

Compactibility of Asphalt Paving Mixtures and Relation to Permanent Deformation

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Most current specifications require asphalt paving mixtures to be compacted to a specified density, which in general is equivalent to a certain percentage of laboratory compaction. The application of such a density requirement in conditions of high in-service pavement temperatures and heavy traffic loading has resulted in many cases in excessive permanent deformation within the asphalt layers. For this reason, research has been carried out with the objective of studying the compaction characteristics of asphalt concrete mixtures by using an exponential function that represents the rate of increase in density versus the increase in compactive effort. The effect of mix variables such as filler content, binder content, and type of binder is included in the experimental program. Marshall specimens for each mix were subjected to compaction levels of from 5 to 100 blows on each face. Each specimen was then tested for creep at 40°C under a controlled constant stress (0.1 MPa) for 30-min load duration. Based on the experimental data and using linear regression analysis, a relation between compactibility and stiffness characteristics for each mix is established that is important in controlling permanent deformation distresses.

Permanent deformation at high in-service temperatures is considered to be a structural as well as a mixture design problem with asphalt pavements. At high temperatures, excessive permanent deformations that accumulate in the wheel path are a common failure mode of asphalt pavement layers subjected to heavy traffic loading conditions. Such failure was found to be associated with the densification of these layers under traffic (1). The degree of asphalt layer densification and its rate vary from one location to another depending on the wheel load condition and its repetition.

Compaction under traffic will gradually occur in an asphalt concrete layer placed at a density that corresponds to the 50-blow Marshall design (2,3). Furthermore, it is assumed (4) that the density achieved under long-term traffic compaction is reasonably close to that established by the 75-blow Marshall test. Barksdale (4) studied the relative beneficial effects of traffic compaction on both 50- and 75-blow mixes. He found that the use of a 75-blow mix increased fatigue life by 25 to 50 percent when the relative effect of traffic compaction was considered. Permanent performance, on the contrary, was found to be not sensitive to level of compaction as used in the Marshall mix design method but directly related to binder content.

Based on density and voids observations taken on pavements in Kuwait (1) and elsewhere (5-9), it appears that arbitrarily selected 50- and 75-blow Marshall compaction effort is inadequate as a realistic standard for controlling further traffic densification. The characteristics of such asphalt mixtures may not be representative of their performance in service. Therefore, an attempt is made in this paper to examine the compactibility of the asphalt concrete surface mixture currently used by the Kuwait Highway Department.

The effect on this mixture of the level of compactive effort used in the Marshall mix design method has been studied by using two different types of binders: (a) the conventionally used asphalt cement (AC), 60/70 penetration grade, and (b) a proposed sulfur-extended asphalt (SEA) binder with 40/60 sulfur/asphalt (S/A) ratio by weight. The variables studied include the effect of both filler content and binder content in the mixes. Further investigations were performed to evaluate the creep behavior of these mixtures at various compaction levels.

The purpose of this study is to contribute information that will provide a means of selecting an asphalt mix design that correlates with the actual performance of the tested mixture under expected environmental and traffic conditions.

PERMANENT DEFORMATION AND CORRELATION WITH TRAFFIC DENSIFICATION

The results of an earlier study (1) that included measurements of permanent deformations in asphalt pavement sections located in Kuwait showed that shear distortion in terms of rutting, shoving, and corrugation is associated with the densification of asphalt layers under traffic. The asphalt concrete portion of the pavement sections consisted of 180-mm surface and base courses. A 120-mm sand asphalt subbase layer was laid in one pavement section and a 200-mm sand gravel subbase layer below the other. Rut depth was measured in the wheel path at different locations after 2.2 million equivalent 80-kN standard axle-load applications. Values of measured permanent deformations ranged between 15 and 44 mm depending on the traffic pattern and speed at each location.

Volumetric compaction analysis carried out on cores taken from these locations showed that the densification under traffic mostly took place in the asphalt concrete surface courses. This may be due to the relatively high temperature and stress concentration these layers experienced during the service life of the pavement. From extraction tests, the ranges of asphalt content of the top 80 mm of asphalt concrete layers with 12- and 18-mm maximum grain size were 5.2 to 6.2 percent and 4.8 to 5.6 percent, respectively. The density of these layers at locations with a rut depth of more than 25 mm was almost close to 100 percent of the 75-blow Marshall mix design value.

Variations in volumetric composition by asphalt content and the way in which the end values of air voids (V_A) and asphalt saturation (S_A) are related to the estimated traffic conditions at the test locations and consequently to the measured permanent deformations are shown in Figure 1. Cores taken from locations where permanent deformation measured more than 25 mm were found to have air voids of 3 percent and less and asphalt saturation greater than 80 percent.

Creep tests carried out on the asphalt concrete core samples at a temperature of 40°C and a constant axial stress of 0.1 MPa for 60 min resulted in stiffness values less than 10 MPa for locations with critical values of air voids (less than 3 percent). The creep test results show that stiffness depends to a large extent on the volumetric composition of the mix. Increasing the compaction results in a relative increase in the volume of mineral aggregates, which improves the strength of the asphalt mix by increasing the component of its frictional resistance. This appears to be valid only as long as the air voids in the mix do not reach a critical end value. As soon as the percentage of air voids in the mix drops below this critical value, due to further traffic densification, significant losses in the component of frictional resistance start to oc-

Figure 1. Relation among volumetric composition, stiffness of asphalt concrete, and measured permanent deformation.

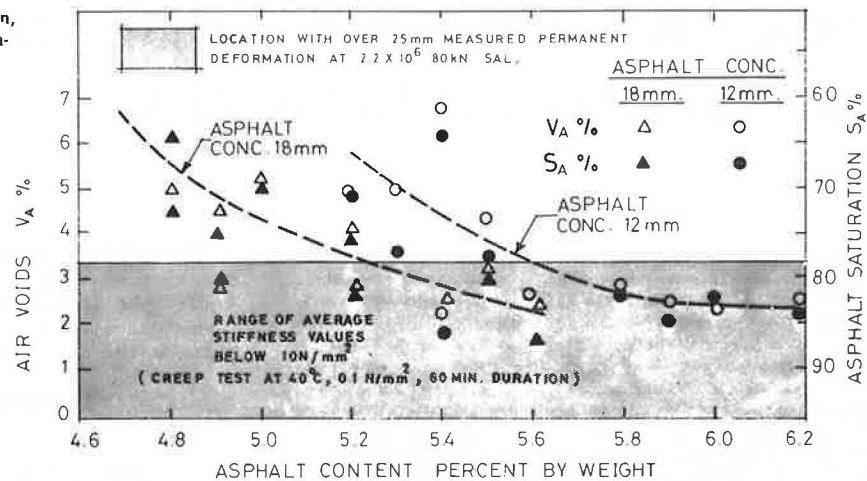


Table 1. Trials on asphalt concrete surface course mixes to investigate effect of compaction effort.

Item	Mix 1	Mix 2	Mix 3
Percent passing sieve size			
12.70 mm	100	100	100
9.51 mm	84	84	84
4.76 mm	62	62	62
2.00 mm	42	42	42
1.19 mm	31	32	33
0.25 mm	18	21	24
0.149 mm	9	14	19
0.074 mm	5	9	14
Binder content (percent by weight of aggregate)			
AC, 60/70 penetration	4.5	5.5	6.5
	5.0	6.0	7.0
	5.5	6.5	7.5
SEA, 40/60 sulfur/asphalt ratio by weight	5.5	6.5	7.5
	6.0	7.0	8.0
	6.5	7.5	8.5

Notes: Average mixing temperature for A mixtures = 155°C and for B mixtures = 140°C. Compaction temperature ranged from 120°C to 130°C.
The number of compaction blows on each end = 5, 15, 25, 50, 75, 100.

cur, which results in low stiffness values and excessive permanent deformation.

The analysis of volumetric composition shows how, in the case of heavy traffic conditions and high in-service pavement temperatures, a change of about 0.5 percent in the asphalt content will result in a drastic change in permanent deformations, as measured at these test locations.

The results of the above analysis emphasize the importance of including two parameters that affect the required relative density in the design of an asphalt mix. The first is defined as the initial percentage value of Marshall density achieved at the time the mix is placed on the road. The other parameter controls the compactibility or resistance to compaction that could be determined from a compaction curve that shows the rate of change in density versus compaction effort.

MATERIALS AND PROCEDURES

Materials

The materials selected for the study were those currently available for use in asphalt paving mixtures in Kuwait. The coarse and fine mineral aggregates used in this investigation were sieved and recom-

Table 2. Rheological properties of asphalt binders used in experiment.

Property	AC 60/70	SEA 40/60 Sulfur/Asphalt by Weight
Penetration at 25°C, 100 g, 5 sec (1/10 mm)	62	38
Softening point, ring and ball (°C)	48	52
Viscosity (Pa·s)		
140°C	0.45	0.21
120°C	1.45	0.68
60°C	2.73×10^2	4.60×10^2
40°C	8.20×10^3	18.20×10^3

bined in the proper proportions to give the required gradations. The coarse aggregate was crushed, naturally occurring gravel, predominantly of the igneous and quartz groups of rock, of a maximum grain size of 12.5 mm. The fine aggregate used in the mixes consisted of 40 percent natural sand, predominantly quartz, and 60 percent crushed sand with the same mineralogical characteristics as that of the coarse aggregate used. There was less than 2 percent material passing the 0.074-mm sieve in the sands used, and the average sand equivalent value was 60.

To study the effect of fines content (less than 0.074 mm) on the compactibility of the asphalt mixes, three mix gradations were prepared. The essential difference between them was the fraction passing the 0.074-mm sieve, as given in Table 1. The limestone powder used in this study as mineral filler is mostly calcite and some dolomite. It is non-plastic and has a liquid limit of 15 to 20. The percentage passing the 0.074-mm sieve is in the region of 75 to 80 percent by weight. Two types of bituminous binders have been used with the three aggregate mixes in this investigation. The first is a 60-70 penetration grade AC locally produced in Kuwait. The second binder is an SEA with a 40/60 S/A ratio by weight. Rheological properties of both binders, including viscosity values at mixing, compaction, and in-service pavement temperatures (see Table 2), have been determined by means of rotor and cone-and-plate viscometers (1).

Specimen Preparation and Testing

The three dense-graded asphalt mixes were evaluated for heavy traffic loading design, as recommended by the Asphalt Institute, by using the 75-blow Marshall design procedure (ASTM D1559). SEA binder was pre-

pared by having the melted elemental sulfur, 40 percent by weight, mixed together with the heated AC, 60 percent by weight, at a mixing temperature of about 145°C. A homogenizer that operates at a constant speed of 1500 revolutions/min was used for the emulsification process with a shearing time of 8 min. The spacing between the rotor and the bottom of the mixing hopper was maintained at about 1.0 mm to avoid any possible sedimentation of sulfur during the mixing process. The prepared SEA binder was immediately used in the preparation of the Marshall test specimens by means of techniques normally used with conventional asphaltic concrete.

After at least 1 day of predrying at 110°C, the aggregates were thoroughly dried before use by heating overnight at 160°C. The hot aggregates were mixed for about 15 sec, the asphalt binder was added, and mixing continued for another 45 sec at 160°C for the AC and at 145°C for the SEA.

Optimum binder content for the three mixes was determined for both AC and SEA binders by using the Marshall procedure. A total of 432 Marshall briquettes were prepared from the three mixes with the two binder types at three binder content levels: optimum percentage and 0.5 percent by weight above and below the optimum value. Each mix was subjected to five different levels of compaction effort. The compaction of the briquettes was carried out in a machine that delivered 5, 15, 25, 50, 75, and 100 blows (each of 21 J) to each side of the specimen. One-half of the specimens prepared were tested for bulk density, voids content, Marshall stability, and flow. The other half were tested for creep. All specimens were kept for 4 weeks at room temperature before being tested so that any possible aging effect of the binders could be used in the test results.

The permanent deformation characteristics of the asphalt mixes were evaluated by performing creep tests on the prepared Marshall specimens at a constant temperature of 40°C. The creep tests were performed in the unconfined condition in an environmental chamber that controlled the temperature of the specimen during the test. An axial constant stress of 0.1 MPa was applied on all test specimens. This stress level was recommended by Van de Loo (11) to keep the creep response within the linear range of usual asphalt concrete mixes. Both ends of the specimen were lightly coated with a silicone lubricant and sprinkled with powdered graphite to minimize friction between the end of the specimen and the compression platen. The specimens were subjected to a single step loading for 60 min by using a universal servohydraulic testing machine. The output for both load and axial strain was measured on a strip chart recorder.

DISCUSSION OF TEST RESULTS

Comparison of Marshall Mix Design Data

At different compactive efforts, Marshall design data for the mixes under consideration are compared as shown in Figures 2-6. As the applied compaction level increased, the following trends were apparent:

1. Compaction level was found to have considerable influence on the Marshall stability values of the asphalt concrete A mixes studied. For mix 1, which had low filler content (5 percent by weight), increasing the compactive effort to a maximum of 100 blows resulted in about a 270 percent increase in Marshall stability. However, for mixes with 9 and 14 percent filler content, only 100 and 25 percent

Figure 2. Effect of compaction on stability and voids content: mix 1.

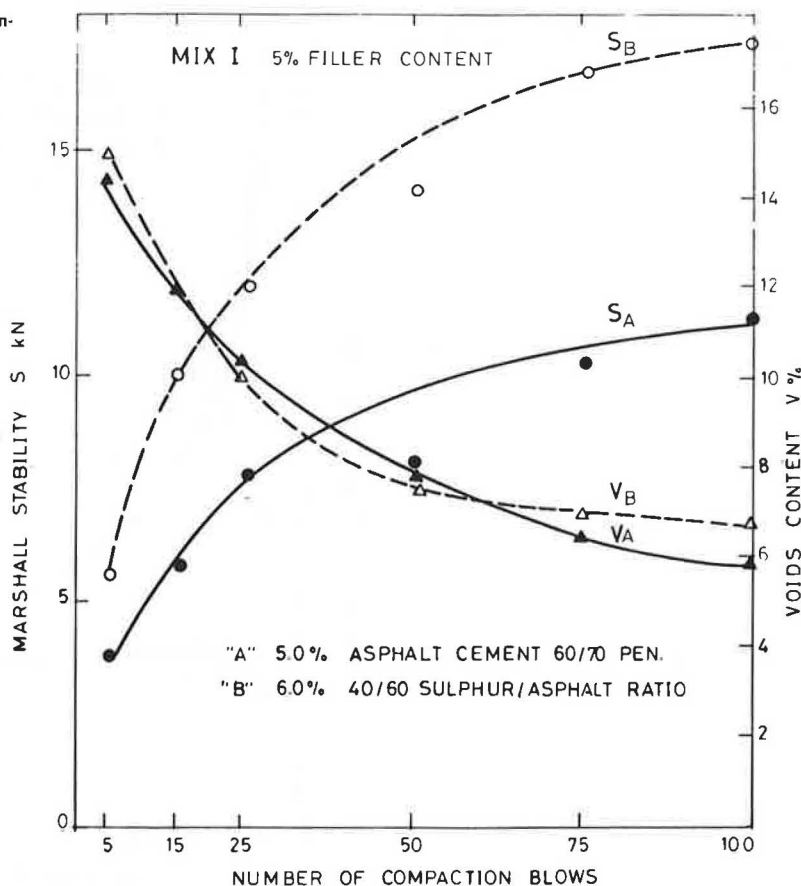


Figure 3. Effect of compaction on stability and voids content: mix II.

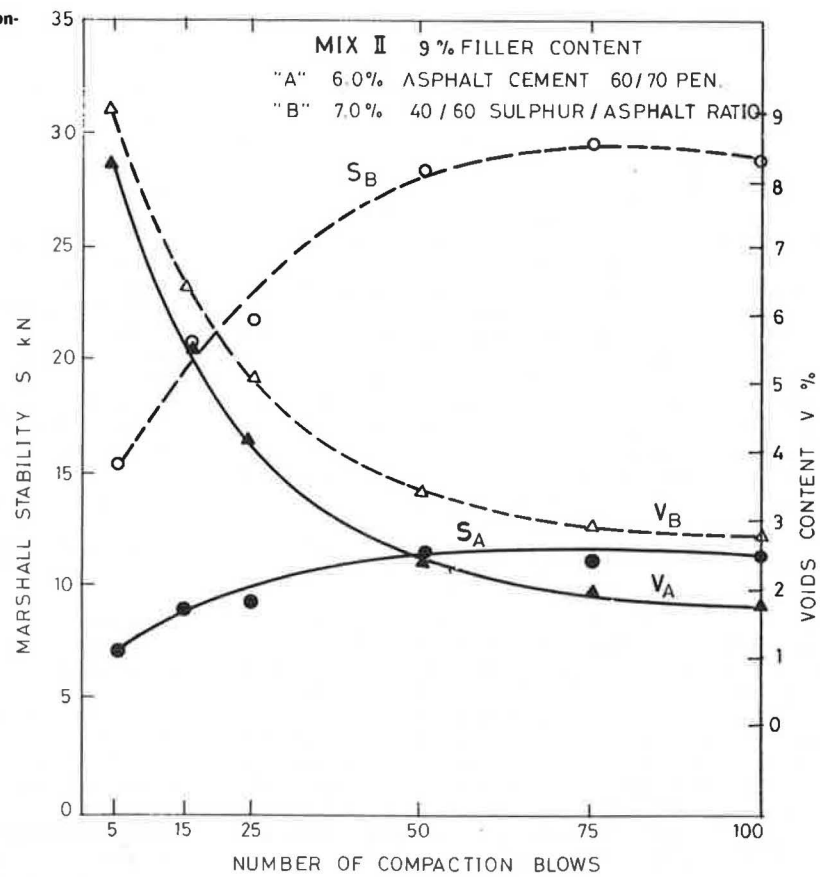


Figure 4. Effect of compaction on stability and voids content: mix III.

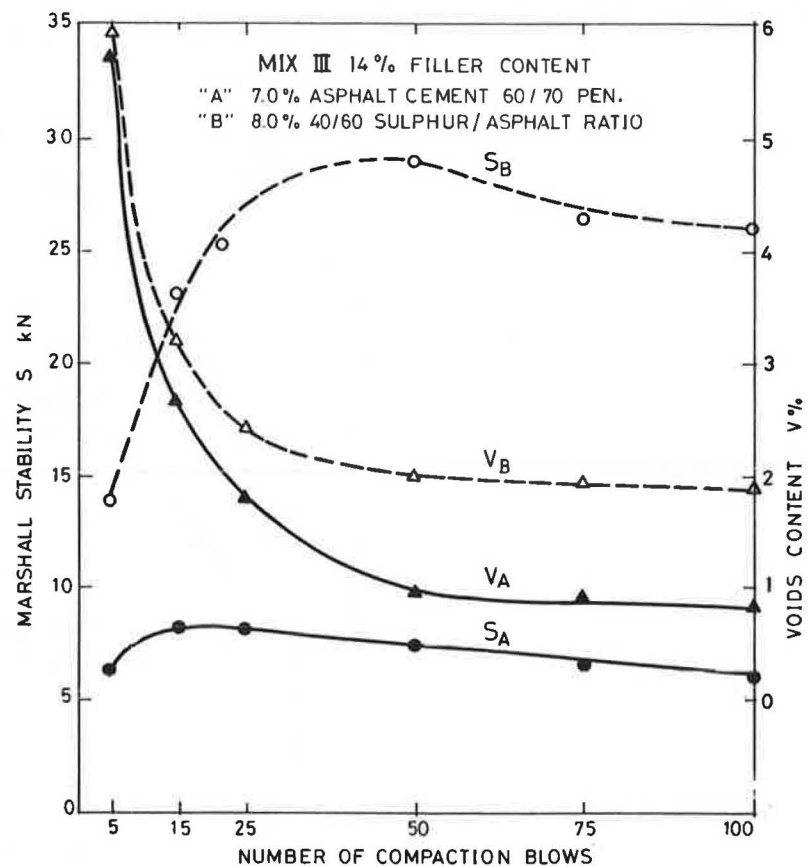


Figure 5. Percentage of voids filled with binder versus number of compaction blows.

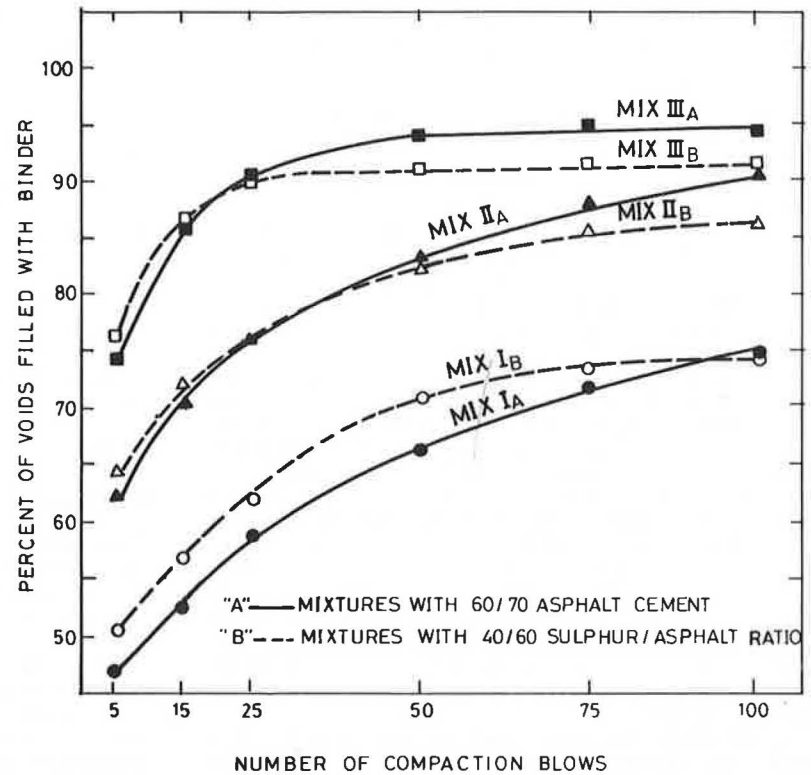
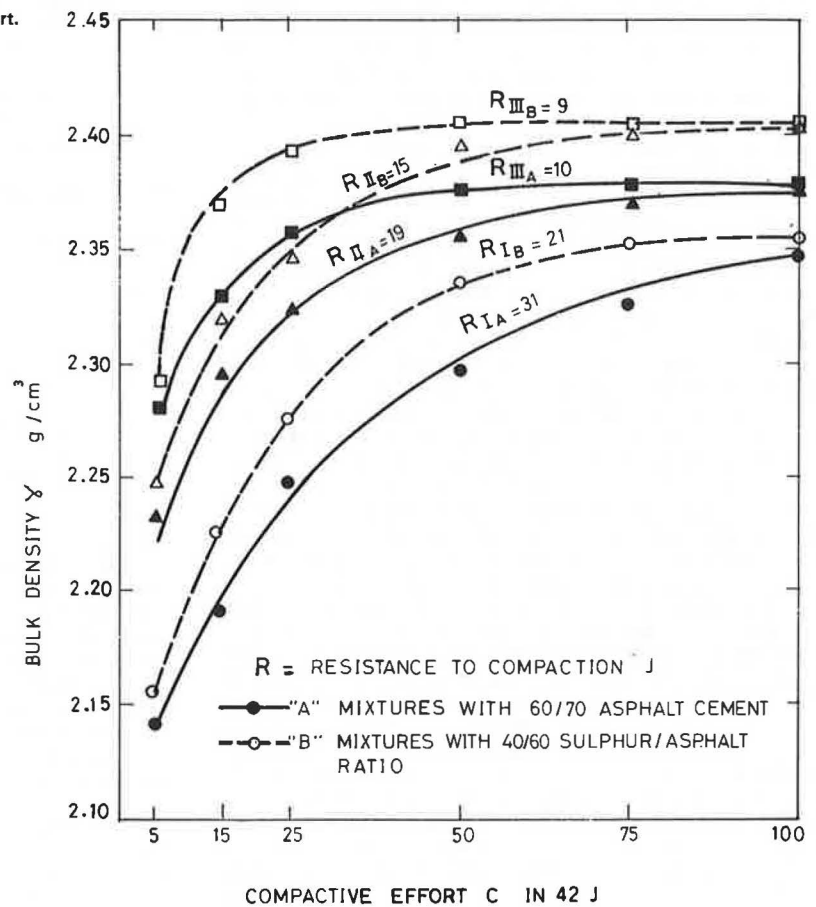


Figure 6. Variation of bulk density versus compactive effort.



increases in stability values were found to be associated with an increase in compactive effort to 50 and 25 blows, respectively. No significant change occurs in Marshall stability values for mix 2 (9 percent filler) above the 50-blow compaction level. However, for mix 3 (14 percent filler), about a 20 percent decrease in Marshall stability value has been found by increasing the compaction level from 25 blows to 100 blows.

2. A similar trend in the relation between Marshall stability values and compaction level has also been found for sulfur-asphalt concrete B mixes. Marshall stability values for these mixes were much higher than those for conventional asphalt concrete. The stiffening effect of sulfur in mix I_B with 5 percent filler content at 50-blow compaction resulted in a stability increase of about 200 percent compared with that of mix I_A . At the same compaction level, mix III_B with 14 percent filler content showed a greater stability increase—about 400 percent compared with that of mix III_A . It was shown that the given sulfur additive had a significant stiffening effect in mixtures with a greater percentage of filler content. This could be related to the formation of sulfur needles through unconfined growth in the mixtures with relatively lower void levels (12). Sulfur needles extended across the voids provide the beneficial structure mechanism that results in the increase of stability values.

3. Changing the filler content in the mix has a significant effect on the percentage of voids measured at different compactive efforts. Voids content in mixes with low filler content (5 percent by weight) decreases from 14 to 3.8 percent by increasing the compaction level up to 100 blows. The higher the filler content in the mix, the less compactive effort is required to achieve an end value of voids percentage. Mixes with 14 percent filler content achieved their end values of voids content ($V_A = 0.85$ percent for mix III_A and $V_B = 1.9$ percent for mix III_B) at about 50-blow compaction. The voids content in these mixes remains almost unchangeable when the compactive effort is increased to the 100-blow level (see Figure 4).

4. Sulfur-asphalt concrete mixes were found generally to have higher voids content than conventional asphalt concrete mixes at all compactive efforts. At low compaction levels, the difference is considered to be negligible, and it increases with the increase in the number of compaction blows. The percentage of voids filled is slightly higher in sulfur mixes than in the same mixes with no sulfur. It remains higher over the whole range of the compaction levels for mixes with 5 percent filler content. For mixes that contained higher filler contents, higher values of percentage voids filled were measured up to a certain compaction level (50 blows for mixes with 9 percent filler content and 25 blows for mixes with 14 percent filler content), above which the percentage of voids filled in conventional mixes continues to increase at a much higher rate than that for sulfur mixes (see Figure 5). Due to the low viscosity of SEA binder compared with that of AC 60/70 at the applied compaction temperatures, sulfur-asphalt mixes could be densified at a lower compactive effort than conventional mixes. After a certain level of density is achieved, the formation of sulfur crystallization across the voids provides a higher resistance to the densification process so that the volumes of aggregates in these mixtures remain almost unchanged under further compaction.

5. Compaction curves for the mixes under consideration are represented in terms of bulk density (γ) versus compaction effort (C) (number of blows $\times 42$ J), as shown in Figure 6. The shape of these

curves presents in principle the compactibility of each mix, or the resistance of each mix to compaction, due to changes in filler content and binder type. All sulfur-asphalt mixes tested generally displayed lower resistance to compaction than conventional mixes. This is only valid up to a certain compaction level, above which the densification process shows that conventional mixes display less resistance to compaction than mixes with sulfur. Mixes with higher filler content achieve higher relative densities at a lower compaction level. At 50-blow compaction, 99.89 percent of the maximum achievable density was measured for mix III_A (14 percent filler) and 97.67 percent was measured for mix I_A (5 percent filler). In addition, at 50-blow compaction mix I_B with sulfur additive achieved 99.05 percent of its maximum density compared with 97.67 percent of the same mix with no sulfur additive.

Determination of Resistance to Compaction

A mathematical model has been formulated by Arand (13) that describes the compaction process by using an exponential function that represents the rate of increase in density versus the increase in compactive effort. This approach has been applied to determine the resistance to compaction of the asphalt paving mixes considered in this study. It is noted that there is a differential relation between the rate of change of density of the mix and that of compactive effort applied, which can be expressed in the form

$$d\gamma/dC = (1/R) (\gamma_\infty - \gamma) \quad (1)$$

where

$d\gamma$ = rate of change of bulk density,
 dC = rate of change of compactive effort,
 R = resistance to compaction (multiplied by 42 J),
 γ_∞ = maximum achievable bulk density (g/cm^3), and
 γ = bulk density at a certain compaction level (g/cm^3).

By integration, this equation leads to

$$\int [d\gamma/(\gamma_\infty - \gamma)] = (1/R) \cdot \int dC \quad (2)$$

$$-1_n(\gamma_\infty - \gamma) = (C/R) + 1_n B \quad (3)$$

where

$B = \gamma_0 - \gamma_\infty$,
 γ_0 = bulk density at the start of the compaction process (g/cm^3), and
 $\gamma C = \gamma_\infty - (\gamma_\infty - \gamma_0) \cdot \exp(-C/R) = \text{bulk density at compaction level } C (\text{g/cm}^3)$.

For $C = 0$, the exponential compaction function $\exp(-C/R) = 1$.

Experimentally determined bulk density values for Marshall specimens prepared at different compactive efforts have been approximated through use of the exponential compaction function, and the parameter R has been determined accordingly. For the mix variables considered in this analysis, the exponential compaction functions were found, to a high degree of approximation, to be suitable for describing the compaction process of these mixes. An example for calculating the parameter R is given in Table 3.

The effect on R of variable filler and binder content for mixtures with and without sulfur additive has been determined. Figure 7 shows the variation of $R \times 42$ J with the percentage of filler content. Conventional AC mixes exhibit higher values

of resistance to compaction than sulfur AC mixes at a low percentage of filler content. Varying the binder content in the range of ± 0.5 percent of the optimum for mixes containing 5 percent filler content resulted in R values ranging from 25 to 34 for conventional mixes and from 16 to 24 for sulfur AC mixes. However, for AC mixes with 14 percent filler content, R values were found to vary from 6 to 12 in the range of ± 0.5 percent of the optimum binder content for both AC mixes with and without sulfur. This means that introducing sulfur in the ratio of 40/60 S/A in AC mixes with relatively high filler content resulted in no significant change in resistance to compaction. Generally, values of R are

less affected by changes in mix composition with sulfur AC mixes than with conventional AC mixes.

Stiffness and Its Relation to Resistance to Compaction

In regions where in-service pavement temperatures are high and permanent deformation of the asphalt layers is a problem, most investigators use design procedures that can estimate the rutting that will occur in practice. Creep tests have recently been used on laboratory-prepared specimens to rank asphalt pavement mixes and to predict permanent deformation (11).

Table 3. Calculating resistance to compaction (R).

Mix	Filler (%)	Bitumen (%)	Max Theoretical Specific Gravity	C (blows)	γ^a	Voids (%)	R(x42 J)
I _A	5	4.5	2.440	0	2.097		
				5	2.138	12.29	29.50
				15	2.202	9.84	29.43
				25	2.241	8.19	31.52
				50	2.302	5.66	33.07
				75	2.332	4.43	33.48
				100	2.348	3.77	32.39
III _A	14	7.0	2.386		2.360		
				0	2.180		
				5	2.255	5.52	9.95
				15	2.330	2.37	9.62
				25	2.348	1.62	11.59
				50	2.367	0.82	12.05
				75	2.369	0.74	12.62
				100	2.370	0.70	
					2.370		

^a $\gamma_0, \gamma_5, \dots, \gamma_{100}$

Figure 7. Effect of variable filler and binder content on resistance to compaction.

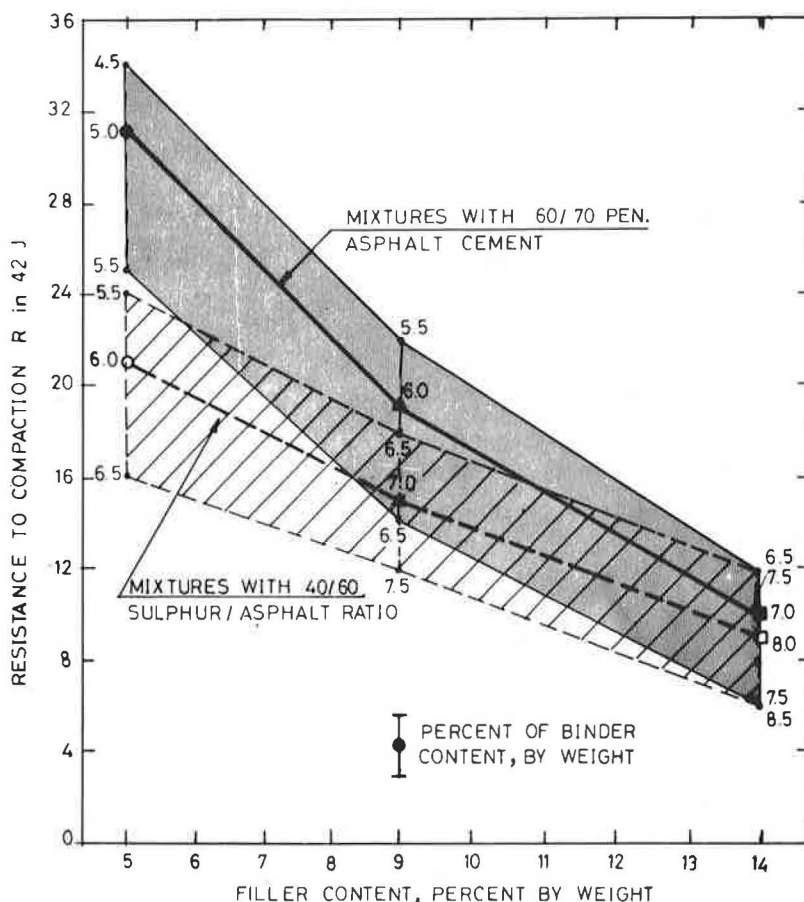
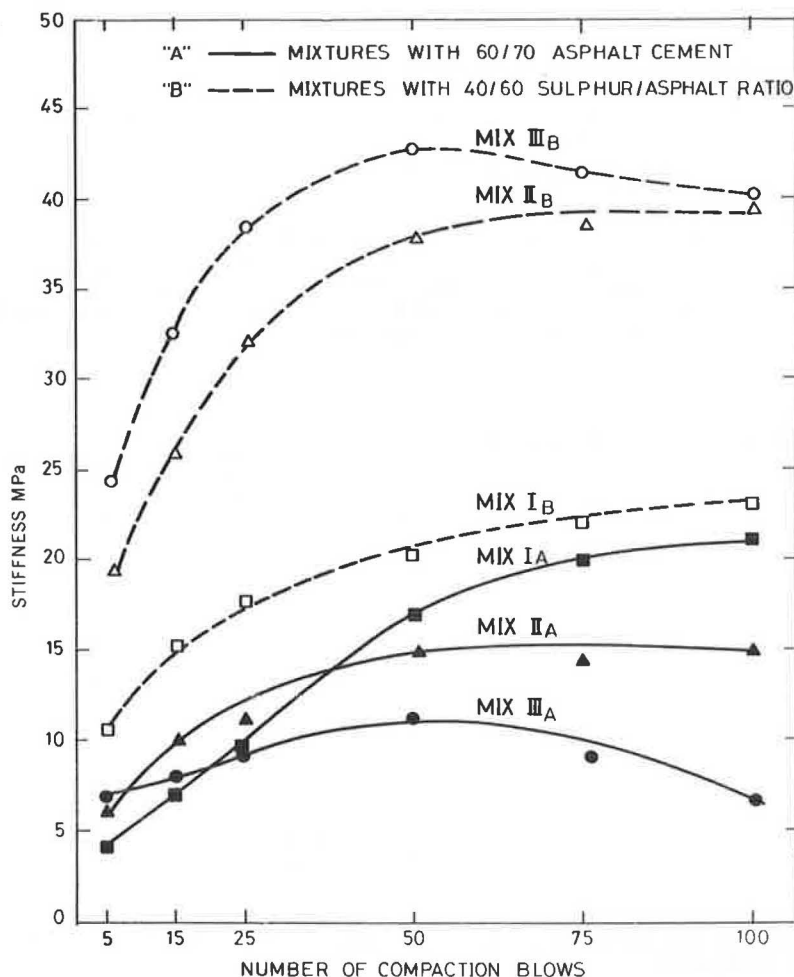


Figure 8. Stiffness versus number of compaction blows.



The results of creep tests carried out on Marshall specimens at a temperature of 40°C and a constant axial stress of 0.1 MPa for a load duration of 60 min are given in terms of stiffness values. Figure 8 shows the effect of variable compactive efforts on the stiffness of the asphalt paving mixes at optimum binder content. For mixes I_A and I_B (with 5 percent filler content), up to 100-blow compaction level, the decrease in voids content is associated with a continuous increase in stiffness values from 4.4 to 21.5 MPa for mix I_A and from 8.0 to 23.2 MPa for mix I_B. However, for mixes III_A and III_B (with 14 percent filler content), the decrease in voids content is associated with an increase in stiffness values only up to 50-blow compaction level. Exceeding this level of compaction resulted in a decrease in stiffness values. This decrease is related to the critical end value of voids content achieved at this stage of densification, which produces a higher rate of increase in plastic deformation of the mix.

As expected, sulfur AC mixes are found to be of greater stiffness than conventional AC mixes at all compaction levels. But it is interesting to note that the higher the filler content in the mix, the more effective is the sulfur additive in increasing the stiffness. Using SEA binder in mixes with 14 percent filler content resulted in stiffness values about 3.7 times those of the conventional mix. However, for mixes with 5 percent filler content, the stiffness values averaged only 1.5 times those of the conventional mix. As discussed earlier, this is related to the formation of sulfur needles in the

mixtures with the higher filler content (lower voids content), a beneficial structure mechanism that results in the increase of stiffness of the mix.

For all mixes studied, stiffness decreased with increasing percentage of binder content within the range of ± 0.5 percent of the optimum value. Susceptibility to change in stiffness with respect to binder content was found to increase as the percentage of filler content in the mix increased. Figure 9 shows the effect of variable filler and binder content on the stiffness of specimens compacted at 75-blow compaction level. For both conventional and sulfur-asphalt concrete mixes, measured stiffness values in megapascals, at variable filler and binder contents, were plotted as a function of resistance to compaction in joules, as shown in Figure 10. The purpose was to find out whether a relation could be established between the stability of the mix in terms of its stiffness value (S) and its compactibility in terms of its resistance to compaction (R). It is interesting to note that the general linear form of the curve showing stiffness versus resistance to compaction for conventional asphalt concrete mixes, within the range of change in both filler and binder content, is similar to that developed by Arand (14). It was possible to establish for these mixes a relation of the form $S = 5.28 + 0.49 R$ with a correlation coefficient of $r = 0.96$.

For sulfur-asphalt concrete mixes, no single relation between S and R was found as in the case of conventional mixes. This is due to the effectiveness of sulfur additive in reducing the resistance to compaction and in increasing the structural rein-

Figure 9. Effect of variable filler and binder content on stiffness.

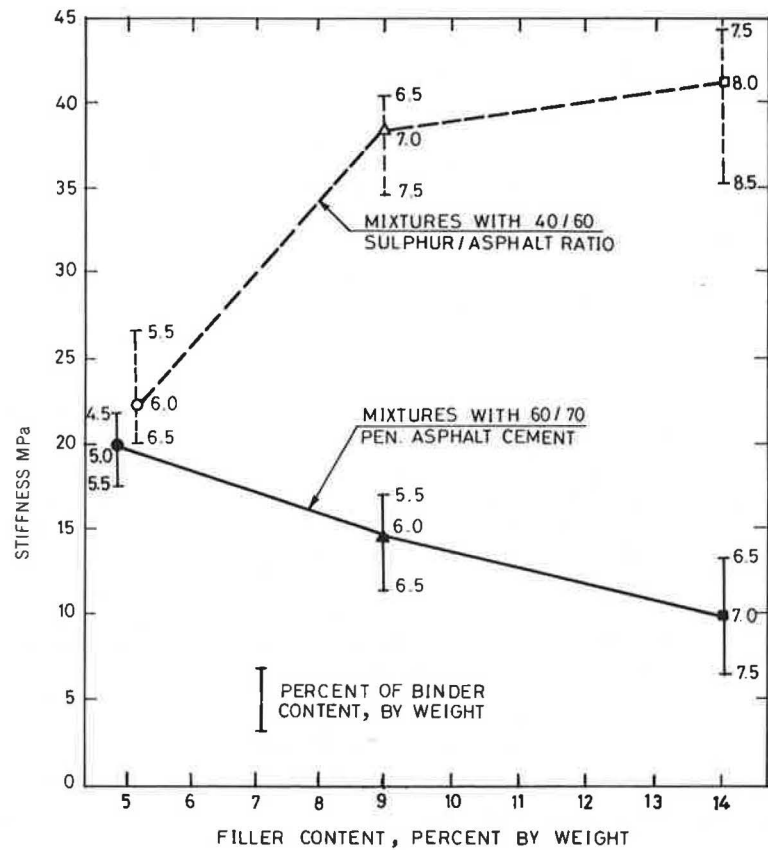
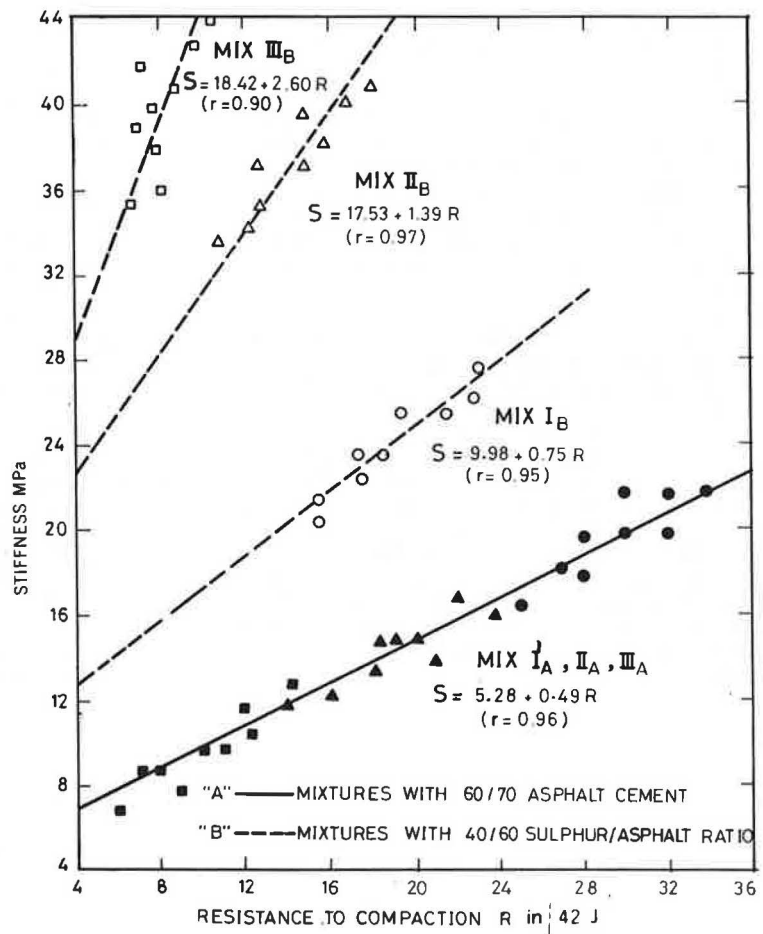


Figure 10. Stiffness versus resistance to compaction.



forcement of sulfur crystals by increasing the filler. In Figure 10, a set of three linear relations between stiffness and resistance to compaction is shown for sulfur-asphalt concrete mixes with low, medium, and high percentages of filler content. It is noteworthy that mixes III_B, which have the highest percentage of filler content, have the highest stiffness at the lowest range of values of resistance to compaction, which is contrary to the situation with conventional mixes. This phenomenon emphasizes the beneficial effect of introducing sulfur into asphalt mixes that have a relatively high percentage of filler content to modify their permanent deformation performance.

SUMMARY AND CONCLUSIONS

This paper has presented the results of a laboratory investigation to determine the relation between permanent deformation characteristics of asphalt paving mixes defined in terms of stiffness values derived from static creep tests and the compactibility of these mixes in terms of resistance to different Marshall compaction levels. A dense gradation of an asphalt concrete surface mix has been considered in this analysis at three different levels of both filler content and binder content. In addition, two types of binders were applied: 60/70 penetration grade AC and an SEA with 40/60 S/A ratio by weight. The analysis indicated that use of the Marshall mix design is feasible and practical in evaluating asphalt paving mixes with respect to traffic densification if the volumetric composition values of the mix, controlled by a certain percentage of the values achievable at a given level of laboratory compaction, are supported by another parameter that defines compactibility in terms of resistance to compaction.

The resistance to compaction of asphalt mixes was determined from compaction curves showing density versus compactive effort. The values obtained for resistance to compaction were found to be significantly affected by mix variables such as filler content, binder content, and type of asphalt binder. The sensitivity of other mix variables--such as type of mineral aggregate and gradation--to resistance to compaction can also be studied through the use of compaction curves. This in turn can help modify the job mix formula tolerances to suit particular pavement service conditions.

For the conventional mixes as well as the sulfur-asphalt concrete mixes tested, relations were established for each mix between values of resistance to compaction and stiffness values. Generally, the higher the resistance of a mix to compaction, the higher is its measured stiffness value and, consequently, the better its permanent deformation performance is expected to be. For sulfur-asphalt concrete mixes, the same trend was followed as for conventional mixes, but changing the percentage of fines in the mix was found to affect the constants in the linear relation between stiffness and resistance to compaction. The higher the percentage of fines in the mix, the higher is the measured stiffness of the mix at a lower value of resistance to compaction.

The conclusions drawn based on the results of the experimental data are applicable to the materials and testing procedures of this research only and should not be extended beyond these limits without the appropriate verification.

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Publication of this paper sponsored by Committee on Characteristics of Bituminous Paving Mixtures to Meet Structural Requirements.