A Rational Design Approach for Single and Double Surfacing Seals Based on the Modified Tray Test

C. J. SEMMELINK

Important factors influence the performance of surfacing seals, or surface treatments, such as the loss of voids that results from the wear of the aggregate and the effect of traffic on the embedment of the aggregate in the underlying layer on which it is constructed. Research results are given that indicate the likely reasons why single seals are generally more susceptible to fatting-up than double seals. It is shown how the modified tray test can be used to avoid this problem. A rational approach to the design of single and double seals that incorporates the actual measured void content instead of an accepted average quantity is outlined. The accurate determination of the stone spread rate with the modified tray test is also discussed.

THE DETERMINATION OF BINDER QUANTITY

Two factors are important in the proper construction and performance of single and double seals: the correct binder application rate and the correct aggregate spread rate.

A certain amount of empty space is present in a single- or a double-seal layer. A portion of this void is lost during the life of the seal because of the effect of traffic on (a) the embedment of the aggregate at the bottom of the seal layer, and (b) the wear of the aggregate at the top of the seal layer.

A certain portion of the void must be left unfilled with binder to ensure good skid resistance. It is currently recommended in the Republic of South Africa (RSA) that a texture depth of 0,64 mm, as measured by the sand patch test, is required to ensure satisfactory skid resistance in wet weather and to prevent hydroplaning.

The void that may therefore be filled with binder is the balance of this void that remains after the estimated amount of loss that results from embedment and wear and the amount required for good skid resistance have been subtracted.

It is clear that a good indication of the actual void content in a seal layer is essential to execute an effective design. This is an area in which problems have been experienced in the past, because there was no way in which the void content could be determined rapidly and effectively. Most design methods therefore assumed a fixed equation for the void content in relation to the average least dimension (ALD) of the aggregate, or a fixed value for the void content regardless of the value of the ALD. However, research conducted at the National Institute for Transport and Road Research (NITRR) has found that there is a wide scatter in the case of the actual void content (*1, 2*). This was confirmed by reports that indicated that some seals, particularly single seals, that were designed according to these methods tended to have too much binder.

National Institute for Transport and Road Research, P.O. Box 395, Pretoria, 0001, Republic of South Africa.

THE BINDER QUANTITY IN A SINGLE SEAL

A simple test, called the modified tray test, was devised to measure the actual void content of the stone to be used. The modified tray test was developed to determine the true layer void content, V_l, and the effective layer thickness (ELT). The test equipment consists of a circular tray with an area of 0,05 m^2 and a wall height of 50 mm. A shoulder piece fits snugly on top of the tray, has the same internal diameter as the tray, and is fitted to a loose-fitting cloth membrane. The purpose of the membrane is to prevent the density sand from flowing into the voids between the aggregate (see Figure 1).

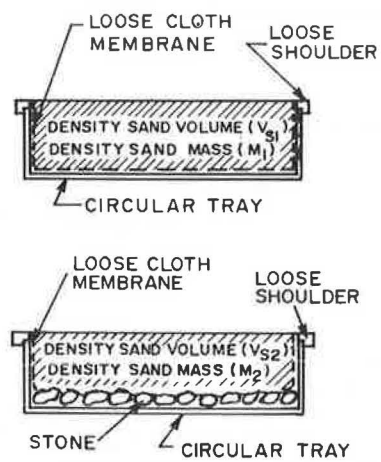

FIGURE 1 Schematic illustration of the modified tray test.

Phase One of the Modified Tray Test

The void space that is occupied by the aggregate sample plus voids in the layer is determined as follows:

$$V_3 = V_{s1} - V_{s2} = (M_1 - M_2)/BDS \quad (1)$$

where

V_3 = volume of the aggregate plus the voids between the aggregates (ml),

V_{s1} = volume of the density sand required to fill the tray without aggregate (ml),
V_{s2} = volume of the density sand required to fill the tray with aggregate (ml),
M_1 = mass of the density sand required to fill the tray without aggregate sample (g),
M_2 = mass of the density sand required to fill the tray with aggregate sample (g), and
BDS = bulk density of the density sand (g/ml).

The ELT in millimeters is determined as follows:

$$ELT = 10.V_3/A \quad (2)$$

where

A = area of the tray (cm^2).

The layer void content, V_l, is determined as follows:

$$V_l = (V_3 - V_a)/V_3 \times 100\%$$

$$= [V_3 - (M_a/RD_a)]/V_3 \times 100\% \quad (3)$$

where

V_a = volume of the aggregate sample required to cover the tray area (ml),
M_a = mass of the aggregate sample required to cover the tray area (g), and
RD_a = relative density of the aggregate sample.

It should be pointed out that the ELT differs from the ALD in that it gives a more average value for the layer thickness of the aggregate. In the case of the ALD only the highest points of the least dimension of the aggregate particles are measured. There is, however, a good correlation between the ELT and the ALD (see Figure 2).

However, the relation between the layer void content, V_l, and the ELT in a single layer is poor (see Figure 3). This explains why the use of only the ELT, or ALD, to determine the quantity of cold binder required for the seal will lead to some seals being too rich in binder. It also explains why it is preferable to measure the true void content with the modified tray test.

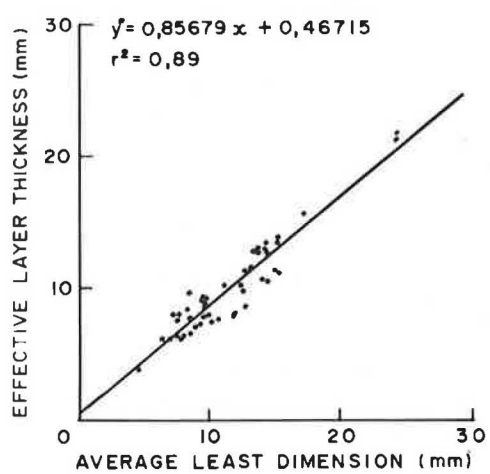

FIGURE 2 Relation between the ALD and ELT of aggregate.

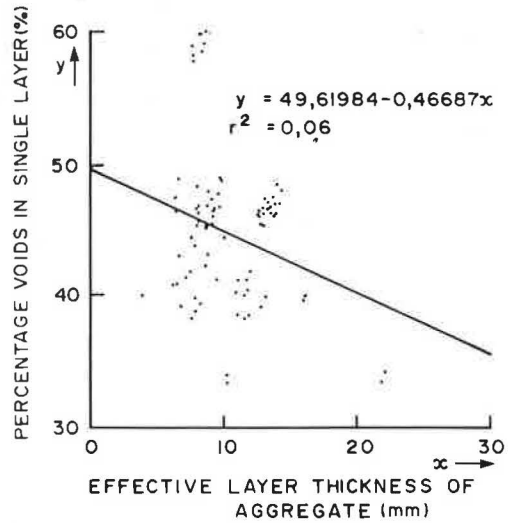

FIGURE 3 Relation between the ELT and the layer void content in a single layer.

The amount of the embedment and wear of the aggregate is determined by means of functions derived from earlier research by Marais that use the ball penetration test for surfacing seals, the 10 percent Fines Aggregate Crushing Test (FACT) value of the aggregate, and the average daily traffic per lane expressed in equivalent light vehicles (*3*). Any vehicle heavier than a light delivery van is taken to be equal to 20 equivalent light vehicles.

The ball penetration test for surfacing seals is used to measure the penetration resistance of a road surface using a steel ball with a diameter of 19,0 mm. The penetration resistance is determined by measuring the depth of penetration of the steel ball after the ball has been given one blow with a Marshall hammer at randomly selected positions on the whole road surface. The road surface temperature at the time of the test is also recorded. The expected penetration is then determined by the following equation:

$$Pen\ T_0 = Pen\ T_1 - K(T_1 - T_0) \quad (4)$$

where

$Pen\ T_0$ = penetration depth at the expected prevalent road surface temperature (mm),
$Pen\ T_1$ = penetration depth at measured road surface temperature (mm),
T_1 = temperature of road at time of test (°C),
T_0 = expected prevalent temperature of road for a particular location (°C), and
K = temperature susceptibility of penetration (mm/°C).

where

K = 0,04 mm/°C for single and double seals (not fatty),
K = 0,05 mm/°C for slurry seals (not fatty),
K = 0,07 mm/°C for Cape seals (not fatty), and
K = 0,08 mm/°C for fatty roads and premix surfacings.

It should be noted that the relationship is valid for all road surfaces and temperatures between 25 and 55° C. A Cape seal is a single seal that is followed by a slurry seal.

The fractional void loss that results from the embedment and wear of the aggregate is determined separately because the wear occurs at the top of the layer and the embedment at the bottom of the layer. It has also been found in research by Marais that the voids are distributed in more or less the same way as when spheres of the same size are tightly packed in one layer (*3*). The total fractional void loss is expressed by the following equation:

$$Z_1 = 2{,}528(D_1 + D_2) - 4{,}587(D_1^2 + D_2^2) + 3{,}058 \times (D_1^3 + D_2^3) \quad (5)$$

where

Z_1 = fractional void loss due to embedment and wear as a decimal,
D_1 = embedment expressed as a decimal fraction of the ELT, and
D_2 = wear expressed as a decimal fraction of the ELT.

The equation is the theoretical relation for the fractional void distribution in a single layer of spheres with a hexagonal packing array, which is the tightest packing pattern for a layer of single-sized spheres.

The fractional void loss that results from the demand for good skid resistance properties is given by the following equation:

$$Z_2 = 0{,}64/(V_l \cdot ELT) \quad (6)$$

where

Z_2 = fractional void loss due to demand for skid resistance as a decimal,
V_l = layer void content as measured with the modified tray test, expressed as a decimal fraction, and
ELT = effective layer thickness as measured with the modified tray test (mm).

The available void fraction that may be filled with binder is the balance of the void content, which is equal to the following equation:

$$Z_3 = 1 - (Z_1 + Z_2) \quad (7)$$

where

Z_3 = decimal fraction of void space that may be filled with binder for a normal life expectancy.

However, to ensure that there is no aggregate whip-off, it is essential that the aggregate be at least half-covered with binder. In other words, 50 percent of the voids should be filled. However, during the initial rolling immediately after spraying and chipping, a certain amount of embedment takes place, which reduces the fraction that has to be filled with binder. The amount of rolling embedment is taken to be 0,90 of the total embedment. The fractional void loss that results from rolling embedment is equal to the following:

$$Z_4 = 2{,}528D_3 - 4{,}587D_3^2 + 3{,}058D_3^3 \quad (8)$$

where

Z_4 = fractional void loss due to rolling embedment as a decimal, and
D_3 = embedment due to rolling expressed as a decimal fraction of the ELT.

The minimum void fraction as a decimal, Z_5, that should initially be filled with binder is therefore equal to the following:

$$Z_5 = 0{,}5 - Z_4 \quad (9)$$

If the available void fraction, Z_3, is greater than the minimum void fraction, Z_5, the seal will have a normal life, which is usually taken to be 10 years. However, if the minimum void fraction is greater than the available void fraction, the seal will have a reduced life expectancy. The life expectancy in years can be estimated from these measurements. It is assumed that the fractional void loss per annum is constant. Therefore, the fractional void loss per annum is equal to the total fractional void loss that results from embedment and wear after the 10-yr period minus the fractional void loss that results from rolling embedment divided by 10. When the fractional void content in the seal reaches the stage at which the fractional void content is equal to the fractional void demand for good skid resistance, the end of the safe life of the seal has been reached. However, just after construction of the single seal, 50 percent of the void space is still available because the aggregate has only been half-covered with binder. The life expectancy of the seal is therefore equal to the following:

$$Y_3 = Y_2 / Y_1 \quad (10)$$

where

$$Y_1 = (Z_1 - Z_4)/10 \quad (11)$$

and

$$Y_2 = 0{,}5 - Z_2 \quad (12)$$

where

Y_1 = fractional void loss per annum,
Y_2 = void space available, and
Y_3 = estimated service life of the seal in years.

The maximum and minimum nominal cold binder application rates for a single seal are equal to the following:

$$B_{max} = Z_3 \cdot V_l \cdot ELT \text{ (when } Z_3 > Z_5) \quad (13)$$
$$B_{min} = Z_5 \cdot V_l \cdot ELT \quad (14)$$

DETERMINATION OF THE AGGREGATE SPREAD RATE

The area of the modified tray test tray is equal to 0,05 m^2. The spread rate of aggregate can therefore be determined easily by determining with a measuring cylinder the bulk volume of the aggregate sample used with the modified tray test apparatus. This bulk volume is then multiplied by 20. It is also possible to determine the void content of the loose bulk volume of the

aggregate, V_b, from the bulk volume, the mass of the aggregate sample, and the relative density of the aggregate. The mass and relative density of the aggregate sample can be recovered from the information of the first phase of the modified tray test.

Phase Two of the Modified Tray Test

Only a portion of the space in a layer of stone lying shoulder to shoulder with a specific ELT is occupied by the stone particles. The balance of the space in the layer consists of the void, V_l. Only a portion of the space in the loose bulk volume of the stone is occupied by the stone particles. The balance of the bulk volume consists of the bulk void, V_b. Therefore, one can theoretically state that the number of square meters that should be covered by 1 m^3 of loose aggregate, A_1, is equal to the volume of the solids in 1 m^3 of aggregate divided by the volume of the solids in 1 m^2 aggregate.

$$A_1 = [1\,000 \cdot (100 - V_b)]/[ELT \cdot (100 - V_l)] \qquad (15)$$

where

ELT = effective layer thickness of stone layer (mm),
V_l = void content of single layer of stone (%), and
V_b = void content of bulk volume (%).

If the spread rate, Q_1, is expressed as a fraction of a cubic meter per square meter, then

$$\begin{aligned} Q_1 &= 1/A_1 \\ &= [ELT \cdot (100 - V_l)]/[1\,000 \cdot (100 - V_2)] \\ &\quad \times 1\,000\ (\times 10^{-3}) \\ &= [ELT \cdot (100 - V_l)]/(100 - V_b)\ (\times 10^{-3}) \qquad (16) \end{aligned}$$

Research conducted at the NITRR has shown that there is an excellent correlation between the actual spread rates that were determined with the modified tray test samples and the measuring cylinder, and the theoretical spread rates using the measured values for the ELT, V_l and V_b (see Figure 4). The fact that the gradient value is almost one appears to prove that the values of the ELT and the void content, V_l, as determined with the modified tray test, are correct.

Therefore, if the test results indicate a substantial difference between the calculated spread rate, Q_1, and the practically determined spread rate, it is safe to assume that a mistake has been made with the measurements of the modified tray test. One can therefore double check the validity of test information.

In order to ensure good shoulder-to-shoulder coverage of the aggregate, it has been found necessary to increase the spread rate by about 5 percent to provide for the fluctuation in the bulk void content of the loose aggregate. This is reinforced by Mackintosh, who concluded (*4*):

> Surplus chips are not only whipped off by traffic, but actually cause the loosening of some chips already held by the binder.... Therefore, excess chips should *not* be applied as an allowance for whip-off. The aim should be such accurate rates of spread and spray that there is practically no whip-off. The only allowance to be made should be a maximum of six per cent, though four per cent is usually enough, for handling losses and imperfect workmanship.

DETERMINATION OF BINDER QUANTITY OF DOUBLE SEALS

Research conducted at the NITRR has shown that exactly the same approach can be followed in the design of a double seal because the void distribution in a double layer of aggregate follows approximately the same pattern as that of a single layer (see Figure 5) (*1*).

Research with the modified tray test has also found that there is a very good relation between void contents of the separate layers of aggregate and the total void content of a double seal. A good relation also exists between the ELTs of the separate layers and the ELT of the double seal (see Figures 6 and 7).

The spread rate of the bottom layer of stone should be reduced by 5 percent to achieve proper keying of the top layer of stone. The theoretical relationship of the calculated voids is as follows:

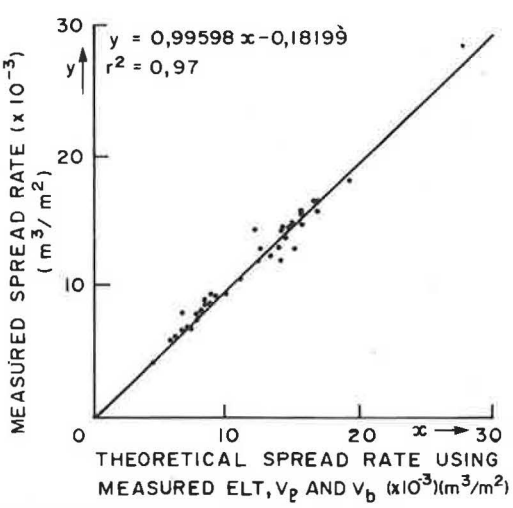

FIGURE 4 Relation between the measured and calculated aggregate spread rates.

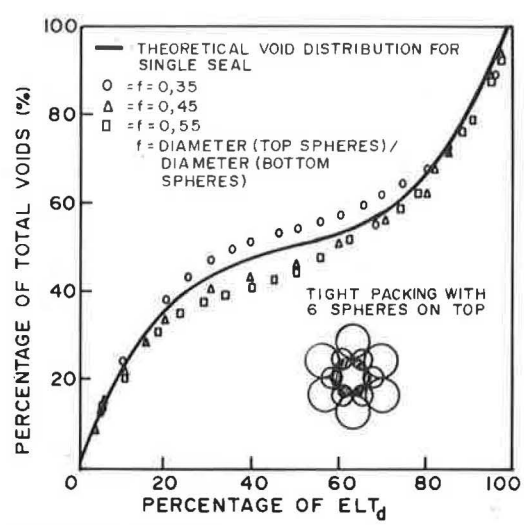

FIGURE 5 Theoretical void distribution in a double seal.

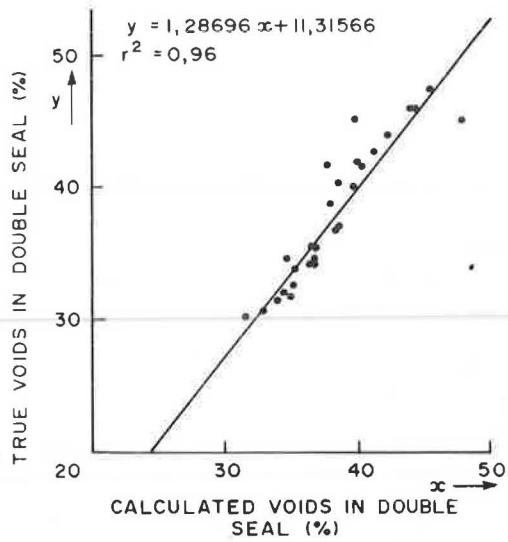

FIGURE 6 Relation between true voids and calculated voids using the measured ELT_d in a double seal with 95 percent stone in the bottom layer.

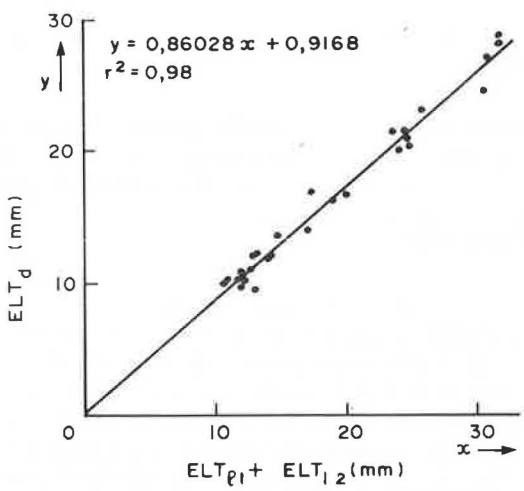

FIGURE 7 Relation between ELT of double seal and the sum of the ELTs of the bottom and top layer with 95 percent stone in the bottom layer.

$$V_{ld} = [ELT_{l1} \cdot (0{,}95 \cdot V_{l1} + 5) + ELT_{l2} \cdot (V_{l2})] \times (ELT_d)/(ELT_{l1} + ELT_{l2})^2 \quad (17)$$

where

V_{ld} = calculated void content of double seal (%),
ELT_{l1} = effective layer thickness of bottom layer of aggregate (mm),
ELT_{l2} = effective layer thickness of top layer of aggregate (mm),
ELT_d = effective layer thickness of double layer of aggregate (mm),
V_{l1} = void content in bottom layer of aggregate (%), and
V_{l2} = void content in top layer of aggregate (%).

It was also found that a fairly accurate estimate of the true void content could be made using only the information from separate aggregate layers (see Figure 8). It was also found that the relation between the void content and the ELT of the double seal was far more pronounced than that of a single seal (see Figure 9). The better relation between the void content and the ELT of a double seal is probably the prime reason why double seals are generally less likely to fat up than single seals.

The only difference between the design of a double seal and the design of a single seal is that 65 percent of the voids in a double seal have to be filled with binder to ensure that the top layer of aggregate is at least half-covered with binder. Therefore, the minimum void fraction that must be filled with binder is as follows:

$$Z_5 = 0{,}65 - Z_4 \quad (18)$$

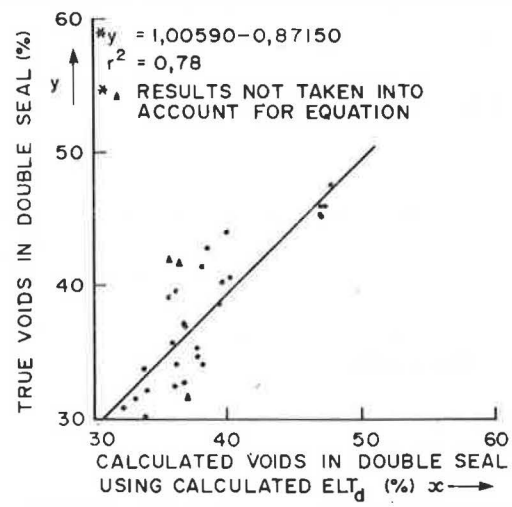

FIGURE 8 Relation between true voids and calculated voids using the calculated ELT_d in a double seal with 95 percent stone in the bottom layer.

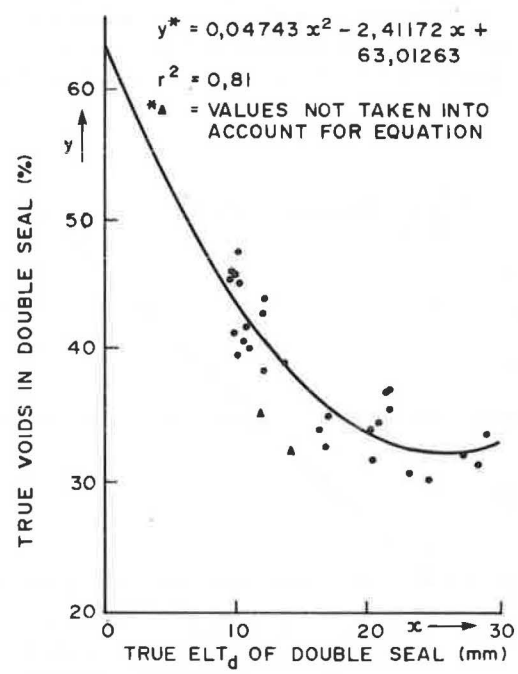

FIGURE 9 Relation between voids and ELT_d for a double seal with 95 percent stone in the bottom layer.

where

Z_4 = fractional void loss due to roller embedment.

At least 65 percent of voids of a double seal have to be filled initially. Therefore, if the minimum required void fraction is greater than the available void fraction, the reduced service life is calculated as follows:

$$Y_3 = Y_2 / Y_1 \quad (19)$$

where

$$Y_1 = (Z_1 - Z_4)/10 \quad (20)$$

and

$$Y_2 = 0{,}35 - Z_2 \quad (21)$$

The stone spread rates for a double seal are determined in exactly the same manner as that of a single seal. However, only the spread rate of the top layer is increased by 5 percent because a slightly lower spread rate is desired for the bottom layer to ensure proper keying of the stone of the top layer.

CONCLUSION

Because it is only necessary to fill at the most 50 percent of the voids in a single seal and 65 percent of the voids in a double seal, the maximum void fraction can be kept within these limits. Therefore, if the available voids to be filled with binder amount to more than 50 or 65 percent for a single or double seal, respectively, they can be safely reduced to 50 or 65 percent, as the case may be.

It is recommended that the minimum, nominal cold binder application rate normally be used. The maximum nominal cold binder application rate gives an indication of how much the seal could absorb without any likely detrimental effects on the performance of the seal.

A correction in binder application rate is applied for both the single and double seal. This is determined by means of a function that was derived from earlier research by Marais and depends on the surface texture of the surface to be sealed, which is determined with the sand patch test, and the average daily traffic (*3*).

The whole design method has been computerized so that it is only necessary to enter the following information:

- The ELT(s) of the aggregate,
- The void content(s) of the aggregate layer(s), V_l,
- The bulk void content(s), V_b,
- The hardness of stone expressed as its 10 percent FACT value,
- The corrected ball penetration value as determined by the ball penetration test,
- The average daily traffic per lane in equivalent light vehicles, and
- The surface texture depth of the existing surface.

The design then gives both the maximum and minimum nominal binder application rates. It also provides the binder required for surface texture correction in terms of liters per square meter of cold binder and the aggregate spread rate in cubic meters per square meter ($\times 10^{-3}$). The years of expected service of a reduced life expectancy are also calculated.

This is the only method used by personnel of the Division of National Roads of the Department of Transport for the design of surfacing seals on national routes, including busy freeways. They are very satisfied with the results obtained thus far.

ACKNOWLEDGMENTS

This work is the result of a continuing research project of the National Institute for Transport and Road Research of the South African Council for Scientific and Industrial Research. It is published with the permission of the Chief Director of the NITRR.

REFERENCES

1. C. J. Semmelink. *Findings of Research on the Rational Design of Single and Double Seals.* Research Paper 1. RP/1. National Institute for Transport and Road Research, Council for Scientific and Industrial Research, Pretoria, South Africa, 1985.
2. C. J. Semmelink. *A Laboratory Study of the Aggregate Spread Rates of Seals.* Research Paper 19. RP/19. National Institute for Transport and Road Research, Council for Scientific and Industrial Research, Pretoria, South Africa, 1986.
3. C. P. Marais. Rational Design of the Single Surface Treatment Technique for Road Maintenance. In *Civil Engineering in South Africa*, Vol. 23, No. 8, 1981, pp. 363-379.
4. C. S. Mackintosh. Rates of Spread and Spray in Bituminous Surface-Dressing of Roads. In *Civil Engineering in South Africa*, Vol. 3, No. 10, 1961, pp. 183-188.