TENTATIVE MIX-DESIGN CRITERIA FOR GAP-GRADED BITUMINOUS SURFACES

C. P. Marais, National Institute for Road Research, Pretoria, South Africa

Since the turn of this century, extensive use has been made of gap-graded bituminous surfacing mixtures in the United Kingdom. The design of these mixtures has largely been empirical, and specifications have been of the recipe type. The excellent performance given by these mixtures, even under the most severe traffic conditions, has prompted engineers in other parts of the world to use these surfaces. Experience has shown that under some climatic conditions the United Kingdom specifications did not always produce the most satisfactory mixtures, and a national method of design was urgently required. This paper covers a research study into factors that affect the performance of gap-graded surfaces and isolates those that are of particular importance. It is shown that the Marshall test method, when used in combination with air permeability and indirect tensile tests, can be used to design gap-graded mixtures. Tentative criteria are established for the mix design of gap-graded bituminous surfaces; they will satisfy normally accepted standards with respect to distortion, fracture strength (toughness), fatigue, imperviousness, and durability.

•THE AMERICAN chemist and highway paving technologist, Clifford Richardson, introduced stone-filled, sand-sheet asphalt surfacing mixtures that could withstand heavy traffic and cold , wet climatic conditions to the London authorities at the turn of this century (1, 2). These mixtures have been modified over the years to meet changing traffic conditions in the United Kingdom and are covered by British Standard 594, which is updated from time to time to keep pace with advances in asphalt technology. This type of mix is characterized by the fact that its stability or distortion resistance is derived almost wholly from the stiffness of the mortar, that is, the bitumen-sand-filler mixture. For this reason the correct selection of the aforementioned components is important. Experience has shown that low stone content mixtures specified in BS 594 are more durable than those with high stone contents and are therefore favored for important highways. A disadvantage of the low stone content mix is its sandpaper texture, which is not suitable for high-speed traffic in wet weather. This problem has largely been overcome by introducing during construction carefully selected coated chippings to give a rugose surface texture.

The good performance of experimental gap-graded mixtures of low and high stone content on a heavily trafficked urban street in South Africa led South African road authorities to take a keen interest in gap-graded surfacing mixtures (3). During the past decade, gap-graded surfaces have, generally speaking, replaced the more critical continuously graded asphalt concrete; their use has become standard practice on urban and rural freeways. Because of the warm climate in South Africa, mixtures conforming strictly to BS 594 did not always perform well, so modifications to this specification were necessary. Varying natural materials such as sand and filler also resulted in varying performance. A need therefore arose for a design method whereby the properties of the mixture could be determined for the selection of an acceptable mixture composition by applying suitable design criteria. Research to meet this need has been in progress in South Africa and the United Kingdom (4, 5).

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This paper describes a laboratory study and field data aimed at establishing the factors that control the performance of gap-graded surfaces and suggests design criteria to ensure adequate distortion resistance, fracture strength, fatigue resistance, imperviousness and durability of these mixtures.

LABORATORY STUDY

Mixture Composition

To cover a wide spectrum of practical gap-graded compositions, we selected a number of stone contents between 30 and 50 percent. Crushed coarse stone of 2 maximum sizes was used in combination with 2 different types of sand. The binder used was a 40-50 penetration grade bitumen vacuum distilled from Middle East crude oil. The bitumen content of each mixture was varied over a wide range. The typed filler and content, 7 percent by mass of aggregate (stone + sand), were not varied in this study. Combined aggregate gradings used in the study are shown in Figure 1. Physical tests carried out on the 2 sands used in this study are given in Table 1.

Mechanical Tests

From performance records of gap-graded surfacing mixtures laid in the United Kingdom it is clear that distortion is far more serious than fatigue cracking. Therefore, this study emphasized the deformation characteristics of the selected mixtures by using an apparatus similar to that used in the British Transport and Road Research Laboratory wheel-tracking test in which a 300- by 300- by 50-mm-thick compacted specimen of surfacing mix was subjected to to-and-fro motion, at 50 passes per min, of a 200- by 50-mm-solid rubber-tired wheel having a contact pressure of 780 kPa (Fig. 2) (6). In addition, Marshall tests (ASTM D 1559-71) were carried out on specimens compacted with 75 blows on each face at test temperatures of 40 and 60 C.

Studies carried out at the National Institute for Road Research (NIRR) have shown that gap-graded mixtures have a superior fatigue life to asphalt concrete and that, for thin surfaces, low rather than high stiffness is desirable for high fatigue resistance (7). A study by Maupin (8) showed that indirect tensile strength is a useful indicator of the fatigue susceptibility of asphalt mixtures, and for this reason the indirect tensile strength of the mixtures was measured at 30 and 40 C. Twenty-five-mm-wide curved loading strips were used to apply the load to the specimens at a rate of loading to 50 mm/min (9). The apparatus used in these tests is shown in Figure 3.

Physical Tests

An important function of a surface is to protect the base layer of the pavement from the entrance of surface water. To accomplish this the surface should be reasonably impervious without being too dense because this would cause fatting up and instability during periods of hot weather and heavy traffic. To study these characteristics we determined the air permeability in fundamental units at a pressure difference of 25 mm water on Marshall, 2 × 75-blow-compacted specimens by using the apparatus shown in Figure 4.

The durability of a surface can be controlled by the air permeability of the mix, which limits the transfer rate of oxygen, water, and microorganisms from the surface to the interior and that of volatile constituents from the interior to the surface (10). The film thickness of the bitumen also plays an important role in the durability of bituminous mixtures. Film thicknesses were calculated for the various gradings and bitumen contents by using the surface area factors recommended by the Asphalt Institute (11).

PERFORMANCE OF IN-SERVICE SURFACES

It has not been possible to observe the in-service performance of all the mixtures investigated in the laboratory. However, a gap-graded mixture containing mine sand, 30 percent stone, and 6 percent 40-50 penetration grade bitumen was laid on an experimental pavement on route S12 early in 1969 (12, 13). The dynamic properties and

Figure 1. Gap-gradings used in laboratory study.

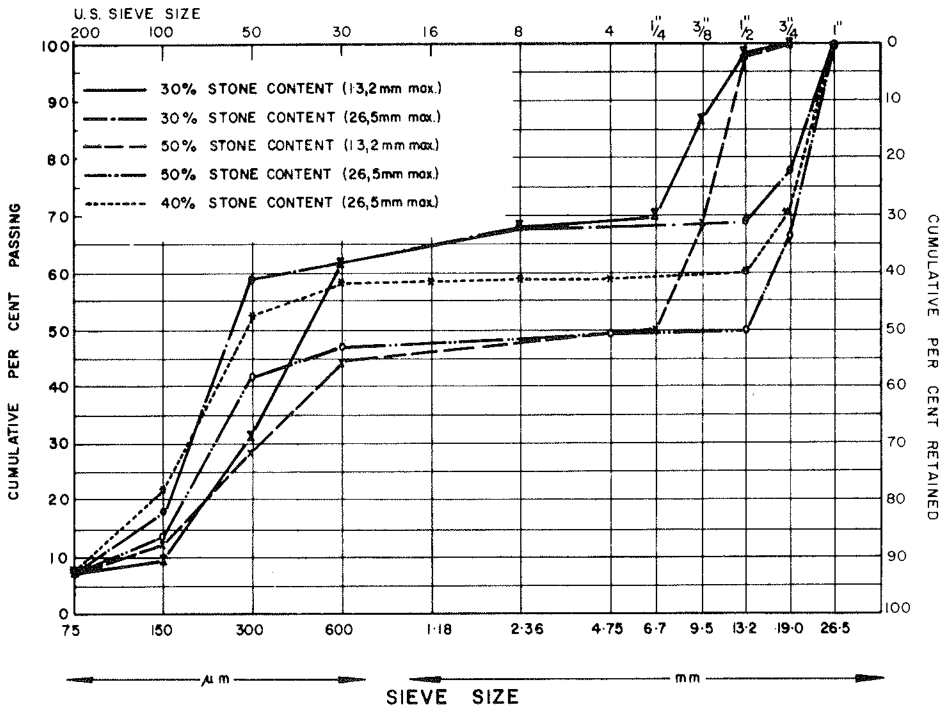


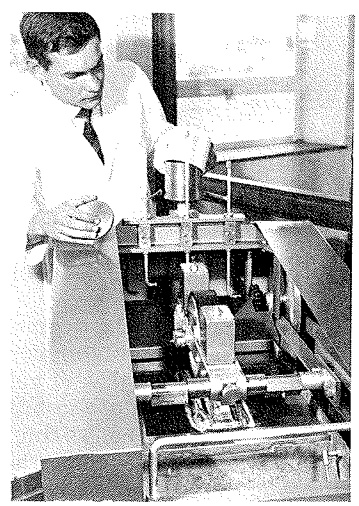
Table 1. Results of physical tests on sands used in this study.

Property	Pit Sand	Mine Sand
Fineness modulus[a]	1.35	0.99
Plasticity index	Nonplastic	Nonplastic
Bulk density, kg/m^3		
Compacted	1 596	1 487
Loose	1 494	1 330
Voids in compacted sand, percent	40	44
Sand equivalent value, percent	28	75
Dry viscosity, sec/100 g[b]	15.2	17.4

[a]Fineness modulus = $\frac{\Sigma \text{ percent retained on 4.75; 2.36; 1.18; 0.60; and 0.15 mm sieves}}{100}$ on a wet grading analysis.

[b]Flow time of 100 g of oven-dried mix: 297 µm + 149 µm sand fraction through a circular orifice 6.30 mm diameter.

Figure 2. Apparatus used for wheel-tracking tests (wheel ballast removed).



fatigue life of this mixture were studied in detail at the NIRR. In situ deformation observations were taken periodically with a precise level on the various pavement design sections. This information has been most valuable in assessing the applicability of some of the laboratory data and will be discussed under the section dealing with the results obtained from the study as a whole.

COMPACTABILITY OF GAP-GRADED MIXTURES

A detailed study has been made of densification after construction on gap-graded and asphalt concrete mixtures (3). Cores were removed from the surface in the wheel tracks of vehicles, and their bulk specific gravity was compared with the Marshall 2 × 75-blow laboratory density of these mixtures. In Figure 5, sections 5 and 34 are continuously graded asphalt surfacing mixtures and sections 83 and 84 are gap-graded with 30 per cent stone content. The rates of increase in bulk specific gravity of the 2 types of surfaces were significantly different; the asphalt concrete densified progressively under the traffic for a period of 3 years after which it reached an asymptotic value close to the Marshall 2 × 75-blow density. The gap-graded mixtures, however, showed hardly any traffic compaction and were, at the time of laying, close to the Marshall 2 × 75-blow density. The same construction compactions were used on both types of mixtures except that a pneumatic-tired roller (intermediate) was not used for gap-graded mixtures. The same traffic passed over the 2 groups of surfacing mixtures. The ease with which gap-graded mixtures reach their final density signifies their excellent in-service performance and their compaction control required during construction. In practice, then, control of compaction of gap-graded mixtures should be at a level of not less than 98 percent of 2 × 75-blow Marshall density.

DISCUSSION OF RESULTS

With regard to the deformation properties of gap-graded mixtures attention was directed to a possible relationship between the results obtained from the wheel-tracking test and the Marshall test.

Wheel-Tracking Test

Tracking tests were continued for approximately 100 min in cases where excessive distortion of the mix did not take place before this time. Measurements of rutting were taken every 10 min throughout the test period. Rut depth-time curves all followed a typical pattern in which a rapid increase in rut depth occurred during the initial period of 10 to 20 min and thereafter stabilized to a reasonably constant rate of tracking. After 45 min of tracking, the rut depth and rate of tracking were determined and used as parameters to characterize the distortion properties of the surfaces under dynamic wheel loads. Tests were carried out at 40 and 60 C. Results have been tabulated by the Asphalt Institute (11).

Marshall Test

Complete Marshall stability, flow, and voids analyses were completed on all mixtures studied. The bearing capacity and angle of internal friction of the mixtures were determined according to the procedures put forward by Metcalf (14). The stability index was calculated by using the stress-strain relationship applicable to the Marshall briquette, that is

$$\text{Stability Index} = S/F \times 15.7 \text{ MPa}$$

where

S = stability value in kilonewtons (corrected) and
F = flow in millimeters.

A detailed examination of the data from both the wheel-tracking and Marshall tests revealed that there were significant relationships among rate of tracking, bearing

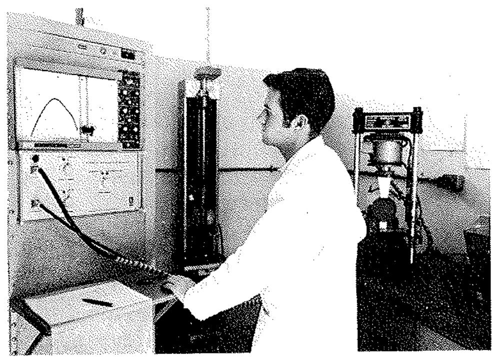


Figure 3. Automatic load-deformation recorder in use during indirect tensile test.

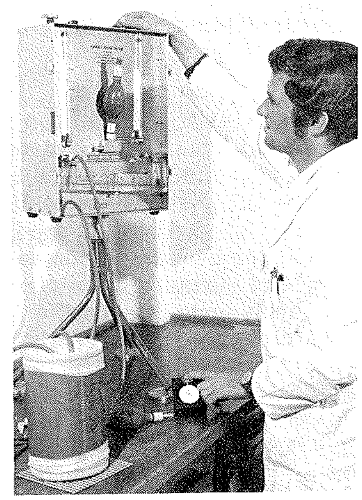
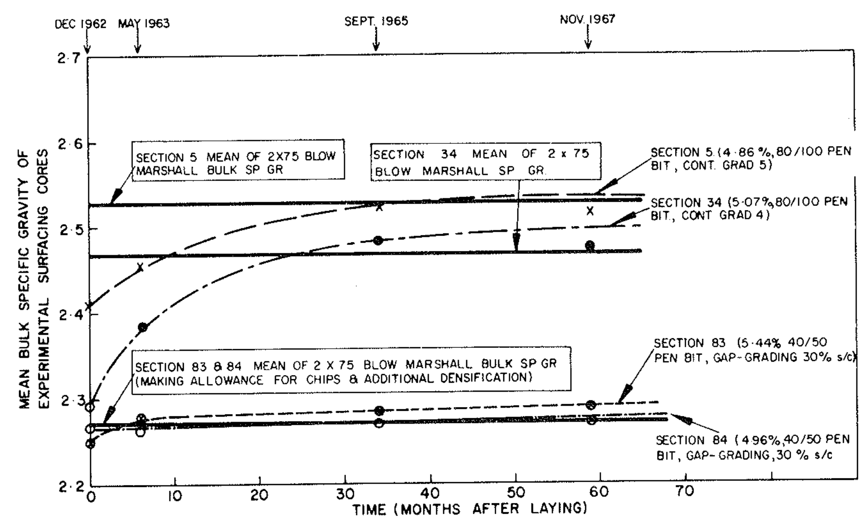


Figure 4. Apparatus for air permeability measurements on compacted Marshall specimens.

Figure 5. Rate of increase in bulk specific gravity of some typical bituminous mixtures caused by traffic compaction.



capacity, stability index, and the ratio of stability to flow at both test temperatures. Rut depth did not present as clear a trend as in the case of rate of tracking. However, because both rate of tracking and rut depth are important parameters with respect to permanent deformation of a surface, we decided that their product, the "tracking index," would be used. This index, at 40 C, was compared to the stability-flow ratio at 60 C of the various mixtures studied. There were 2 reasons for choosing 40 C for the tracking data. First, it was considered to be a reasonable average road surface temperature for hot climates like those in South Africa, and, second, at 60 C information was more limited because of the deep rut depths obtained in the tracking apparatus after only a few passes with the less stable mixtures (11). The relationship found is shown in Figure 6. On analysis, these data were found to fit a mathematical equation of the form

$$\log_{10}TI = 3.2353 - 1.2196 \log_{10}\left(\frac{10_S}{F}\right) \quad (1)$$

where

TI = tracking index (rate of tracking × rut depth at 40 C) in square millimeters × minutes^{-1},
S = Marshall stability at 60 C in kilonewtons, and
F = Marshall flow at 60 C in millimeters.

An examination of Eq. 1 reveals a large increase in the tracking index for stability-flow ratios above 1.5 kN/mm; it was concluded that this would be a limiting criterion to control excessive permanent deformation under traffic. Data feedback from practice have indicated that mixtures with stability-flow ratios below 1.5 kN/mm give rise to compaction problems and early traffic rutting.

A closer examination of the tracking data shows that the mixture containing mine sand, 30 percent stone content (maximum stone size: 26.5 mm), and 6 percent bitumen content falls on the acceptable side of the suggested limit of 1.5 kN/mm for the stability-flow ratio (Fig. 6) (11). This mixture is virtually identical with that laid on the experimental pavement on route S12. Measurements of pavement deformation (75-mm-thick, gap-graded surface supported on a 150-mm, cement-treated base) from 1969 until 1971 have been analyzed. This section was chosen especially because any measurable deformation was considered to result largely from distortion of the surface and not from the stabilized underlying layers. Deformation data was available only for 23 months under heavy traffic and showed the average permanent deformation over a 2.7-m-wide area in the center of the traffic lane to be 1.89 mm. The cumulative equivalent 80-kN axle load was approximately 7.4×10^5 in this lane for the 23-month period.

If a 25-mm rut depth is considered the limit value for retiring a pavement because of poor ridability, then this pavement had reached approximately 7.5 percent of the allowable deformation. However, on the basis of a 20-year life, the pavement had reached 10.5 percent of its life. Possibly this mixture would not deform excessively during the life of the pavement. These field performance data to a limited extent confirm the laboratory results and permit some confidence in the suggested laboratory criterion.

The limit value of 1.5 kN/mm for the stability-flow ratio determined from this study was also confirmed by Brien (4) who suggested stability-flow ratios for conditions in the United Kingdom of 0.98 kN/mm and 1.96 kN/mm for the most extreme climatic conditions (high temperatures). South Africa certainly does not have the most extreme climatic conditions in the world; therefore, a value of 1.5 kN/mm seemed appropriate.

To comply with this criterion, the surface-design engineer should have an understanding of the effect of binder content, stone content, maximum size of stone, and type of sand on the stability-flow ratio. From this study it appears that the sensitivity of this ratio to different bitumen contents depends on the type of sand in the mixture (Fig. 7). In the case of mixtures with mine sand, the bitumen content was not a critical factor with respect to the stability-flow ratio but was very critical in the case of mixtures with pit sand. At the same bitumen content, the mine sand had a lower stability-flow ratio at the lower stone content mixtures; the opposite was generally true for pit

Figure 6. Ratio of stability to flow at 60 C versus tracking index at 40 C for gap-graded mixtures.

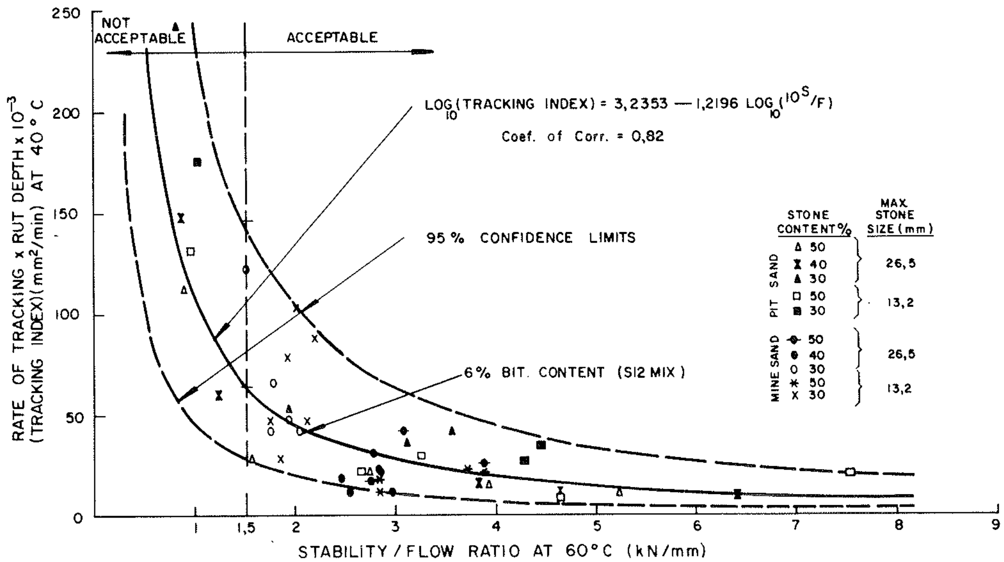
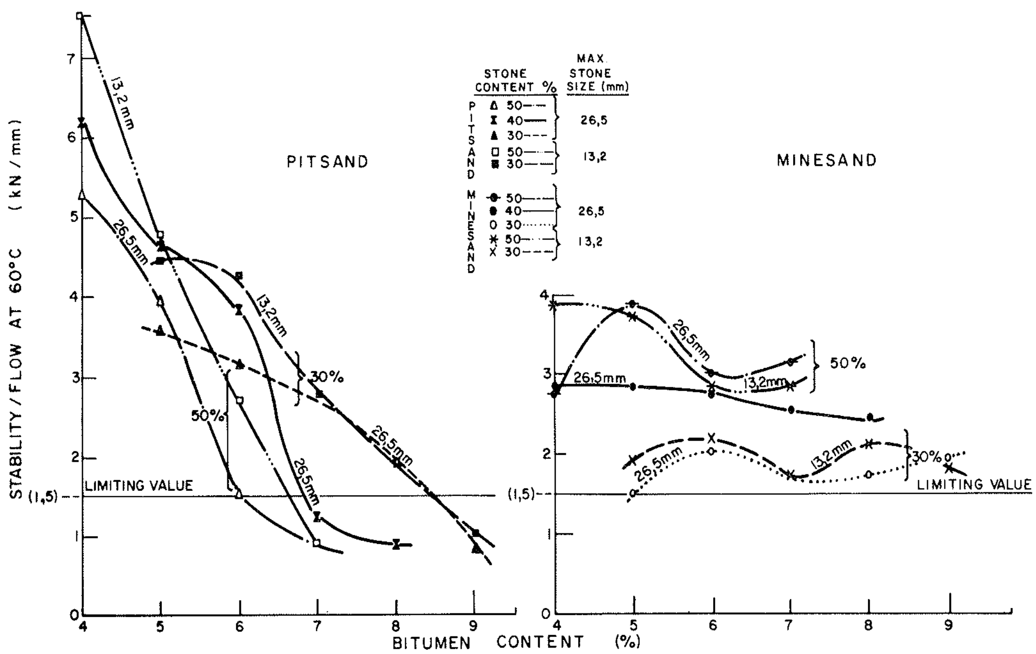


Figure 7. Relationship between permeability and air voids content for various gap-graded mixtures.



sand. There was no significant effect of maximum stone size on the stability-flow ratio for the 2 sizes tested. From this it is clear that type of sand is of paramount importance when one designs gap-graded mixtures.

Indirect Tensile Tests

The purpose of introducing the indirect tensile (split cylinder) test was to use the indirect tensile strength of the mixtures as an index to ensure that they are not designed with too high a stiffness, as defined by Van der Poel (15), or poor fatigue resistance (7). Published data on the relationship between indirect tensile strength, or for that matter direct tensile strength, and fatigue life are limited, and for this reason controlled-strain fatigue tests at 20 C at a strain level of 600 $\mu\epsilon$ were carried out on a range of gap-graded mixtures used in practice. Results are given in Table 2 where they are compared with the indirect tensile strength of these mixtures at 40 C. A linear regression analysis of all the data with respect to indirect tensile strength and Marshall stability showed the best relationship between these 2 parameters to be as follows (11):

$$x = 0.014y + 1.246 \qquad (2)$$

where

y = indirect tensile strength at 40 C in kilopascals and
x = Marshall stability at 60 C in kilonewtons.

The coefficient of correlation of these data is 0.86, which indicates that the relationship could be used with reasonable confidence.

A similar analysis of the data in Table 2 indicates a strong linear relationship between direct tensile strength and log of service life of the form

$$y = 2989 - 588 \log N(x) \qquad (3)$$

where $N(x)$ = service life (Table 2). The coefficient of correlation of these data is 0.8. The relationship is of great significance; it enables a reliable estimate to be made of any desirable level of service life from the indirect tensile strength at 40 C of a particular gap-graded mixture. Indirectly from Eq. 2, Marshall stability may be used to determine the fatigue service life; however, this obviously would not give as good an estimate as would the indirect tensile strength.

From a previous fatigue study it is recommended that surfacing mixtures of a thickness not greater than 75 mm should have a minimum fatigue service life of 5×10^3 repetitions of load at 20 C and a strain level of 600 $\mu\epsilon$. From Eq. 3 this gives a maximum indirect tensile strength at 40 C of 810 kPa or, by using Eq. 2, a maximum Marshall stability of approximately 12.5 kN.

Air Permeability Test

A search of the literature dealing with the fundamental measure of permeability of bituminous surfacing mixtures failed to produce any criterion that could be applied directly. Most workers have adopted limits suggested by researchers dealing with drainage problems related to soils. However, the 2 problems are not related directly because, in the case of soils, water is permanently available in a draining situation at substantial pressure heads whereas, in the case of bituminous surfaces, water is available only when it rains and the pressure head is low (except possibly under the vehicle tire). It would seem that the limits of permeability of 1×10^{-11} to 1×10^{-14} cm^2 set for soils are overrestrictive with respect to surfaces (16). A reasonable limit of permeability of 1×10^{-8} cm^2 is suggested for gap-graded mixtures to ensure that surface water would not enter readily into the surface and thereafter into the base of the pavement. An investigation by McLaughlin and Goetz (17) of gap-graded surfacing mixtures used in Indiana showed that a limit of 1×10^{-8} cm^2 was applied to these mixtures, which presumably gave good in-service performance, thus corroborating the limit of permeability suggested.

The pore structure of a gap-graded mix is controlled largely by the type of sand used and the filler and bitumen content, which in turn control the voids content. The relationships between air permeability and voids content of the mixtures used in this study are shown in Figure 8. As can be seen, at a constant voids content, the mixtures with pit sand were more permeable than those with mine sand and, for both types of mixture, the higher the stone content the more permeable was the mixture. This finding confirms the experience in the United Kingdom that low stone content mixtures are more durable than high stone content mixtures. Because bitumen film thickness and permeability are probably the dominating factors that control the durability of a mixture, a limit on both bitumen film thickness and permeability would guarantee the long-term durability of a surfacing mixture. A tentative value of not less than 6 μm is suggested for bitumen film thickness in practice, which agrees with the limit suggested by Campen et al. (18).

Voids in Mix

The air voids in the various gap-graded mixtures were calculated by taking into account all the factors recommended by the Asphalt Institute (11). Experience has shown that a minimum of 2 percent voids content is necessary in the traffic-compacted surfacing mixture to ensure that there are sufficient voids in the mix to prevent flushing due to expansion of the bitumen during hot weather. Because the laboratory density of gap-graded mixtures is very similar to ultimate in-service density, a limiting voids content for laboratory-compacted Marshall specimens of 2 percent is recommended.

The relationship between stone content and voids content of mixtures containing the 2 types of sand and a range of bitumen contents is shown in Figure 9. It is clear from this figure that, at the same bitumen content, the voids content for both types of sand decreases when the stone content increases. However, in the case of the pit sand, the decrease was less significant at stone contents in excess of 40 percent. At the same bitumen content, mixtures with mine sand had significantly higher voids than those manufactured with pit sand. This difference probably was due to the distribution of voids and their shape within each mixture, which, in turn, was dependent on the particle shape and grading of the sand.

It is interesting that the mine sand that had a higher compacted voids content also yielded mixtures with higher voids than did the pit sand at the same level of bitumen content although this difference was much more exaggerated in the case of the mixtures (Table 1 and Fig. 9). This effect probably was due to the finer grading of the mine sand, which led to reduced bitumen film thickness and a consequent increase in air voids.

Angularity of sand can be determined indirectly by the dry viscosity test, the results of which show mine sand to be more angular than pit sand (Table 1).

Because of the large variation in voids for gap-graded mixtures using different sands, voids content is not a reliable parameter to ensure impermeability of the mixtures (Fig. 8).

A comparison of mixtures made with mine sand and pit sand at the same bitumen content shows the mixtures with pit sand to be generally more resistant to deformation (11). This at first seems illogical because mine sand had a greater inherent stability by virtue of its more angular particle shape; however, deformation of a bituminous mixture depends on a number of interrelated factors such as the angularity and grading of the aggregate, the properties of the filler, the type and grade of the binder, the average film thickness of the binder, and the voids content of the mixture. In addition, the rate of loading and temperature are important variables. A correlation between deformation of a mixture and the properties of the sand is remote. However, because of the importance of the sand fraction, particularly in the case of low stone content, gap-graded mixtures, a more detailed study is in progress at the NIRR where various sands are being investigated with a view to establish more realistic sand specifications for gap-graded mixtures.

Filler

The type of filler (-75 μm) material used in a gap-graded bituminous mixture plays

Table 2. Results of indirect tensile strength and fatigue service life of gap-graded surfacing mixtures.

Mixture Composition	Peak Stiffness at 20 C (GPa)	Indirect Tensile Strength at 40 C (kPa)	Average Service Life N(x) at Strain of 600 $\mu\epsilon$ (load repetitions)[a]
40 percent stone, 5.0 percent 60-70 penetration grade bitumen (7.4 μm film thickness)	6.0	604[b]	9.71×10^3
44 percent stone, 6.7 percent 60-70 penetration grade bitumen (8.6 μm film thickness)	4.1	316[b]	1.95×10^4
30 percent stone, 6.0 percent 40-50 penetration grade bitumen (4.9 μm film thickness)	2.8	186	5.94×10^4
44 percent stone, 5.0 percent 60-70 penetration grade bitumen (6.9 μm film thickness)	6.4	434[b]	1.40×10^4
50 percent stone, 5.3 percent 40-50 penetration grade bitumen (6.0 μm film thickness)	5.4	825	1.04×10^4
40 percent stone, 5.8 percent 40-50 penetration grade bitumen (6.0 μm film thickness)	3.5	500	2.87×10^4
30 percent stone, 6.1 percent 40-50 penetration grade bitumen (6.0 μm film thickness)	3.3	455	1.83×10^4

[a]From Freeme and Marais (7). [b]Calculated from Marshall stability value.

Figure 8. Relationship between permeability and air voids content for various gap-graded mixtures.

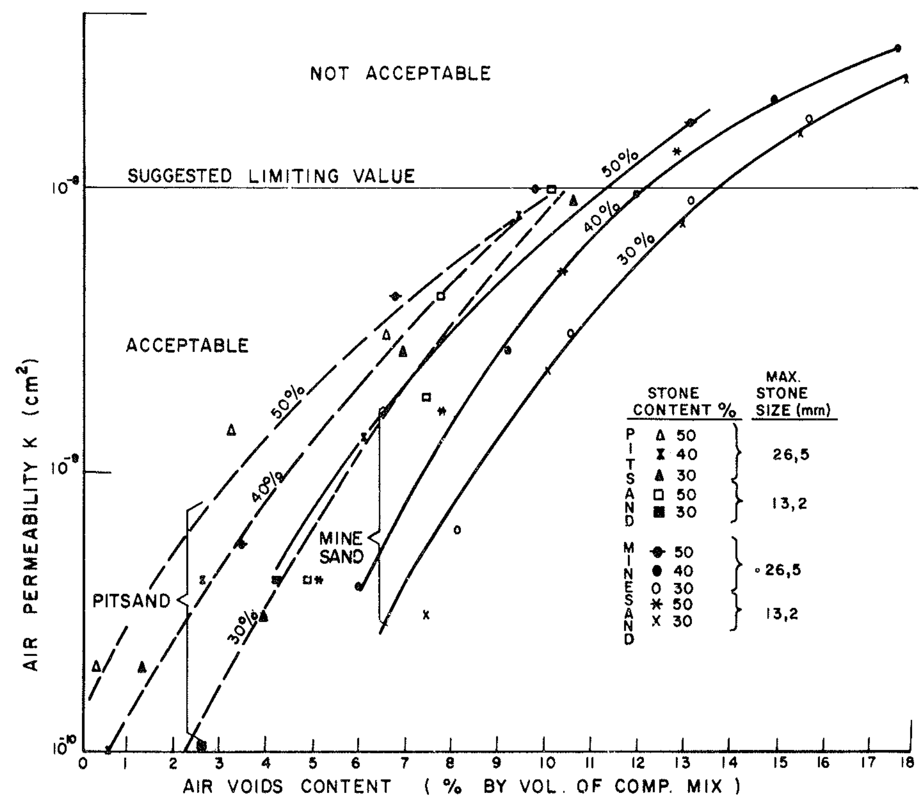


Figure 9. Relationship between stone content and voids content for various gap-graded mixtures.

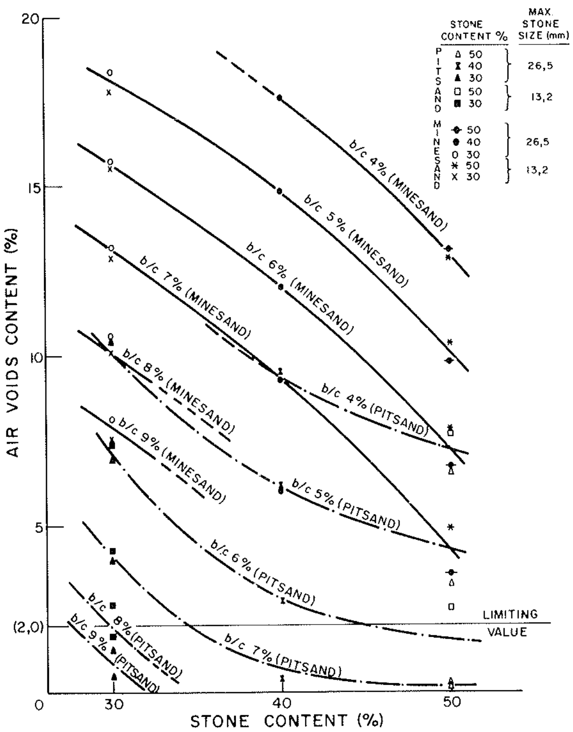


Table 3. Design criteria for gap-graded surfacing mixtures.

Test Property	Surfacing Property	Max	Min
Marshall stability-flow ratio at 60 C, kN/mm	Deformation or distortion	–	1.5
Indirect tensile strength at 40 C, kPa	Toughness, fatigue resistance, and fracture strength	810	–
Marshall stability at 60 C, kN	Toughness, fatigue resistance, and fracture strength	12.5	–
Immersion index	Stripping by water	–	0.75
Air permeability, cm^2	Imperviousness, durability	1×10^{-8}	–
Voids in mix, percent	Balance in design	–	2.0
Film thickness of bitumen[a], μm	Durability	–	6.0
Filler-bitumen ratio	Balance in design	–	1.0

[a]Calculated by using factors recommended by the Asphalt Institute (11).

an important role with respect to its stability, voids content, permeability, and bitumen demand, by which it affects the deformation and durability characteristics of the mixture. Studies made by Lee and Rigden (19) have shown that the fineness of the filler as determined by its bulk density in benzene is an excellent index to the deformation characteristics of the binder-filler mixture. For this reason BS 594 requires the filler to comply with a bulk density in benzene value of between 0.50 and 0.95 g/ml. The filler-bitumen ratio is also important to obtain a balanced composition and a mixture with adequate resistance to distortion. A study by Kraemer (20) recommends that this ratio should not be less than 1.0.

Effect of Moisture on Mix Properties

To ensure that moisture does not affect the stability of the surface adversely, specimens of mix compacted under 2 × 75-blow Marshall compaction should be soaked in clear potable water for a period of 24 hours at 60 C and thereafter tested for Marshall stability. The ratio of the soaked stability divided by the stability obtained under the standard Marshall test conditions is the immersion index, which should not be less than 0.75 for acceptable surfacing mixtures.

CONCLUSIONS AND TENTATIVE MIX-DESIGN CRITERIA

Several conclusions may be made as a result of this study.

1. An acceptable correlation exists between the Marshall stability-flow ratio and the rate of tracking at 40 C for gap-graded mixtures when tested with a wheel-tracking machine.
2. Fatigue service life of thin surfaces of gap-graded mixtures can be established and controlled within acceptable bounds by using the indirect tensile strength of the mixture at 40 C.
3. A reasonably good correlation between Marshall stability and indirect tensile strength exists to enable engineers in practice to control the fatigue resistance of gap-graded mixtures by specifying an upper limit to the Marshall stability value.
4. The sand used in the manufacture of gap-graded mixtures has a predominant effect on the properties of the mixture.
5. Maximum size of coarse stone used in a gap-graded mixture within the limits of 26.5 mm and 13.2 mm does not have a significant effect on the properties of the mixture.
6. Stone content of gap-graded mixtures is an important variable. The higher stone contents result in mixtures having greater resistance to distortion in the case of mine sand and lower resistance in the case of pit sand. Optimum stone content therefore depends on the type of sand.
7. Higher stone content mixtures result in surfaces with lower fatigue service lives and greater permeability at a given voids content.

The results of this study, combined with information from the literature, have permitted tentative limiting criteria to be established to control the following properties of a gap-graded bituminous surface:

1. Deformation or distortion,
2. Fracture strength,
3. Fatigue resistance,
4. Durability,
5. Imperviousness, and
6. Balanced composition.

These properties are governed by various laboratory tests that enable asphalt engineers to design suitable gap-graded mixtures in practice. Obviously, the intensity and type of traffic using a pavement as well as pavement geometrics and microclimate do influence surface performance. For example, a mixture that just complies with the deformation criteria would not be suitable for hot summer conditions under heavy truck traffic on a pavement with sharp bends and extreme sideway stresses.

This study has not investigated the influence of grade of bitumen because it is usual in gap-graded mixtures to use a hard penetration grade such as a 40-50. However, cases exist in South Africa where 60-70 penetration grade bitumens have been used with success. Design criteria should take account of the grade of bitumen used.

Tentative mix-design criteria for gap-graded bituminous surfaces with stone contents within the range of 30 to 50 percent are given in Table 3. Some of these criteria require verification by controlled road experiments; such a program has been instituted at the NIRR.

Although the design criteria given in Table 3 do not, as is the case with many design methods, indicate the optimum binder content that should be used for a particular aggregate composition, the designer should always aim at introducing as much bitumen into the mix as it will tolerate without exceeding the bounds of the criteria established. This will, in effect, result in the most durable mixture that will satisfy all the necessary requirements of a good surfacing mixture.

This study has enabled mechanical test properties to be reduced to a minimum because the Marshall test fulfills all the necessary requirements of the mixture for design purposes. This results in a great saving in testing time and in the cost of additional testing equipment.

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