates forming the mat, for either random or flat-side packing orientation.

It can be established from the above relationships that , for a given aggregate size, the random packing orientation results in a much higher mat voids content than when the aggregates pack lying on their flat side with their least dimension vertical. This observation conforms with the general observation that as the aggregates are re-oriented by initial compaction to lie on their flat side, the mat voids content is reduced. However, the assumption that chip seal mats have a voids content of 50% when initially constructed, without reference to the size of aggregates nor the aggregate packing, does not appear to be tenable. It appears likely that the terminal voids content after long-term compaction by traffic would also depend on aggregate size. Therefore, the generally assumed value of 20% may be in contention.

7. CONCLUSIONS

This study used a laboratory model to evaluate the voids content in uni-layer chip seal mats and to investigate the effect of aggregate size on the mat voids content for two packing orientations of the mat aggregates; random and flat-side packing. The results indicated that, for a given packing arrangement, the voids content of newly-placed single layer chip seal mats is highly dependent on aggregate size. The larger the aggregate the lower the mat voids content. Therefore, the generally assumed voids content of 50% thought to characterise newly-placed chip seal mats does not appear to hold. If the terminal voids content is dependent on the initial voids content of the mat, then the generally assumed value of 20% may be disputed. The voids content in mats with aggregates in random packing orientation tends to be higher than that in mats with aggregates in flat side packing for the same aggregate size. The above have implications for the optimum quantity of bituminous binder to apply in the construction of seal coats. More research on chip seal voids is required to improve our understanding of the subject though.

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Fig. 2. Aggregate-mat volume relationship in 10mm aggregate mat

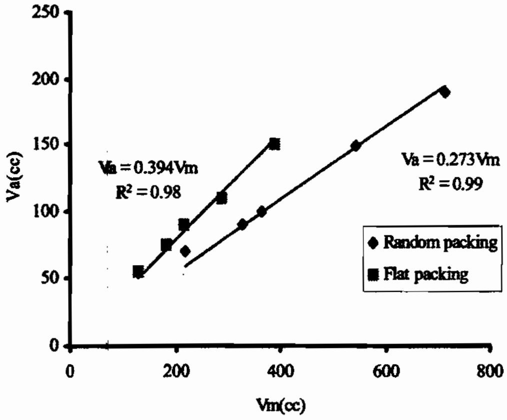


Fig. 3. Aggregate-mat volume relationship in 13 mm aggregate mat.

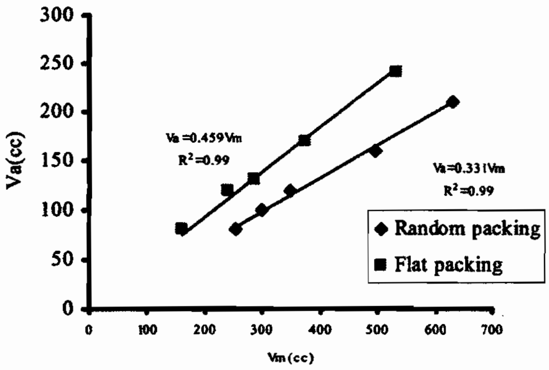


Fig. 4. Aggregate-mat volume relationship in 14mm aggregate mat

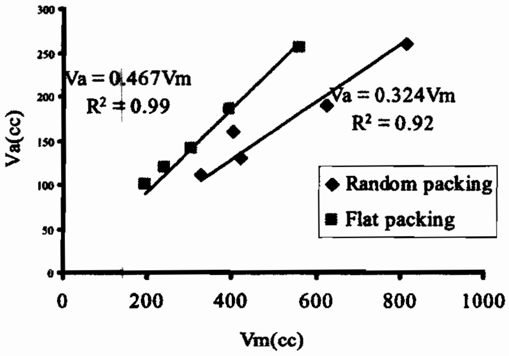


Fig. 5. Aggregate-mat volume relationship in 19mm aggregate mat

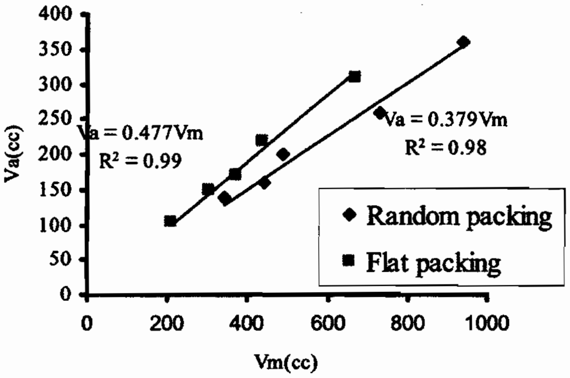


Fig. 6. Aggregate-mat volume relationship in 25mm

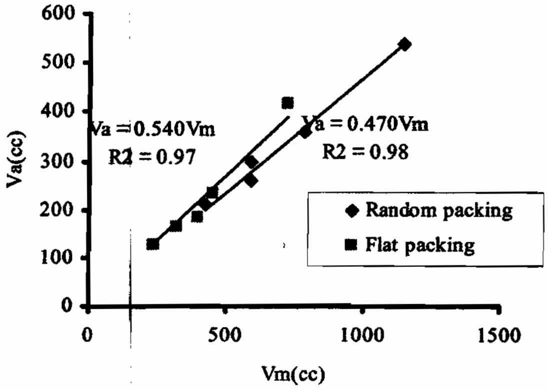
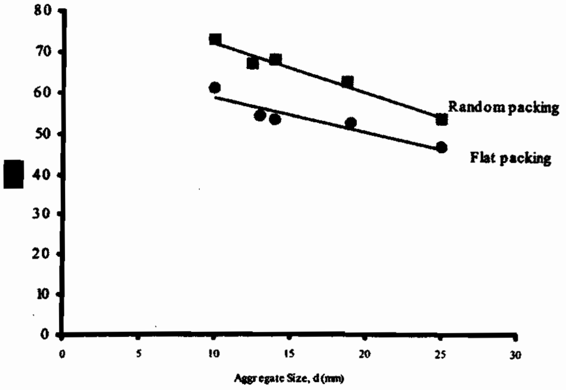


Fig. 7. Aggregate size- voids content relationship in



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