AGGREGATE PARTICLE ORIENTATION IN ASPHALT PAVEMENT MIXES

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abstract: A study was conducted to determine whether differences exist in aggregate particle orientation between field asphalt and laboratory compacted samples produced using Marshall and Gyropac equipment. Field asphalt samples obtained from the Accelerated Loading Facility (ALF) asphalt deformation trial in Queensland and laboratory compacted samples were sectioned and the orientation angle of the exposed aggregate particles determined manually by visual inspection of the cut faces. The Tukey's Chi-Square method was used to ascertain whether aggregate particles have a preferred orientation. Two quantitative measures of orientation direction were developed, ie. (i) the mean orientation angle, and (ii) the proportion of particles oriented within 22.5^0 of the horizontal. The results suggested that aggregate packing in the Marshall and Gyropac compacted samples was different to that in field compacted mixes.

1. INTRODUCTION

The spatial arrangement of aggregates within the pavement structure, usually referred to as aggregate packing, is rather complex since the irregularly shaped particles has a very wide size range. Nevertheless, differences in aggregate packing structure in different sets of asphalt specimens could be observed through an examination of the aggregate particle orientation.

Progress has been made over the last few years in developing new procedures for manufacturing asphalt specimens and testing them in the laboratory. One of the recent development is the move to introduce the gyratory method of laboratory compaction as a possible replacement for the Marshall drop hammer method of compaction. In the US, the SHRP gyratory compactor has been developed while in Australia a similar but lighter weight machine, the Gyropac, has been introduced.

Ideally, a laboratory prepared asphalt specimen should exhibit similar test properties (modulus, creep, etc.) to a field sample of the same mix. The closer this situation is approached, the more likely it is that testing of the laboratory sample will give a reliable prediction of the performance of the asphalt in a pavement. As such, the laboratory compaction procedure should therefore produce an aggregate packing structure to that which is achieved in a road pavement.

This paper presents the results of a study undertaken to determine whether there were differences in aggregate particle orientation between field asphalt and laboratory compacted samples produced using Marshall and Gyropac equipment. Evidence of aggregate particles having a preferred orientation (as oppose to having random orientation) was investigated with the application of the Tukey Chi-Square method. Two quantitative measures of aggregate particle orientation were also developed.

2. PREPARATION OF SAMPLES

2.1 Selection of Samples

Asphalt samples from the Accelerated Loading Facility (ALF) deformation trial in Queensland (Oliver, 1994) were used in this study. Visual inspection of cut faces of samples removed from the pavement indicated that the aggregate used contained a proportion of elongated particles which would assist in determining particle orientation. The C2 (AUSTROADS) mix was selected for study since it had the highest proportion of coarse aggregates. The aggregate gradation for C2 mix is given *Table 6* in the *Appendix*. (*note:* AUSTROADS is the national association of road transport and traffic authorities in Australia).

Conventional construction plant (pavers and rollers) was used to construct the ALF trial sections and the sections were considered to be representative of a road pavement. A slab of C2 mix, cut to the full depth of the asphalt surfacing (approx. 75 mm), was removed for laboratory testing.

Asphalt used for the Marshall and Gyropac specimens was sampled at the mixing plant from the batch of mix used for the C2 trial section. The 50 blow Marshall cylinders were compacted using an automatic compactor by the contractor's staff. The Gyropac mix was conditioned for 1 hour at 150^{0}C and then compacted for 200 cycles in a 100 mm diameter mould.

2.2 Cutting of Samples

Three Marshall and three Gyropac cylinders were cut orthogonally to their circular cross-section along the diameter (ie. if a cylinder was placed on the bench on one of its flat ends, the cut would be a vertical one slicing the cylinder into two equal halves). A rectangular surface approximately 100 mm wide by 65 mm high was thus exposed for examination.

Two sets of cross-sections were prepared from the slab removed from the ALF pavement. Three samples approximately 180 mm long by 85 mm high and 10 mm thick were cut parallel to the direction of rolling (longitudinal samples) and a further three cross-sections cut transversely to the direction of rolling (transverse samples). A 100 mm by 65 mm frame was placed on each sample so that an area of the same size as that of the Gyropac and Marshall samples was defined. The frame was positioned to exclude the stress absorbing membrane interlayer (SAMI) layer underneath the asphalt.

In all, three specimens were prepared for each of the following four conditions examined:

(i) field pavement - longitudinal
(ii) field pavement - transverse
(iii) Gyropac compaction
(iv) Marshall compaction

2.3 Treatment of Cut Faces

A hot air blower was used to slightly soften the bitumen on the cut surfaces and produce a blacker background. This enhanced the visual contrast between the aggregate particles and the surrounding bitumen.

The prepared cut surface of each sample was then photographed using conventional 35 mm camera. Approximately A4 sized photographs were prepared for use in the aggregate orientation study.

3. MEASUREMENT OF DIRECTION OF AGGREGATE ORIENTATION

3.1 Methods of Measurement

The initial step in any method to determine the orientation direction of aggregate particles is to identify the projections of the particles on a given plane (equivalent to examination of a cross-section of a sample cut parallel to a selected plane). In this study, the projections of aggregate particles on the vertical plane was considered.

Three methods have been considered by previous researchers (Lees and Salehi, 1969; von Quintus, 1991) for the measurement of particle orientation, namely:

(i) the least projection method,
(ii) the center of area method, and
(iii) the long dimension method.

In the least projection method, the elongation direction is the direction of the two parallel lines with the minimum amount of separation that can be drawn tangent to the particle projection. In the case of the center of area method, the elongation direction is the direction of the longest straight line that can be drawn through the center of area of the projection. The center of area is considered to be a two-dimensional equivalent of the center of mass, that is the point about which the particle pivots when suspended in a fluid.

In the third case, the long dimension method, the orientation direction for each particle projection on the cut section is determined by finding the direction of the longest line that can be drawn on the particle. Although the first two methods may be considered to be somewhat more accurate than the long dimension method, for the purpose of this research the long dimension method was adopted since it is least time consuming and no significant loss of accuracy results from its use (von Quintus, 1991).

3.2 Procedure Adopted

Orientation direction was measured by visual inspection of photographs. The sign convention shown in *Fig. 1* was used. In the case of field samples, the horizontal direction was taken as the plane of the surface of the pavement. For the Marshall and Gyropac samples, horizontal was taken to be the plane through the top (flat) face of the cylinder.

To exclude all particles which did not have a clear orientation but which might appear to the eye to have a longer direction, only aggregate projections with aspect ratios (length/breadth) of 2.0 and above were considered in the analysis. A simple gauge was manufactured so that such particles could be rapidly identified on the photographs.

Since the packing of coarse aggregate particles might be expected to have a greater effect on asphalt properties than packing of fine aggregate particles, the decision was made to include in the analysis only those particles which had any cross-sectional dimension greater than 4.75 mm.

4. TREATMENT OF DATA

Individual specimens and cross-sections were examined to determine the orientation directions of the aggregates. However, in the analysis triplicates have been combined to give about 200 data points for each method of compaction, similar to the number used by Lees (1969) in his study. For the purpose of data analysis, angles were grouped into classes of 10 degree intervals.

Initial examination of the data indicated that the distributions of the orientation angle were approximately symmetrical about 0^0 (see *Fig. 2a*). It was therefore decided to consider only the absolute value of the angles in subsequent analyses. This resulted in a range of angles from 0^0 to 90^0 rather than from -90^0 to $+90^0$ (see *Fig. 2b*).

5. RESULTS

The frequency distribution of aggregate orientation angles are shown in *Fig. 3* for the four compaction conditions studied. To assist with the interpretation of results, the bottom two graphs illustrate the idealised situations where: (i) particles are randomly orientated, and (ii) all particles have the same orientation (0^0 to 10^0 in the example).

Examination of the frequency distributions in *Fig. 3* suggest that there is a preferred orientation in all four cases (ie. none of the cases shows that the orientation is entirely random). It appears that the two field compacted samples have similar distributions and that a higher proportion of particles in these samples are orientated parallel to the horizontal (angles close to 0^0) than is the case for Gyropac and Marshall samples. The two laboratory compaction procedures appear to have similar distributions.

An alternative representation of results which was used in a U.S. NCHRP study (von Quintus, 1991) is the cumulative frequency polygon. The results are shown in this form in *Fig. 4.* Also included in this figure is an indication of the range of results obtained for field cores in the NCHRP study reported by von Quintus (1991). It can be seen that the current results for the two (Australian) field conditions are not dissimilar to the U.S. cores.

6. DETERMINATION OF THE EXISTENCE OF A PREFERRED ORIENTATION

A modification of the Chi-square (χ^2) test was suggested by Tukey (Harrison, 1957; Rurnak, 1957) for use as a test of "preferred orientation" of directional data. A theoretical derivation of the test has been published by Middleton (1965). The Tukey's Chi-Square value with two degrees of freedom is given by the following expression:

$$\chi^2 = \frac{(\Sigma x_j \sin\theta_j)^2}{\Sigma \sin^2\theta_j} + \frac{(\Sigma x_j \cos\theta_j)^2}{\Sigma \cos^2\theta_j} \quad \text{....................} \quad (1)$$

where,

$$x_j = \frac{X_j - \overline{X}}{\sqrt{X}}$$

X_j = observed frequency in class j, and

$\overline{X}$ = expected frequency in class j.

This test was applied to each individual specimen and cross-section and in most cases the test indicated that there was a preferred orientation. In one of the Marshall compacted specimens, the random orientation condition was approached.

7. DETERMINATION OF ORIENTATION DIRECTION

There is no universally accepted procedure for quantifying the mean orientation direction (or the preferred orientation) of aggregate particles. In this study, two methods of determining the orientation direction are suggested, namely:

(i) calculation of a mean orientation angle by vector addition, and
(ii) calculation of the proportion of particles orientated horizontally.

7.1 Mean Orientation Angle by Vector Addition

The observed orientation angles were resolved, for each 10^0 class, into vertical and horizontal components using the sine and cosine of the mid-point of the absolute angle of the class. Each orientation direction was afforded equal weight (ie. the length of the particles was not used).

The horizontal component of the orientation angle of each class is defined as the observed frequency multiplied by the cosine of the angle. The vertical component is defined as the observed frequency multiplied by the sine of the angle. The components in the horizontal and vertical directions were summed and the ratio of the sums gives the tangent of the angle which the resultant vector makes with the horizontal.

From the arctangent of this value, the absolute angle of orientation, termed the *"resolved orientation angle"*, was obtained. The resolved orientation angle for each of the four cases studied is given in *Table 1.*

Table 1. Resolved Orientation Angle

Compaction Condition	Resolved Orientation Angle (^{0})
Field - Longitudinal	18.4
Field - Transverse	21.9
Gyropac	30.8
Marshall	34.8

To assist in interpretation of the Resolved Orientation Angle, the following extreme cases can be considered;

- all particles aligned with the horizontal: resolved orientation angle = 5^0 (the mid-point of the 0^0 to 10^0 class interval)
- particles randomly orientated: resolved orientation angle = 45^0

7.2 Percentage Horizontal Method

A second means of characterising particle orientation in a sample is to calculate the percentage of particles having a particular preferred orientation. The preferred orientation direction used in this study was taken as the horizontal. Referring to *Fig. 5*, particles in Zone I, that is within 22.5^0 of the horizontal are considered to have a preferred horizontal orientation. The ratio of the number of particles in Zone I to the number in Zone IV provides better discrimination between samples. The ratio is, however, very sensitive to the number of particles in Zone IV (in some cases this is only one or two particles). The more robust percentage horizontal parameter (ie. percentage $0^0 \leq \theta \leq 22.5^0$) is, therefore, preferred.

Table 2. Percentage of Particles Horizontal

Compaction Condition	Percentage Horizontal
Field - Longitudinal	69.0
Field - Transverse	61.5
Gyropac	48.1
Marshall	42.2

8. DISCUSSION OF RESULTS

The variability associated with the two parameters used (Resolved Orientation Angle and Percentage Horizontal) appears to be such that the observed differences between the Gyropac and Marshall samples are not likely to be significant. The results also suggest that there was no significant difference between longitudinal and transverse field samples. This is more evident when three more samples were taken from the slab used to obtain the longitudinal and transverse samples and tested. For the repeat of the field-longitudinal samples, the resolved orientation angle obtained was 22.6^0 and percentage horizontal of 58.3%.

The differences between field and laboratory compacted (Gyropac and Marshall) samples are quite large and likely to be significant. However, a more extensive testing program would be required to verify this point.

9. CONCLUDING REMARKS

Based on the results of this study, the following conclusions can be made:

1. The field compacted samples studied had aggregate particles more closely aligned with the horizontal than did the laboratory compacted Gyropac and Marshall samples. This suggests that aggregate packing in the Marshall and Gyropac compacted samples was different to that in the field compacted asphalt mix.

2. Although the Gyropac results indicated a slightly closer orientation of particles to the horizontal than Marshall, there was insufficient data to confirm this.

3. For the field mix, little or no difference was found between aggregate orientation in the longitudinal (parallel to the direction of rolling) direction and the transverse direction.

4. There was insufficient data to determine the repeatability and reproducibility of the orientation parameters. A larger investigation would be required to verify the above conclusions on a statistical basis.

5. Two quantitative measures of aggregate orientation is proposed to enable greater understanding of the packing of aggregates in asphalt mixes.

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APPENDIX

TABLE 3

RESOLVED ORIENTATION ANGLE
SUMMARY OF INDIVIDUAL SPECIMEN RESULTS

Specimen	Field Slab Transverse	Field Slab Longitudinal	Field Slab (repeat) Longitudinal	Gyropac	Marshall
1	19.7	16.6	19.5	37.4	30.5
2	22.2	18.8	25.4	27.9	40.0
3	23.1	19.5	22.6	27.6	34.0
Mean	21.7	18.3	22.5	31.0	34.8
Std Dev.	1.754	1.520	2.947	5.593	4.829

Using equation (1) Tukey's χ^2 was calculated for the two samples with the highest resolved angle (Marshall specimen 2) and the lowest resolved orientation angle (field slab - original, longitudinal specimen 1).

TABLE 4

TUKEY'S χ^2 PARAMETER FOR TWO INDIVIDUAL CASES

Specimen	Tukey's χ^2
Marshall Specimen No. 2	0.77
Field Slab - Original Longitudinal Specimen No.1	25.98

TABLE 5

EXTRACT OF χ^2 TABLE

Probability	0.25	0.5	0.999
χ^2 for 2 degrees of freedom	0.57	1.38	13.8

Interpretation of the results using Table 5 indicates that the Marshall specimen had a virtually random orientation while the field slab specimen was very strongly orientated.

TABLE 6

AGGREGATE GRADATION FOR C2 (AUSTROADS) MIX

Sieve Size (mm)	13	9.5	6.7	4.8	2.4	1.2	0.6	0.3	0.15	0.075
% passing	100	94	70	57	42	31	22	15	8	5.6

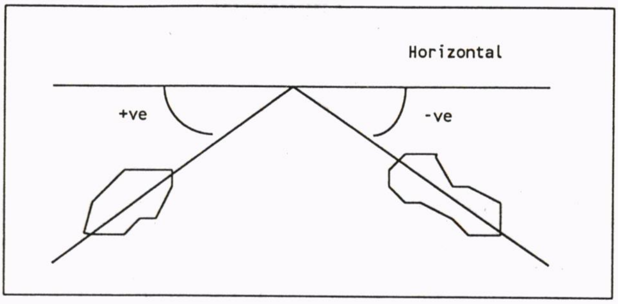

Fig. 1 Angle signing convention used

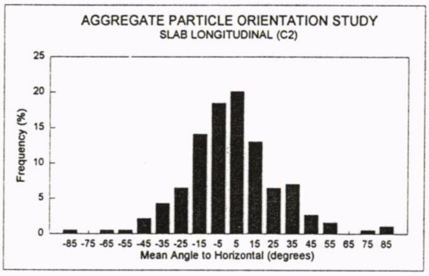

Fig. 2a Example of frequency distribution for angles -90 to +90

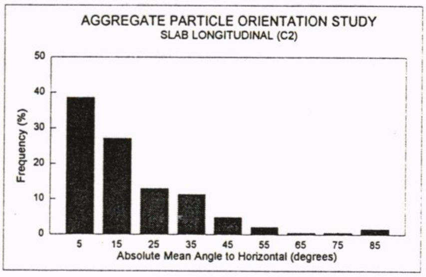

Fig. 2b Distribution in 2a but using absolute values for angles

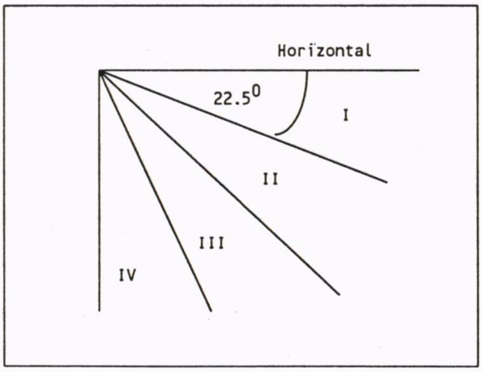

Fig. 5 Zones used to calculate the percentage horizontal parameter

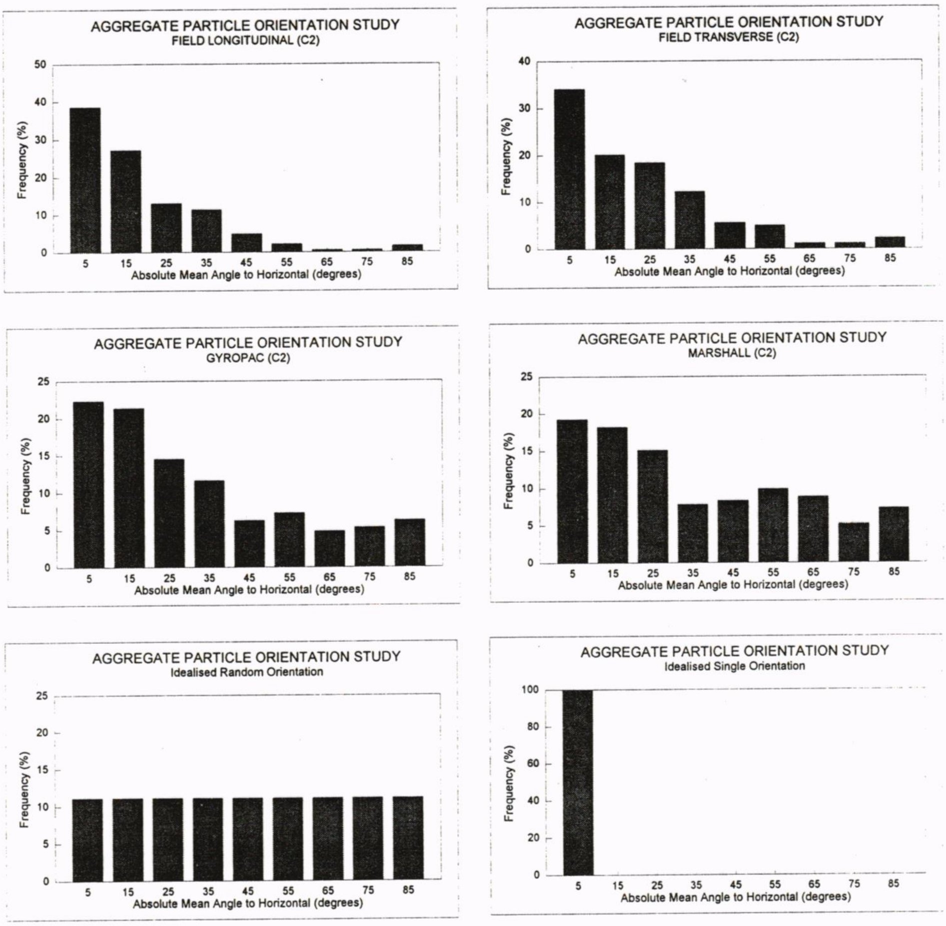

Fig. 3 Histograms of Frequency Distribution of Absolute Angles.

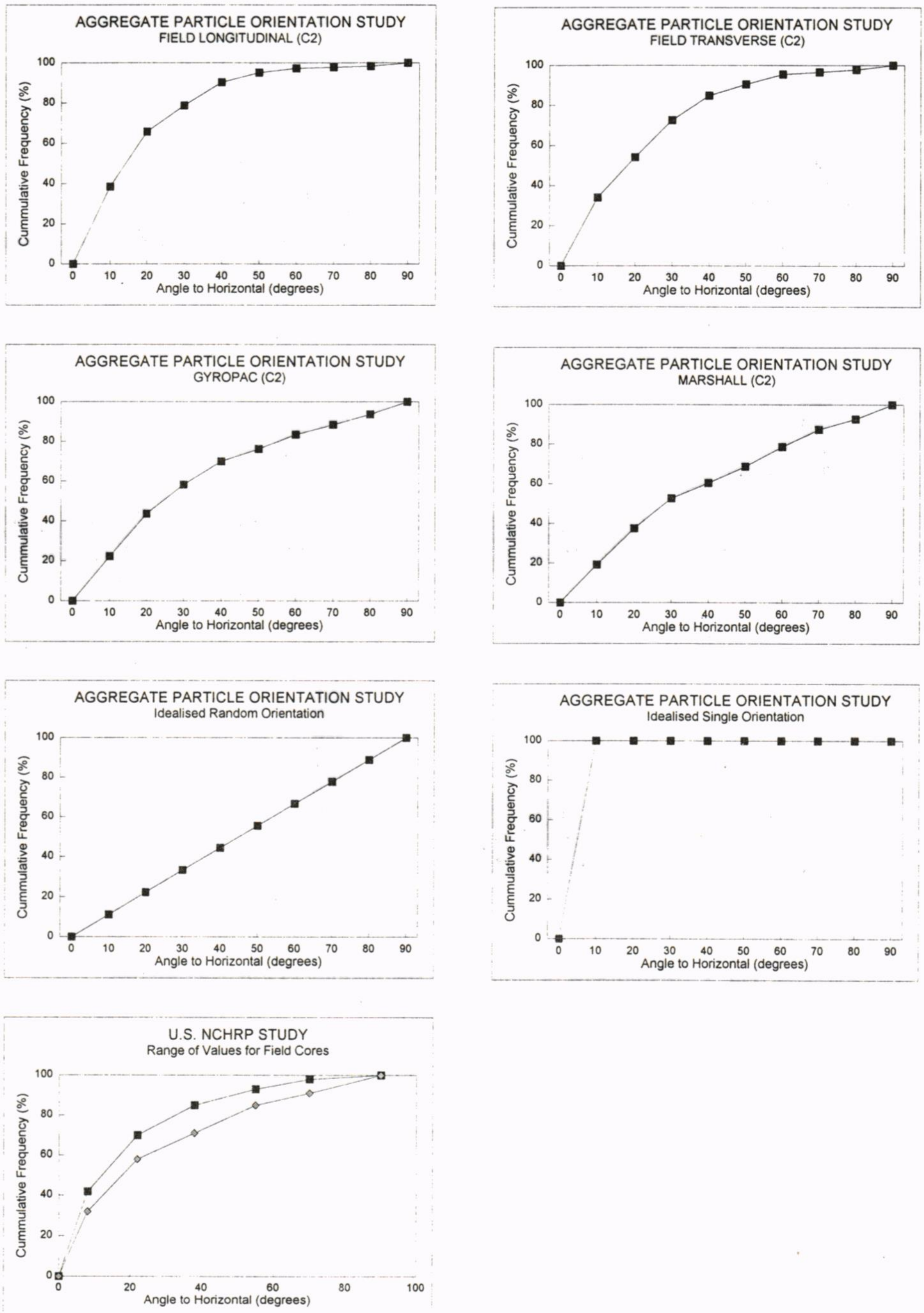

Fig. 4 Cummulative Frequency Distribution of Absolute Angles