INFLUENCE OF AGGREGATE SHAPE ON ENGINEERING PROPERTIES OF ASPHALTIC PAVING MIXTURES

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The following properties characterize flaky aggregates as opposed to cubical aggregates: (a) tendency to stratify (lowest energy level), (b) low compactibility, (c) larger specific surface area for the same fraction, and (d) higher breakage value (lower moment of inertia). These properties may be expected to produce the following characteristics in asphaltic mixtures: (a) weakness planes, which favor a low load-carrying capacity and strength anisotropy; (b) low density; (c) high optimal bitumen content; and (d) high breakage value, which distorts the original grading and causes the formation of voids free of bitumen or fines, thereby reducing the load-carrying capacity still further. The subject was investigated with the aid of a literature survey on the influence of aggregate sphericity on the engineering properties of asphaltic mixtures and laboratory tests designed to give a reliable picture of aggregate behavior in pavements. The influence of aggregate sphericity in the extreme cases of asphaltic mixtures is characterized by dense and open gradings, i.e., a solid mass and minimum void percentage respectively. The conclusion, which occasionally contradicts the findings of others, is that flaky aggregates (specifically the hard, crushed type used in laboratory studies) may be regarded as a conventional material from the engineering viewpoint, i.e., that they may be used for producing asphaltic mixtures.

•QUARRY aggregates frequently contain a high proportion of noncubical material, mainly as a result of the mineralogical composition of the rock and the type of quarrying equipment. The use of these aggregates in asphaltic paving mixtures is somewhat problematic. The uncertainty over this is reflected in the discrepancies between the various standard specifications and the results of various studies.

A comprehensive, up-to-date survey (1) established that "aggregate shape is discussed in literature primarily in terms of differences between natural aggregates (gravels and sands) and crushed aggregates (crushed gravel or crushed stone)." Crushed material has a higher angularity and roughness than does natural aggregate; therefore, the sphericity of the aggregate (proximity of the particle to the sphere or cube) is not eliminated when comparing the engineering properties of mixtures consisting of both types. Studies on such asphaltic mixtures are found in the literature (2-12). A quantitative study that can claim to have eliminated sphericity was conducted by Li and Kett (13), which consisted of Marshall and Hveem tests on specimens made with dense-graded aggregate and covered a wide range of sphericity. The conclusions of this study were as follows: (a) Shapes with $a/c > 3$ (Appendix, Fig. 21) are critical; and (b) the maximum proportion of critically shaped flaky material that may be used without detriment to stability is about 40 percent. The latter conclusion is controversial because the obtained stability values of both cubical and flaky aggregates are far above the accepted level. Moreover, when using unconventional materials, the tests performed serve as partial criteria for field conditions.

Sponsored by Committee on Characteristics of Aggregates and Fillers for Bituminous Construction.

STUDY OBJECTIVE

In order to reach engineering conclusions concerning the use of flaky aggregates for the preparation of asphaltic mixtures, we compared, under actual road condition and in conjunction with a series of laboratory tests, the engineering properties of flaky aggregates with those of cubical aggregates (routine particles). The scope of this paper is confined to laboratory tests whose object was to approximate actual road conditions.

Flaky aggregates may be attributed with the following properties as compared with cubical aggregates: (a) tendency to stratify (lowest energy level), (b) low compactibility, (c) larger specific surface area for the same fraction, and (d) a higher breakage value (lower moment of inertia).

The preceding properties may be expected to produce the following characteristics in aggregate mixtures: (a) weakness planes, which favor a low load-carrying capacity and strength anisotropy; (b) low density; (c) high optimal bitumen content; and (d) high breakage value, which distorts the original grading and results in the formation of voids free of bitumen or fines, thereby reducing the load-carrying capacity still further.

Some of the preceding properties have been found in the single-sized flaky aggregate. For example, findings given elsewhere (14, 15) demonstrate that flaky aggregates have a higher void percentage (low compactibility) than similar mixtures containing cubical aggregates.

In asphaltic mixtures, the grading may tend to mask or eliminate the properties of the flaky aggregate. Stratification is likely to be prevented, interparticle contact intensified, and breakage reduced. In addition, the overall surface area of the aggregate is likely to be increased so that variation due to shape would be negligible. Insofar as these assumptions are confirmed in practice, flakiness does not disqualify the aggregate as a conventional ingredient for asphaltic mixtures.

In this study, two gradings were investigated: (a) dense grading, percentage passing $^3/_4$ in., 100 percent; No. 4, 61 percent; and No. 200, 6.5 percent; and (b) open grading, percentage passing $^3/_4$ in., 100 percent; No. 4, 28 percent; and No. 200, 2 percent. These gradings represent the two extreme cases of the influence of sphericity. The study consisted of a series of laboratory tests designed to give a reliable picture of flaky aggregate behavior in road pavements.

The study objective necessitates a knowledge of the following.

1. Marshall test: The influence of aggregate shape on the rates of stability and flow is measured in the Marshall tests. This is a routine test that enables one to determine strength indexes (stability and flow) for the design of asphaltic mixtures. However, because this test does not enable one to determine all the properties of aggregates under road conditions, the influence of aggregate shape on the engineering properties of asphaltic mixtures was investigated with the aid of the following laboratory tests.
2. Triaxial shear test: In this test, part of the specimens were compacted parallel to the direction of the maximum principal stress σ_1 and the other part perpendicular to this direction. The results of this test enable one to determine the following: (a) the load-carrying capacity under conditions simulating the wheel load on the road surface (namely, compacting parallel to the maximum principal stress); (b) the cohesion coefficient and the internal angle of friction, which is a representative parameter of the aggregate matrix (3); and (c) the influence of shape on anisotropic properties.
3. Moving-wheel test: This test enables one to determine the influence of shape on the grooving effect and is the most approximate to actual road conditions. It is carried out by means of a wheel traveling on an asphaltic concrete slab on a single track at a specified load and number of cycles. It provides information mostly on the fatigue and on horizontal surface resistance.
4. Breakage value test: Flaky aggregates have poorer mechanical properties than do cubical aggregates of the same category (Appendix). Therefore, a higher breaking percentage may be expected in asphaltic mixtures containing flaky aggregates. This breakage favors the formation of voids free of bitumen and fine, which causes the specimen to weaken. The breakage value and its influence on the mechanical properties of asphaltic mixtures were investigated on specimens compacted by common laboratory methods—dynamic compaction (Marshall), kneading compaction, and static compaction

(triaxial shear and moving wheel)—and with the aid of a moving steel wheel. The latter method is the most approximate to road conditions.

5. Splitting test: The load-carrying capacity of asphaltic mixtures is governed, among other things, by its ability to withstand tensile stresses. Because the air pockets that form as a result of breakage of the aggregates are liable to decrease the tensile strength, the splitting test is used to determine this property.

6. Weight-volume ratio test: Standards and specifications establish definite values of void percentage in asphaltic mixtures. A high void percentage may give rise to oxidation of the bitumen, and a low void percentage may cause it to rise to the surface. For this reason, it is important to investigate the influence of shape on the compactibility of asphaltic mixtures. This property was tested by using various compaction methods (dynamic, kneading, and static) to eliminate the effect of the mode of compaction. Another reason for employing several methods was to investigate the possibility of arranging the flaky particles in a stratification pattern. Theoretically, such a pattern would produce higher densification rates in asphaltic mixtures containing flaky particles.

ASPHALT TESTS

Marshall Test

Specimens were compacted with 50 blows on each side. The test results (Marshall stability and flow versus bitumen content, shape being the parameter) are shown in Figures 1 and 2. The bitumen content throughout this paper refers to the weight of the aggregates. For dense grading, Figure 2 shows that flaky particles produce a somewhat lower Marshall stability (15 to 20 percent), but the absolute value for both shapes is higher than normal. The latter is due to the extra hardness of the aggregate in question (Appendix). Figure 1 also shows that sphericity does not influence flow values.

In the case of open grading, Figure 1 shows that the stability of specimens containing flaky aggregates is 500 to 600 lb (about 55 percent) lower than specimens containing cubical aggregates and that sphericity has no influence on the flow values. The decrease of stability values in specimens containing flaky aggregates is mainly attributable to the considerably higher breakage of these particles as compared with cubical particles and, to a negligible extent, to their shape.

As for optimal bitumen content, Figures 1 and 2 show that, in both dense and open gradings, the particle shape has no influence on this property. From this, the following may be concluded: (a) An increase in specific surface area is negligible in comparison with the specific surface area of the total mass of the particles (particularly of the fine fraction), and (b) the optimal bitumen content is not increased by the breakage of the aggregates because of the relatively insignificant increase in specific surface area of the aggregates. As is known, even a greater increase in the specific surface area of the aggregates brings about a relatively small increase in the optimal bitumen content as shown in Figure 3 (16).

It should be noted that a decrease in the difference between the breakage percentages of cubical and flaky particles will decrease the difference between stability values: dense grading, from 600 lb (about 20 percent) to 150 lb (10 to 15 percent); and open grading, from 500 lb (about 55 percent) to 180 lb (about 35 percent) (Fig. 4). In the case of open grading, if identical densities are used as a basis of comparison, the stability values of specimens containing cubical aggregates are similar to the values of specimens containing flaky aggregates (Fig. 5). This result may be attributed to the somewhat low compactibility of the flaky particles as compared with that of the cubical particles in this grading. Therefore, to achieve identical densities, we used a higher compaction energy in specimens containing flaky aggregates. This additional energy compensates for the decrease in the stability values resulting from the greater breakage of these particles.

The results prove that in dense mixtures the flaky particles are prevented from assuming a stratification pattern perpendicular to the direction of compaction (lowest energy level) as a result of laboratory compaction techniques. This is confirmed by the data shown in Figure 6 (dense grading), which shows that the orientation angle is

Figure 1. Marshall stability versus bitumen content, dynamic compaction.

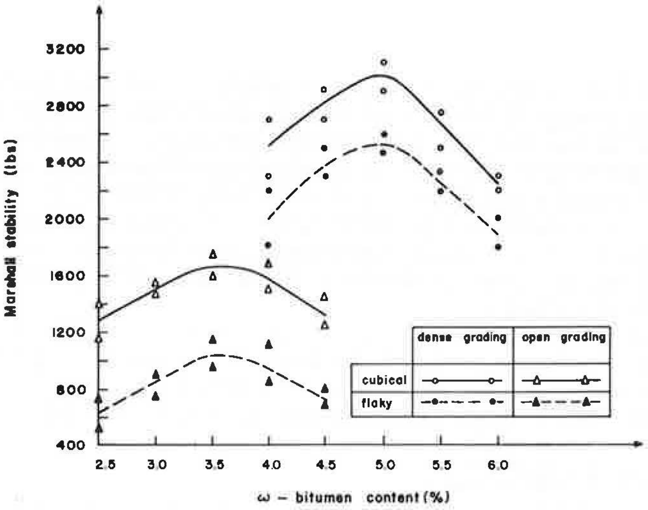


Figure 2. Marshall flow versus bitumen content, dynamic compaction.

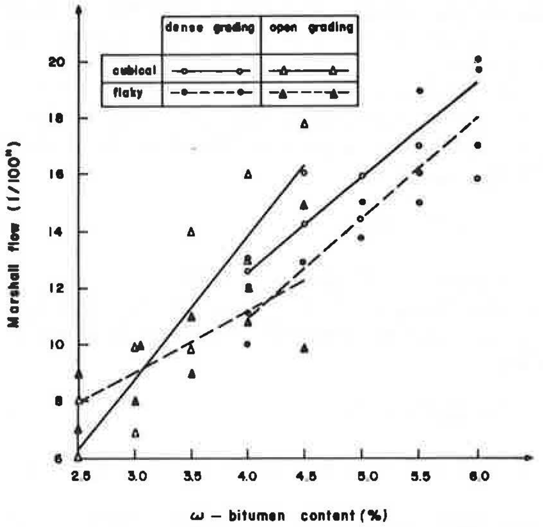


Figure 3. Optimal bitumen content versus specific surface area.

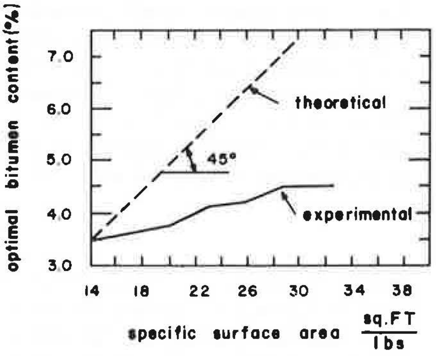
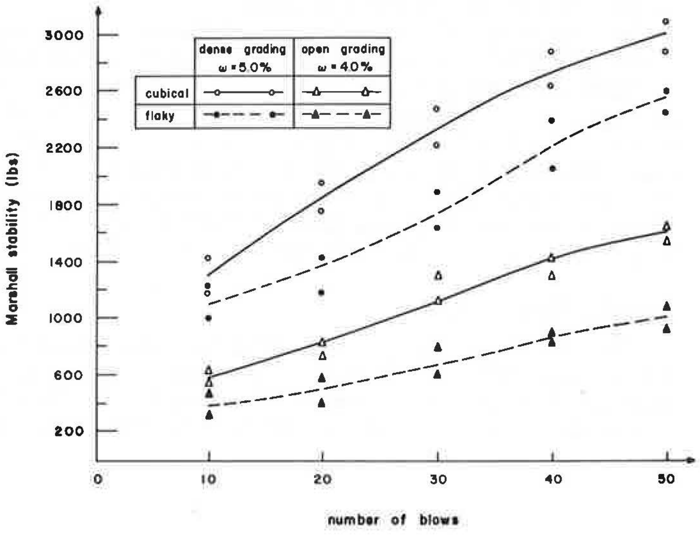


Figure 4. Marshall stability versus compaction energy.



less than 45 deg (the axis of symmetry with respect to the perpendicular) but is still large enough to prevent the formation of weakness planes. This finding does not conform to the observations of Puzinauskas (5). As for the influence of sphericity, he concluded that elongated or flattened particles accentuate the anisotropy as compared with rounded particles. In other words, the structure index (load-carrying capacity ratio of parallel and perpendicularly compacted variants) is higher in the former case. However, Puzinauskas' conclusions were based on a comparison of crushed aggregate with natural gravel; therefore, it may be stated that the sphericity factor in this case was not isolated.

In conclusion, the Marshall test results indicate that the stability of the flaky specimens for dense grading is higher than is usual for asphaltic mixtures. This result was obtained with flaky aggregates corresponding to the B.S. classification of "100 percent flaky," which has a high crushing value of 31 percent for the fraction of -½ in. +⅜ in.

Triaxial Shear Test

Dense Grading—The tests were carried out on statically compacted 4- by 8-in. specimens having a uniform bitumen content of 5 percent by weight (which is optimal according to the Marshall stability test). Part of the specimens were compacted parallel to the direction of loading (double-plunger method) and the other part perpendicular to this direction. The test was immediately preceded by immersion in water at 60 C for ½ hour and was carried out at the same temperature. The basis used for comparing compressive strengths—equal density—is justified in the case of dense grading because of the similar compactibility of both shapes.

As can be seen from Figures 7 and 8, the sphericity influences neither the deviatoric stress, regardless of the direction of loading, nor the anisotropy. The implication of the relation between the deviatoric and lateral stresses as shown in the figures is an isotropic internal angle of friction Φ (18), given by

$$\sin \Phi = \tan\gamma/(\tan\gamma + 2) \tag{1}$$

where γ denotes the slope of the straight line shown in Figures 7 and 8.

The figures indicate that the cohesion is anisotropic. In this case, a strength factor D should be considered, which is defined by the intersection of the tangent to Mohr's circle and the axis $\sigma = 0$ and is expressed by

$$D = d\,(1 - \sin \Phi)/2\cos \Phi \tag{2}$$

where d denotes the deviatoric stress for $\sigma_3 = 0$. D differs from conventional cohesion (18).

Thus it is seen that sphericity has no influence on the strength factor either. The preceding results are attributable to the low breakage of the flaky particles at the center (shear zone) of the specimen.

Open Grading—Specimens were prepared, tested, and compacted as in the case of dense grading. The optimal bitumen content used was 3.5 percent.

Analysis of the grading after compaction revealed a segregation effect that resulted in a higher concentration of fines at the bottom of the specimen; however, because this effect is common to both shapes, it may be assumed that it does not distort the situation. Results (Figs. 9 and 10) show that sphericity has no influence on the compressive strength regardless of the direction of compaction and that the shape has no influence on the anisotropy or on the strength parameters. Unlike in dense-graded mixtures, in this case both the angle of internal friction and the cohesion are anisotropic.

Moving-Wheel Test

The series of moving-wheel tests (6), carried out on 38.0- by 18.0- by 4.5-cm specimens compacted under a 40-ton load, was designed to determine the influence of sphericity on the grooving resistance, the fatigue behavior of the asphaltic mixture under simultaneous vertical load and impact, and the fatigue behavior of the mixture under

Figure 5. Marshall stability versus density, open grading.

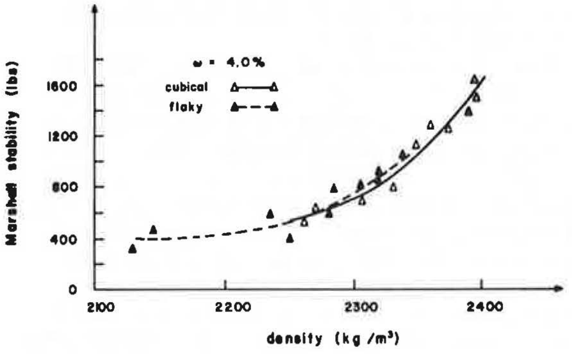


Figure 6. Specimen cross sections (dynamic compaction).

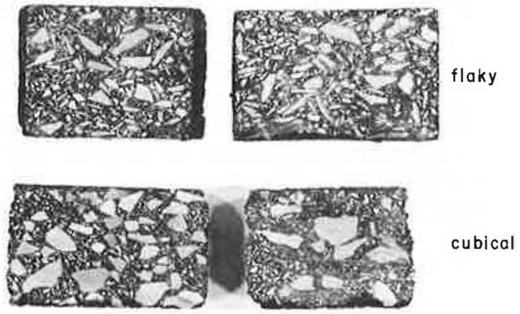
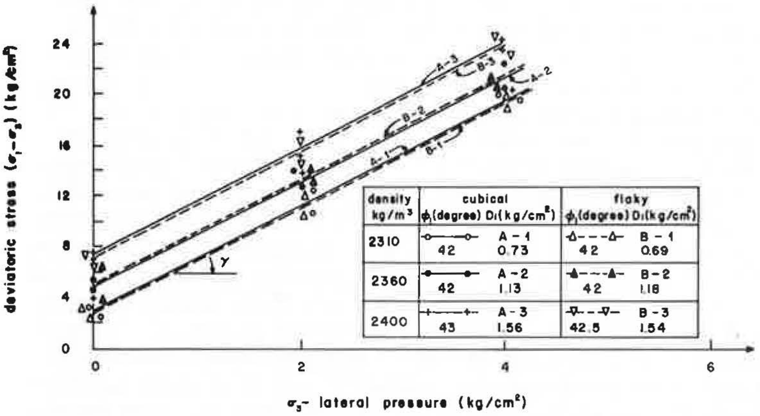
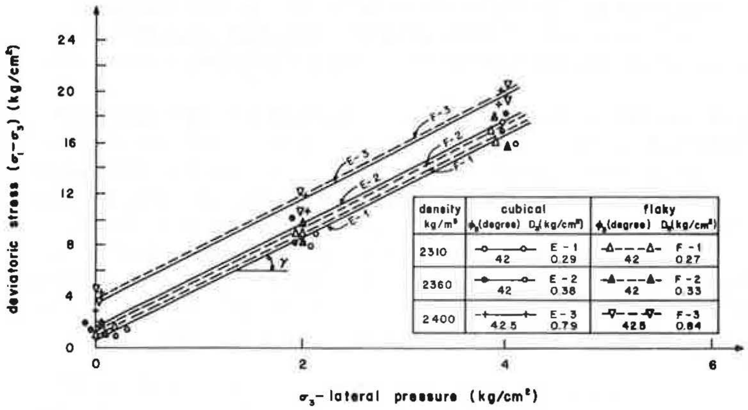


Figure 7. Deviatoric stress at failure versus lateral pressure, parallel compaction (dense grading, bitumen content 5.0 percent).



density kg/m³	cubical ϕ_1(degree)	cubical D_1(kg/cm²)	flaky ϕ_1(degree)	flaky D_1(kg/cm²)
2310	○——○ 42	A - 1 0.73	△- - -△ 42	B - 1 0.69
2360	●——● 42	A - 2 1.13	▲- - -▲ 42	B - 2 1.18
2400	+——+ 43	A - 3 1.56	▽- - -▽ 42.5	B - 3 1.54

Figure 8. Deviatoric stress at failure versus lateral pressure, perpendicular compaction (dense grading, bitumen content 5.0 percent).



density kg/m³	cubical ϕ_2(degree)	cubical D_2(kg/cm²)	flaky ϕ_2(degree)	flaky D_2(kg/cm²)
2310	○——○ 42	E - 1 0.29	△- - -△ 42	F - 1 0.27
2360	●——○ 42	E - 2 0.38	▲- - -▲ 42	F - 2 0.33
2400	+——+ 42.5	E - 3 0.79	▽- - -▽ 42.5	F - 3 0.84

repeated loading. Some of the specimens were tested at room temperature (20 to 25 C); the vertical pressure was about 90 psi. Other specimens were tested under water at 60 C; the vertical pressure was about 60 psi. Figures 11 and 12 show the apparatus used in this test and also a specimen after the test was performed.

The influence of aggregate sphericity in both dense and open gradings under the conditions of these tests (room temperature of 20 to 25 C, water at 60 C) is shown in Figures 13, 14, and 15. From these figures, it may be concluded that sphericity has no significant effect on the grooving rate, whereas a rise in test temperature from 20 to 60 C causes the grooving rate to rise sharply. In the moving-wheel test, the elimination of the differences in the load-carrying properties between specimens containing cubical aggregates and specimens containing flaky aggregates, as compared with the Marshall test, may be attributed to the decrease in the breakage percentage of flaky particles.

It is noteworthy that, on a semilogarithmic scale, the curve that describes the relation between the degree of grooving and the number of cycles per second has the form of a straight line.

Breakage Value Test

Flaky aggregates, as compared with cubical aggregates of the same category, have poor mechanical properties (Appendix). Therefore, the breakage value of flaky particles in asphaltic mixtures may be expected to be higher. This is confirmed by the grading test performed after the compaction of laboratory specimens. It was found that the chief cause of breakage is not shear but is compaction. In the coarse fraction (-$^3/_4$ in. +$^1/_2$ in.), the following breakage values were determined for flaky particles in dynamically compacted specimens (50 blows each side): (a) dense grading, approximately 60 percent as compared to almost 0 percent for cubical particles; and (b) open grading, approximately 80 percent as compared with 30 percent for cubical particles. The higher breakage of flaky particles in dense grading does not cause any significant change to take place in the grading. On the other hand, this breakage gives rise to the formation of air pockets that are free of bitumen and that reduce the stability values by some 15 percent (Fig. 1). In open grading, as may be expected, the breakage percentage of flaky particles is more significant as compared with cubical particles. Therefore, the number of air pockets is greater (and the change in the grading accordingly more significant), which results in a sharp decrease (about 55 percent) in the stability value as compared with specimens containing cubical aggregates (Fig. 1). The breakage of flaky particles changes their shape to cubical and to cubical-flaky (a shape in between cubical and flaky). In dense gradings, at a compaction energy of 50 blows, approximately 40 percent of flaky particles change in shape and become cubical-flaky. In open grading, 40 to 50 percent and 10 to 15 percent of flaky particles change shape to cubical-flaky and cubical respectively. From these results, it can be concluded that, in both dense and open gradings, after breakage there remains a quantitative difference between cubical aggregates (whose breakage does not alter their shape) and flaky aggregates.

To decrease the breakage value, we reduced the dynamic compaction energy from 50 to 10 blows (at a rate of 10 blows at a time). This in turn decreased the difference in the breakage values between flaky and cubical particles and increased the difference between the various shapes. The decrease in the breakage percentage of flaky particles (-$^3/_4$ in. +$^1/_2$ in.) resulting from the decrease in the compaction energy from 50 to 10 blows was as follows: dense grading, from 60 to 40 percent; open grading, from 80 to 50 percent; and cubical particles, from 30 to 20 percent. The decrease of the difference in breakage percentages may be attributed to the decrease of the difference in the stability rates between specimens containing cubical aggregates and specimens containing flaky aggregates (Fig. 4).

Other attempts to reduce the breakage percentage of the particles, such as the adoption of the kneading compaction method (17), failed to yield the desired result. On the other hand, the following results were found: (a) In the center of the specimens (dense grading) examined in the triaxial shear test, the breakage rate of flaky particles

Figure 9. Deviatoric stress at failure versus lateral pressure, parallel compaction (open grading, bitumen content 3.5 percent).

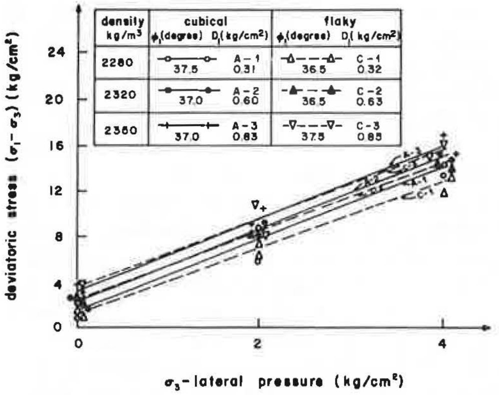


Figure 10. Deviatoric stress at failure versus lateral pressure, perpendicular compaction (open grading, bitumen content 3.5 percent).

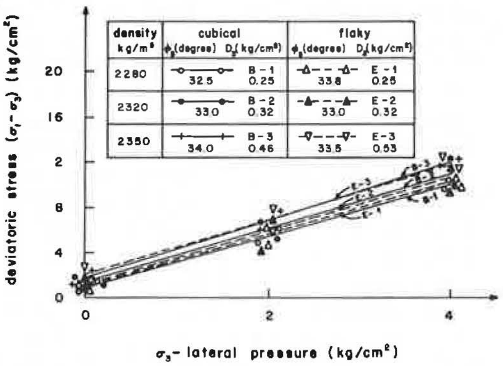
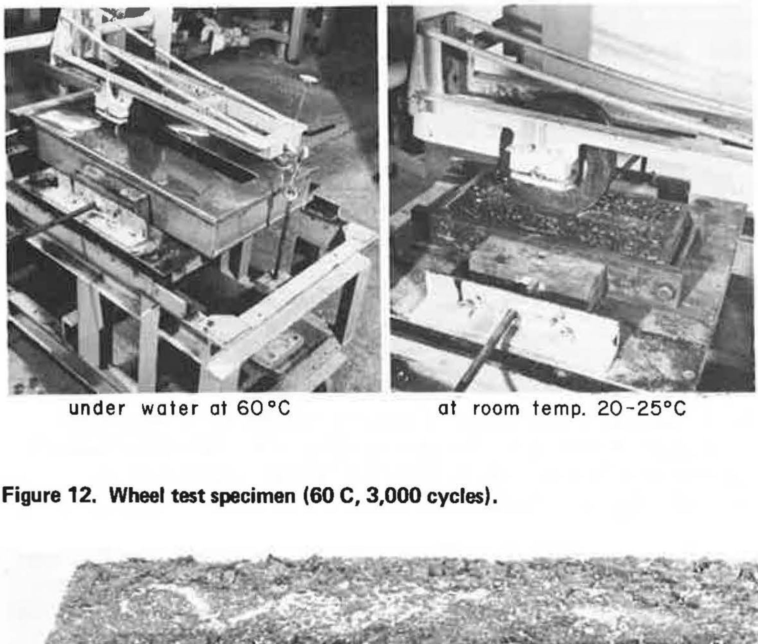


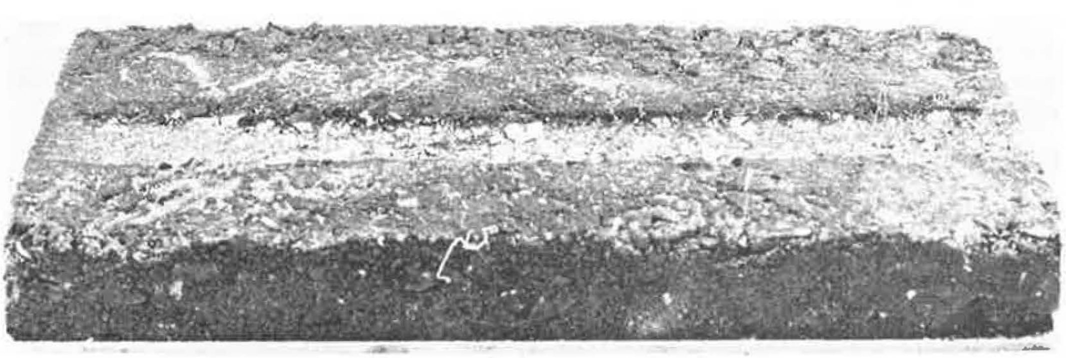
Figure 11. Wheel test apparatus.



under water at 60°C

at room temp. 20-25°C

Figure 12. Wheel test specimen (60 C, 3,000 cycles).



was approximately 25 percent, whereas the breakage of cubical particles was relatively negligible; and (b) in the loading-wheel test, the breakage value of flaky particles was approximately 30 percent in dense grading and 50 percent in open grading, whereas the breakage fraction of cubical particles was about 25 percent. Because the triaxial shear and moving-wheel tests showed that aggregate sphericity has no influence on load-carrying capacity (as opposed to the difference obtained in the Marshall test), it is reasonable to assume that the reduction of the difference in the breakage values between flaky and cubical particles, which was obtained in these tests as compared with the Marshall test, contributes to this result. In other words, the difference in load-carrying capacities decreases as the breakage fraction of flaky particles decreases.

These results give rise to the following questions: (a) What is the breakage value of hard flaky particles in road pavements; and (b) What is the influence of breakage on the decrease in tensile strength of asphaltic mixtures? The answer to the second question is discussed in the next section. To obtain an answer to the first question, we used a steel wheel to compact the specimens (Fig. 16). This method, which may be compared to the method employed on site, involves compacting the specimen for 24 min with a steel wheel 20 cm in diameter and 10 cm in width. The load applied on the specimen is 100 kg. It was found that in using this compaction method the breakage percentage of flaky particles is smaller than that obtained with specimens compacted by common laboratory methods. In dense grading, the breakage percentage of flaky particles ($-^3/_4$ in. $+^1/_2$ in.) is about 15 percent and in open grading about 30 percent. The breakage value of cubical particles was negligible in dense grading and was about 15 percent in open grading. This relatively small breakage value will give rise to a negligible change in the shape of flaky particles. In dense grading, about 15 percent change shape to cubical-flaky; in open grading, about 30 and 10 percent change shape to cubical-flaky and cubical respectively. From these results, it may be concluded that hard flaky particles may be expected to have a lower breakage value on the road than in laboratory specimens.

Another contribution of the mobile steel-wheel compaction method is that it enables one to determine the pattern of flaky particles in road pavements. From Figure 17 it may be concluded that the use of flaky particles does not produce a stratification pattern in the aggregates. In other words, the use of flaky particles in road pavements does not create weakness planes perpendicular to the direction of compaction.

Splitting Test

The splitting test can be used to determine the tensile strength (23) of asphaltic mixtures and to examine the influence of breakage on tensile strength. In this test, cubical specimens with 10-cm sides were used. Dense grading and a bitumen content of 5 percent were used in all the specimens, which were statically compacted at a pressure of 15 tons. Before splitting, the specimens were immersed in water at a temperature of 60 C.

The results of the splitting test are given in Table 1. This table shows that the use of hard flaky aggregates, as compared with cubical aggregates of the same category, does not decrease the tensile strength of the specimen and does not affect its anisotropic properties.

Weight-Volume Ratio Test

Single-size unstabilized flaky mixtures are less compactible than their cubical counterparts (20, 21). Because open-graded asphaltic mixtures also contain aggregates of various sizes, there is a possibility of eliminating, or at least of reducing, the influence of sphericity on compactibility.

A flaky mixture cannot be expected to have a lower void percentage as compared with a cubical mixture because this is only possible if the flaky particles assume a stratification pattern, which was proved to be impossible. This conclusion was confirmed by investigating the influence of sphericity on density by using the three compaction methods: dynamic, kneading, and static. The void percentage in asphaltic mixtures containing flaky aggregates was never smaller than that of mixtures containing

Figure 13. Grooving versus bitumen content with number of cycles (N) as parameter, dense grading at 24 C.

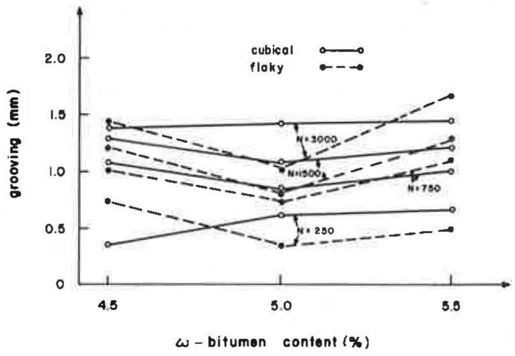


Figure 14. Grooving versus bitumen content with number of cycles (N) as parameter, open grading at 23 C.

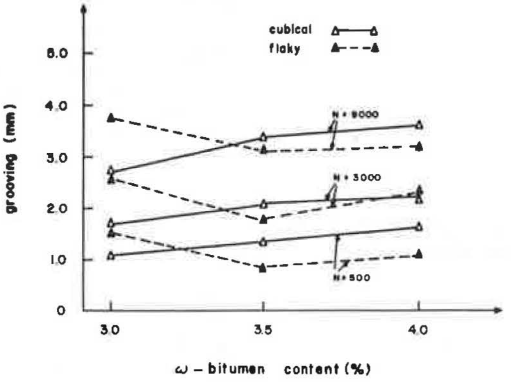


Figure 15. Grooving versus bitumen content with number of cycles (N) as parameter, dense grading at 60 C.

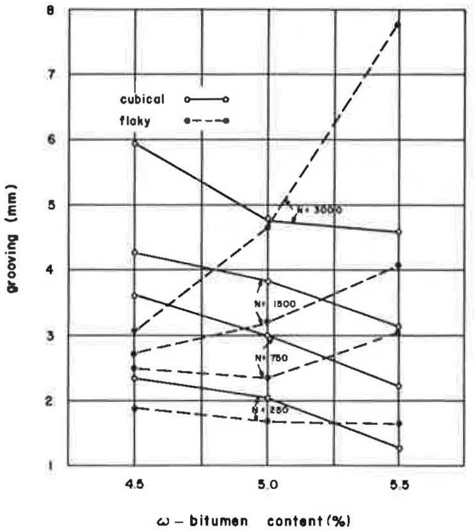


Figure 16. Steel wheel, compaction apparatus.

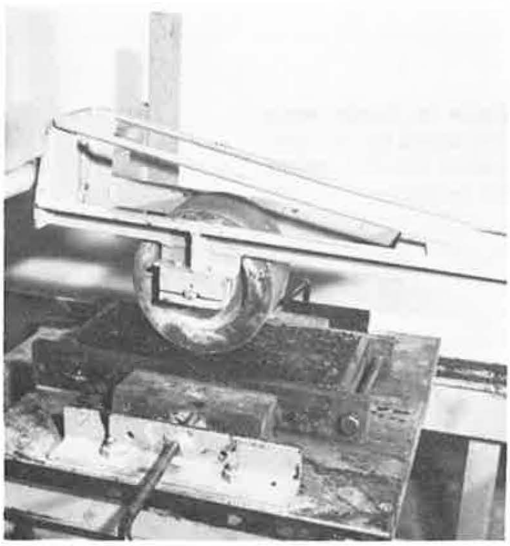


Figure 17. Sections of steel wheel, compacted specimens.

(a) flaky

(b) cubical

Table 1. Splitting test results.

Aggregate	Density (kg/m^3)	Compaction Direction[a]	$q_{parallel}$ (kg/cm^2)	$q_{perpendicular}$ (kg/cm^2)	$q_{parallel}/q_{perpendicular}$
Cubical	2,310	Parallel	27.1	–	1.6
	2,310	Perpendicular	–	16.9	1.6
Flaky	2,295	Parallel	24.2	–	1.5
	2,300	Parallel	32.9	–	1.5
	2,300	Perpendicular	–	19.2	1.5

[a] In relation to direction of load.

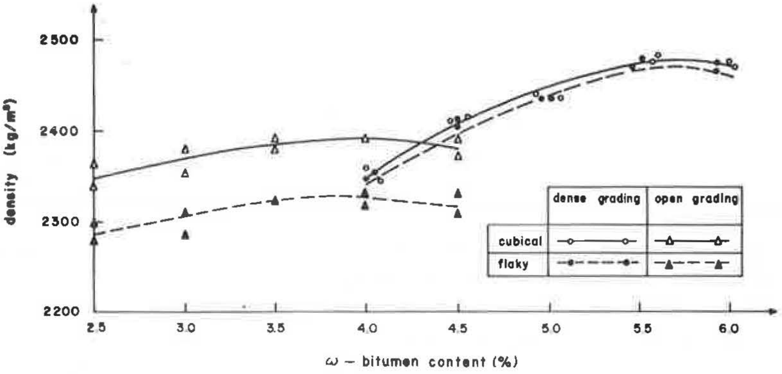


Figure 18. Density versus bitumen content.

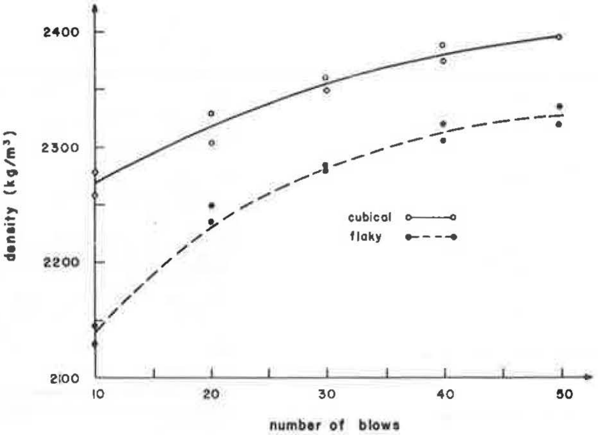


Figure 19. Density versus compaction energy, open grading (bitumen content 4.0 percent).

Table 2. Summary of findings.

Mixture Property[a]	Dense Grading	Open Grading
Marshall stability	No influence of shape; stability (reduced by 15 to 20 percent) in flaky mixtures in the case of higher breakage due to mode of compaction; stability higher than average for all shapes	Stability similarly reduced (by 55 percent); reduction of breakage narrows stability gap to 35 percent
Breakage value	Typical for laboratory compaction techniques used; lower in the case of wheel compaction and simulated field conditions	Typical for laboratory compaction techniques used; lower in the case of wheel compaction and simulated field conditions
Density	No influence of shape	Lower density in flaky mixtures (by 3.5 to 5.5 percent)

[a] There was no influence of shape in the following properties: Marshall flow, load-carrying capacity (triaxial shear test), optimal bitumen content, strength parameters D and Φ, grooving, and splitting test.

cubical aggregates. In the case of dense grading, the values of the void percentage were identical (Fig. 18), regardless of the compaction method. In open grading, the flaky specimens had a density of about 3.5 percent lower than the cubical specimens. Reduction of the compaction energy by the dynamic method increased the difference to about 5.5 percent (Fig. 19). In other words, the influence of sphericity was limited even here. It is noteworthy that, in the case of dynamic and kneading specimens, the density was determined by using the wax method (22). The excessively high results obtained—especially in the open-graded material—are apparently due to the penetration of the wax into the voids. In the case of the statically compacted specimens used in the wheel test, the density was determined by direct measurement. These results prove that, in both open and dense gradings, the flaky particles (like cubical particles) are arranged in a random pattern.

SUMMARY AND CONCLUSIONS

The data given in Table 2 lead to the conclusion, which occasionally contradicts the findings of others, that flaky aggregates (specifically the hard, crushed type used in the laboratory study) may be regarded as a conventional material from the engineering viewpoint, i.e., that they may be used for producing asphaltic mixtures for pavement layers.

In view of the difference in crushing values between the shapes (cubical, 21 percent, and flaky, 31 percent) on the one hand and their identical mode of production and mineralogical composition on the other, it was found that the crushing value is shape-dependent and that flaky material should thus be rejected. This, however, conflicts with the laboratory findings previously mentioned. Hence, it can be concluded that abrasion and crushing value are not always reliable criteria for determining the engineering quality of aggregates in road pavements and should thus be investigated further.

ACKNOWLEDGMENT

This paper is partially based on Greenstein's research work for the M.Sc. degree, under the supervision of Livneh, and is published by permission of the Graduate School of the Technion, Israel Institute of Technology, Haifa, Israel.

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APPENDIX

STUDY MATERIALS

Both coarse and fine aggregates (plus and minus sieve No. 4 respectively) were prepared from the same stone. Mineralogically, both consist of two forms of dolomite: One is yellowish, dense, hard, and fine-grained, and the other is whitish, slightly chalky, hard, and somewhat porous.

The coarse aggregate shape was classified in the three fractions ($-\frac{3}{4}$ in. $+\frac{1}{2}$ in., $-\frac{1}{2}$ in. $+\frac{3}{8}$ in., and $-\frac{3}{8}$ in. + No. 4) by using special sieves with rectangular apertures, as is shown in Figure 20. The description of the cubical and flaky aggregates (thickness-to-width ratio, i.e., $p = c/b$, Fig. 21) is shown in Figures 22 and 23. It can be seen that, under the present definition, shape categories vary mainly according to flakiness (100 percent flaky and 0 percent flaky according to B.S. specifications on flaky and cubical aggregates respectively), whereas elongation is almost the same for each fraction.

Crushing and abrasion tests indicate that the breakage is lowest for cubical aggregates [21 percent in crushing ($-\frac{1}{2}$ in. $+\frac{3}{8}$ in.) fraction and 18 percent in abrasion (grading B in Los Angeles abrasion test)] and highest for flaky aggregates (31 percent in crushing and 27 percent in abrasion with the fractions remaining the same). These data for cubical aggregates also reflect the relatively high hardness of the aggregate used in this study. The reason for selecting this aggregate was the high percentage of flaky aggregates that are found in quarries containing hard stones.

The specific gravity of the coarse material (in all gradings and shapes) was found to be the same (2.66), which indicates uniformity in its mineralogical composition. A similar uniformity was observed for the percentage of water absorption (1.5 percent), which indicates that the surface area is mainly governed by roughness and angularity values, whereas the influence of sphericity is negligible. The specific gravity of the

Figure 20. Rectangular sieves versus standard sieves.

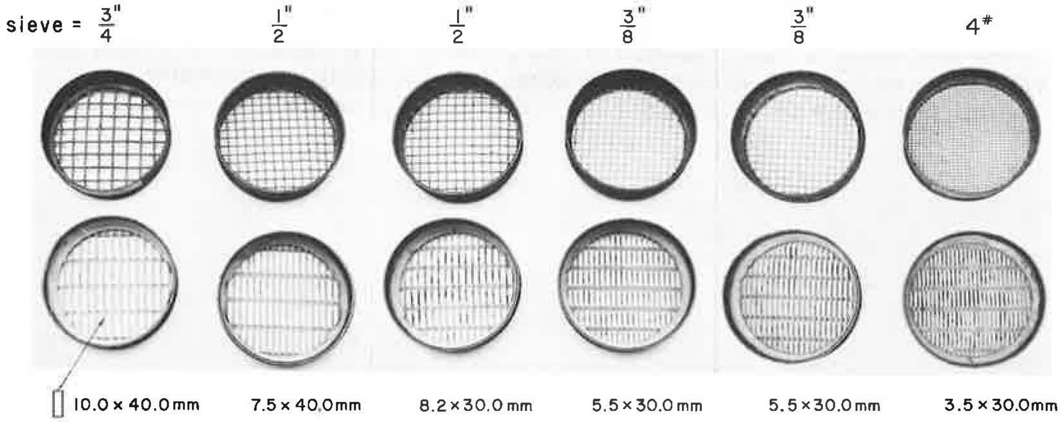


Figure 21. Aggregate dimensions.

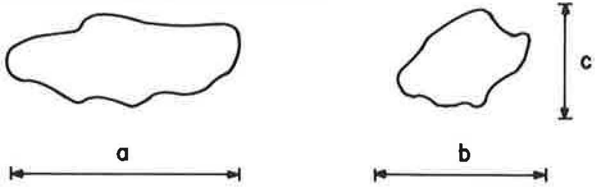
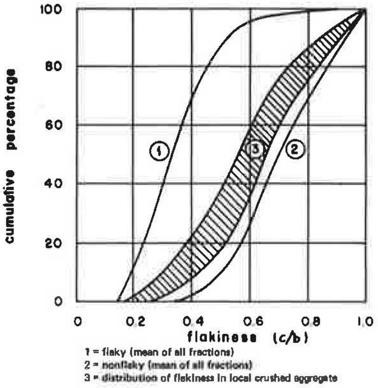


Figure 22. Aggregate shape.

Figure 23. Cumulative flakiness index.



fine material was found to be higher in dense grading than in open grading (2.81 versus 2.78) probably because of the higher content of the fraction passing sieve No. 200 (6.5 percent versus 2 percent). The specific gravity of the latter is 2.88.

The fine material was nonplastic in both gradings. The values of sand equivalent were 58 percent and 73 percent for the dense and open gradings respectively.

A bitumen with a penetration of 80 to 100 was used throughout the study.