APPENDIX A

PUMPING IN A CRACKED PAVEMENT

A.1 INTRODUCTION

Cracks in cementitious layers can allow water to penetrate into the lower layers. If the water gets trapped and cannot drain away through either specially provided drainage layers or a free-draining subgrade, for example sand, it may accumulate and soften the lower layers. This may reduce their elastic moduli resulting in possible overstressing of the upper (cementitious) layers. Under certain conditions it is possible that the water may be pumped out by traffic taking with it some of the fine material from the lower layers. If this is allowed to continue for a long enough period a void may form near the crack.

Pumping is a very serious matter since total distress and a loss of riding quality usually follows very soon after it has started (Otte, 1973a). There has been much speculation on this and many people have been led to believe that pumping actually causes the distress. The prismatic solid finite element program (explained in Chapter 4) provided an opportunity to study this phenomenon analytically.

A.2 ANALYSIS

Only layout H (Figure 4.13, page 71) was considered in this part of the study. After a finite element analysis had been performed to determine the effect of the crack, the mesh was changed and the analysis was repeated but a void was included (Figure A.1). The void (135 mm wide and 5 mm deep) was assumed to represent pumping, or the effect thereof, and it was taken to run across the pavement.

During the study the elastic modulus of the treated base was increased from 12 000 MPa to 50 000 MPa and that of the untreated crusher-run was reduced from 500 MPa to 80 MPa. It is appreciated that moduli of 50 000 and 80 MPa are extremely exceptional, but the major objectives in choosing them were to obtain modular ratios of 100 and 250.

To investigate the effect of progressive softening of the lower layers in the vicinity of the crack the modulus of the second pavement layer, that is the one containing the void, was reduced as shown in Figure A.2. The outcome of this analysis was compared with that when the void was modelled into a layer with a uniform elastic modulus (as in Figure A.1).

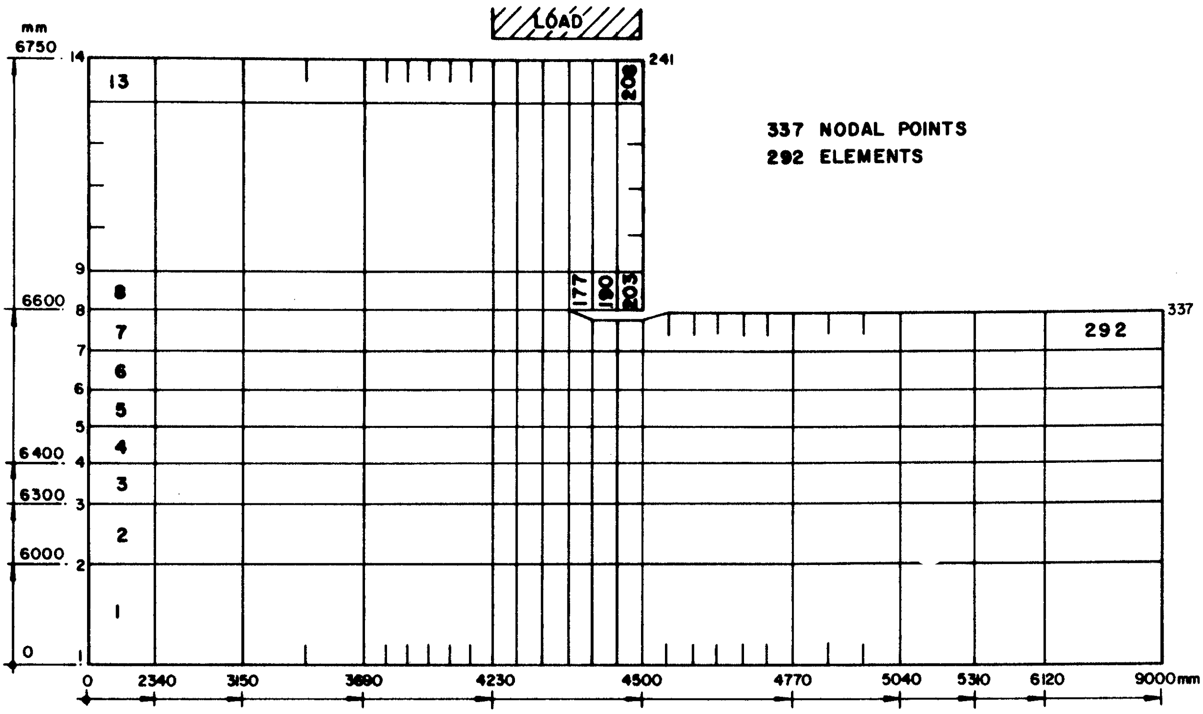


FIGURE A-1

FINITE ELEMENT MODEL AFTER PUMPING

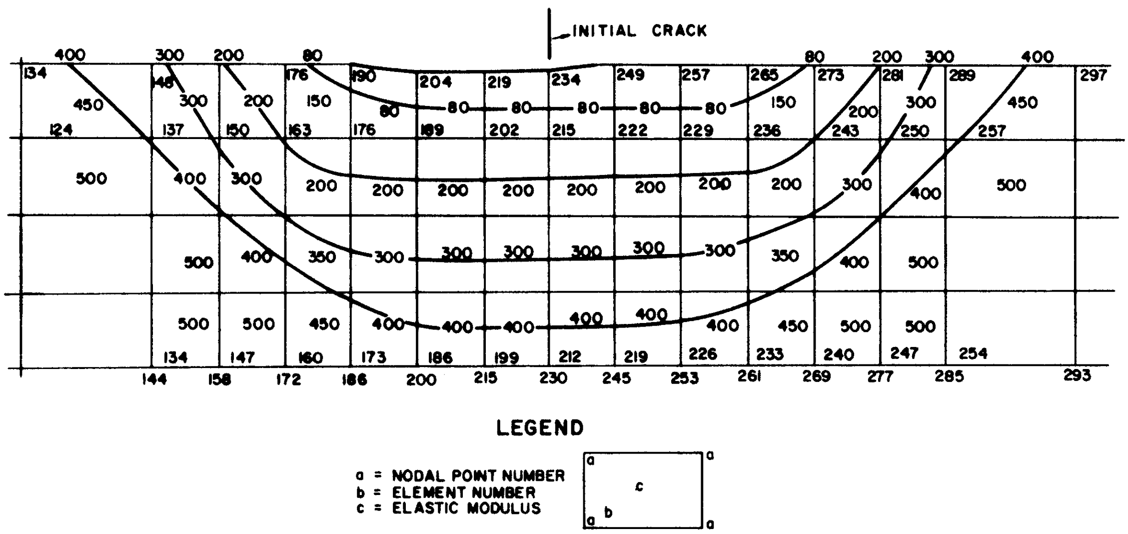


FIGURE A-2

THE REDUCTION IN ELASTIC MODULUS OF THE UNTREATED LAYER IN THE VICINITY OF THE CRACK

A.3 RESULTS

A.3.1 Uniform elastic modulus for support

A.3.1.1 Maximum tensile stress

The maximum tensile stresses in two cracked cases, one without (Figure 4.6) and one with (Figure A.1) the void, were calculated as described in section 4.2. They occurred at the bottom of the treated layer and acted parallel to the crack (σ_{zz}). The increase in stress caused by the void was calculated as the ratio between the two maxima and is reported in Table A.1.

TABLE A.1 : Increase in maximum tensile stress at the bottom of a cracked layer as a result of a void

ELASTIC MODULUS OF TREATED LAYER (MPa)	MODULAR RATIO	MAXIMUM TENSILE STRESS (kPa) IN THE LAYER		RATIO
		Without void	With void	
6 000	12	675	1 205	1,79
12 000	24	1 007	1 488	1,48
20 000	40	1 271	1 691	1,33
50 000	100	1 784	2 121	1,19
20 000	250	1 987	2 254	1,13

The table indicates that the maximum tensile stress increases (from 675 to 1 987) and the ratio between the stresses decreases (from 1,79 to 1,13) with an increase in modular ratio. This information is also reproduced as Figure A.3. It indicates a significant increase in stress below a modular ratio of about 100 and the minimum increase caused by the void seems to be about 1,10 times at very large modular ratios.

A.3.1.2 Comparison of σ_{zz} and σ_{xx} stresses

In the analyses with the void the maximum stress perpendicular to the crack (σ_{xx}) occurred in the centre of one of the elements at the top of the treated layer and some distance away from the edge of the initial crack. Table A.2 compares these values with the maximum stresses parallel to the crack (σ_{zz}) at the bottom of the layer. In all five cases the stresses perpendicular to the crack (σ_{xx}) were much lower than those parallel to the crack (σ_{zz}).

A.3.2 Progressive softening of support

The analysis with the progressively softening support (Figure A.2) was done for a cement-treated layer with an elastic modulus of 12 000 MPa.

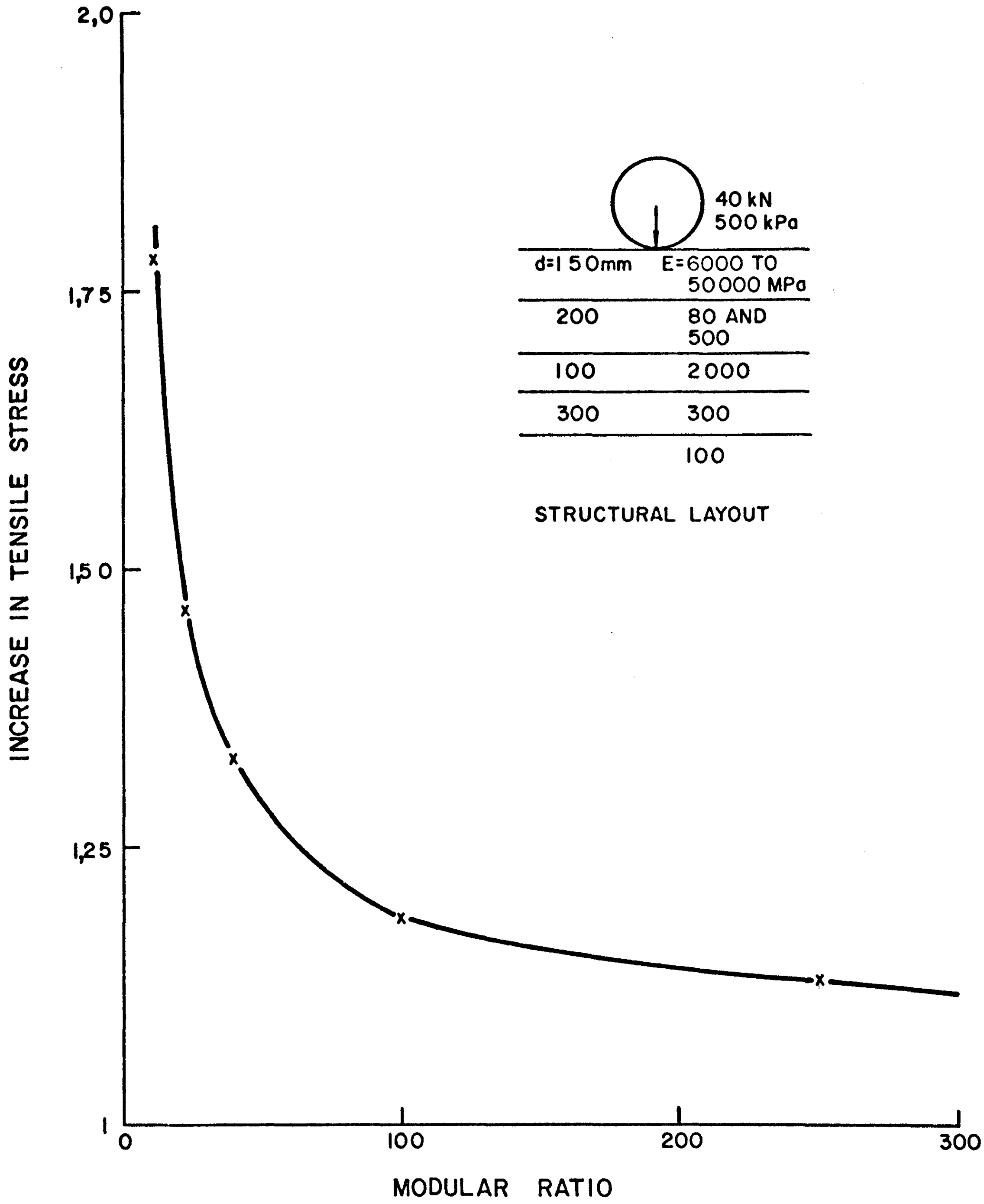


FIGURE A-3

RELATIONSHIP BETWEEN INCREASED TENSILE STRESS AND MODULAR RATIO DUE TO THE PRESENCE OF A VOID

TABLE A.2 : Comparison of maximum stresses perpendicular and parallel to the crack after the void has developed

ELASTIC MODULUS (MPa)	MODULAR RATIO	MAXIMUM TENSILE STRESS (kPa)		RATIO
		Perpendicular to crack (σ_{xx}) (Top of layer)	Parallel to crack (σ_{zz}) (Bottom of layer)	
6 000	12	398	1 205	3,03
12 000	24	416	1 488	3,58
20 000	40	430	1 691	3,93
50 000	100	456	2 121	4,65
20 000	250	628	2 254	3,59

The maximum tensile stress occurred at the same position as in the previous analyses and Table A.3 contains the results to evaluate the effect of the progressive softening before and after the void developed.

Table A.3 indicates that for both cases, with and without the void, the stresses for the progressively softening support were higher than for the uniform support, 1 399 and 1 691 versus 1 008 and 1 488 respectively. This could have been expected from the work by Pretorius (1970). It also appears that the stress increase caused by the pumping and the formation of the void was reduced on the progressive softening support, from 1,48 to 1,21 times.

TABLE A.3 : Effect of progressive softening on maximum tensile stress (kPa)

	CRACKED WITH NO VOID	VOID HAS DEVELOPED	RATIO
Uniform support	1 008	1 488	1,48
Progressive softening	1 399	1 691	1,21

A.3.3 Maximum strain

The failure criterion for cement-treated materials is often expressed in terms of strain (section 2.2.9) and the maximum tensile strain for each analysis was therefore calculated. In all twelve cases the maximum tensile strain occurred in element 203 and it acted parallel to the crack, that is ε_{zz}. The principle of linear extrapolation that was applied for the stress calculation (section 4.2.6) was not used. The values reported in Table A.4 occurred at the centre of the element, 12,5 mm above the bottom of the layer and 12,5 mm from the edge of the crack. The strains (ε_{zz}) were calculated from equation (A.1) and the stresses (σ_{zz}, σ_{yy} and σ_{xx}) were obtained from the finite element analysis (μ = 0,35).

$$\varepsilon_{zz} = \frac{1}{E}\left[\sigma_{zz} - \mu\ (\sigma_{yy}+\sigma_{xx})\right] \text{ .... (A.1)}$$

TABLE A.4 : Maximum tensile strain in a cracked cement-treated layer

ELASTIC MODULUS OF TREATED LAYER (MPa)	MODULAR RATIO	MAXIMUM TENSILE STRAIN ($\mu\varepsilon$)		RATIO
		Without void	With void	
6 000	12	94	164	1,74
12 000	24	67	100	1,49
20 000	40	51	68	1,33
50 000	100	28	34	1,21
20 000	250	80	91	1,14
12 000	+	95	115	1,21

The ratios calculated in Tables A.1 and A.4 are very much the same. This means that the increase caused by the void formed after pumping is the same no matter whether stress or strain is used as the design criterion.

A.4 DISCUSSION

If it is assumed that pumping was very severe and that a void had formed near the initial crack, then Table A.1 indicates an even further increase in tensile stress over that already shown in Tables 4.2 and 4.3. The maximum tensile stress after the void has formed occurred at the same position as before the void had formed and it acted in the same direction. This means that the factors responsible for the typical traffic-associated cracking pattern had not changed and that the pattern itself would therefore probably not be changed by the presence or absence of pumping in the pavement. This seems to indicate that pumping did not cause the traffic-associated cracking, neither did it change the mode of cracking or the cracking pattern, but since it caused an additional increase in stress it accelerated the distress, that is it caused the traffic-associated cracking to occur sooner.

It is however also possible to argue that the pumping did cause the cracking. In some cases the stress or strain may have been relatively low before pumping and the design would probably have tolerated a considerable amount of traffic, which, depending on the traffic pattern, may mean a life of about 5 to 10 years. After pumping the stress and strain may have increased and cracking would occur much sooner, say after 6 to 12 months. Under these conditions, that is when the pavement's life is reduced from a few years to only a few months, it would be reasonable to argue that the pumping had actually caused the cracking. This is because pumping had increased the stress or strain to beyond the point where cracking would not have occurred before the pavement had largely served its functional life. The strains reported in Table A.4 do however indicate that there may not be such a large reduction in expected life (see equation 2.5, page 31). Although the strain ratios are fairly high for modular ratios 12 and 24, the difference in the practical life, that is the time in months or years before the material can be expected to fail in fatigue, is relatively small for all six cases. The above reasoning of pumping causing failure because of a significant reduction in life is therefore not really applicable to these examples.

Table A.2 seems to indicate that traffic-associated cracking does not occur as a result of the σ_{xx} stresses since they are significantly smaller than the σ_{zz} stresses. The pavement with the void next to the crack partially acted as a cantilever resulting in increased tensile stresses near the top of the layer but the stresses at the bottom and parallel to the crack (σ_{zz}) exceeded these by far and the traffic-associated cracking would therefore occur perpendicular to the initial transverse crack. The original theory of the failure mode (Figure A.4) stated that a cantilever would be formed after pumping and this would cause the cracking to start at the top of the treated layer. Table A.2 seems to indicate that this is incorrect. The failure mode, both the previous and the current concept, is explained schematically in Figure A.5.

It was seen (Table A.3) that progressive softening of the lower layers increased the stresses to beyond those developed on a uniform support and it will therefore cause cracking to occur much sooner. Progressive softening is, however, a fairly accurate representation of what can happen when water accumulates in the lower layers. This, and the discussion on the effect of the void on the maximum tensile stress (Table A.1) indicate that the prevention of pumping and the formation of a void is very beneficial in terms of increasing the life of the pavement. Special attention should therefore be paid to avoid the ingress of water and the pumping out of fines.

The design analyzed indicated that the severity of the pumping may be reduced by increasing the modular ratio (Figure A.3) and it therefore

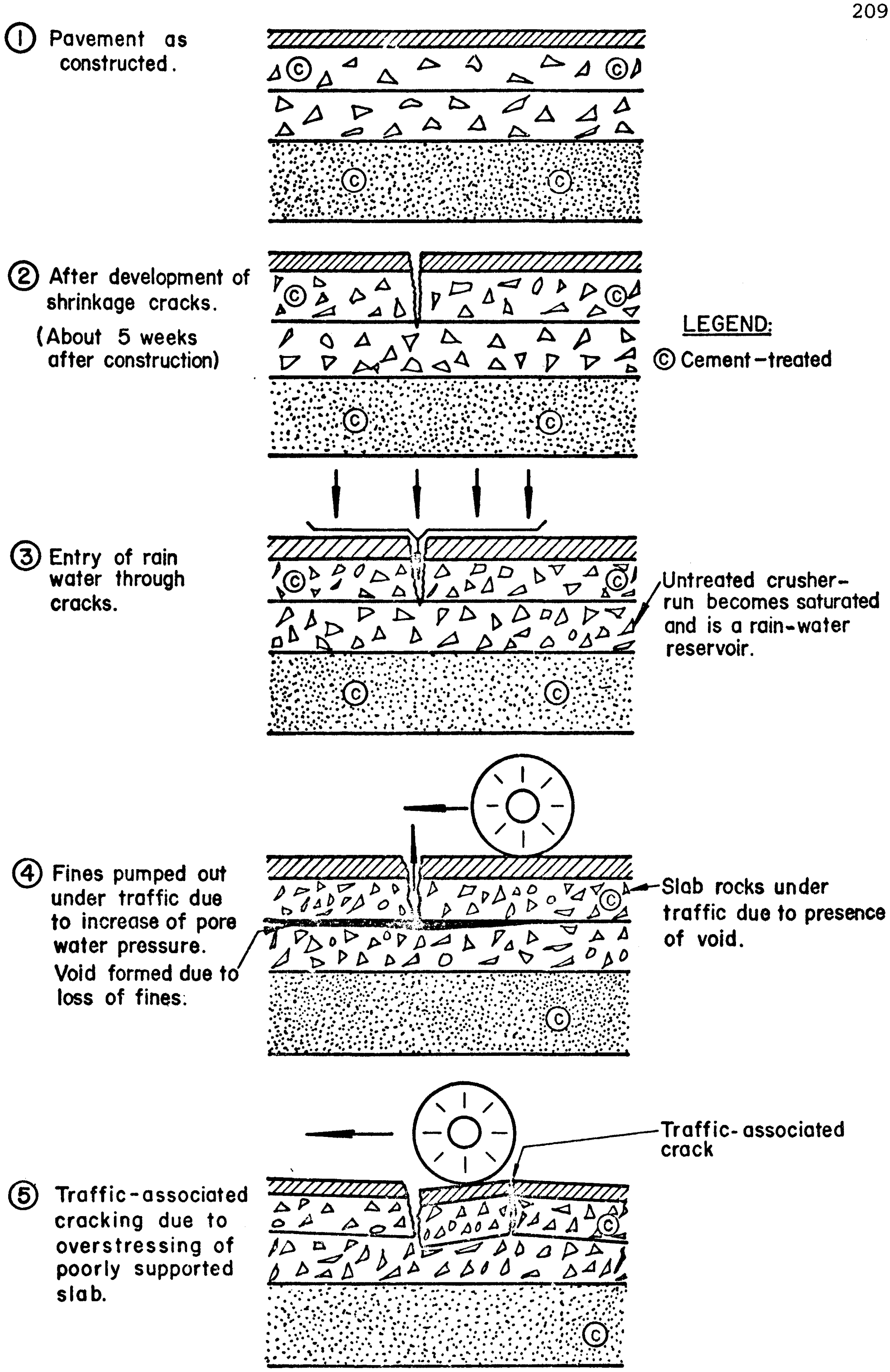
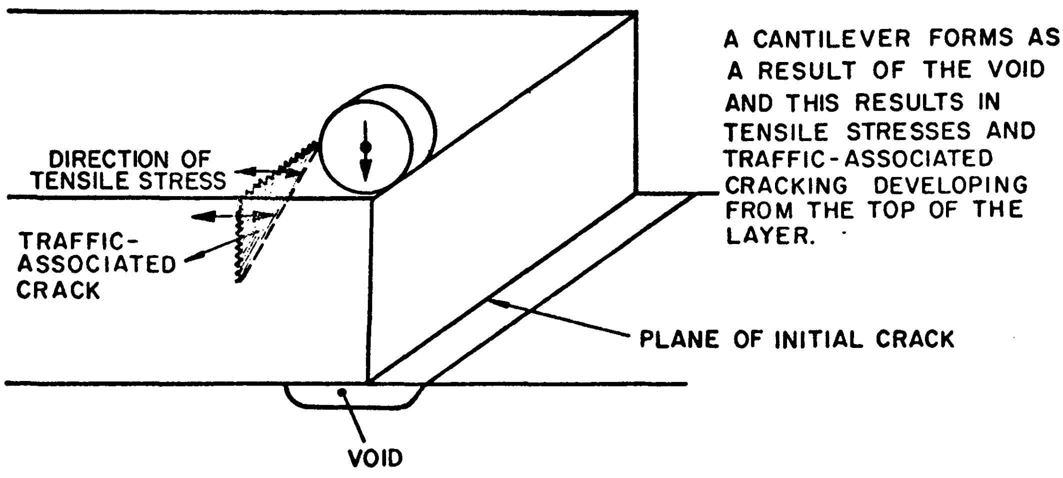
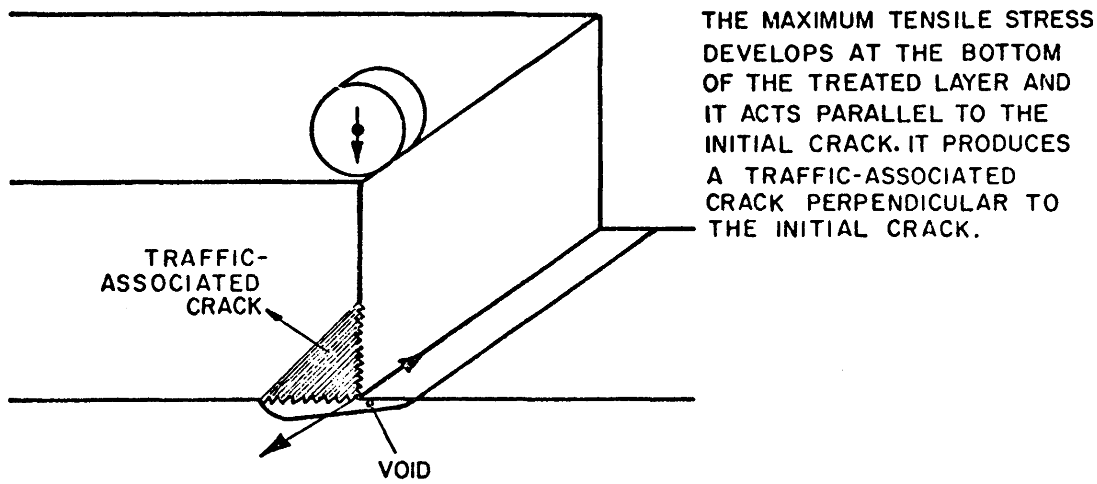


FIGURE A-4

SCHEMATIC DIAGRAM OF MODE OF FAILURE OF A CEMENT-TREATED BASE



PREVIOUS CONCEPT



CURRENT CONCEPT

FIGURE A-5

THREE-DIMENSIONAL SCHEMATICS OF FAILURE MODE ASSOCIATED WITH PUMPING AND TRAFFIC-ASSOCIATED CRACKING appears to be advantageious to strive to the maximum modular ratio. It should also be appreciated that the tensile stress increases significantly with an increase in modular ratio (Table A.1 and Figures 2.1 and 2.3, pages 13 and 15) and that this could cause overstressing of the material and override the advantages of the previous argument. The two apparently conflicting requirements on modular ratio should be fully appreciated and every designer should evaluate his layout in terms of these. It is nevertheless recommended that the modular ratios should be kept to a minimum at all times (section 2.2.4).

A.5 CONCLUSION

(a) Load-associated cracking after excessive pumping is caused by high tensile stresses that develop at the bottom of the treated layer and which act parallel to the initial crack. It is not the result of stresses that were developed because the treated layer cantilevered over a void that was formed after pumping out of the fine material.

(b) Pumping does not cause traffic-associated cracking in treated layers; it merely accelerates the development of these cracks and makes them occur sooner. In cases where severe pumping was followed by traffic-associated cracking these cracks would have occurred anyway but the pumping made them occur much sooner. This is the reason why pumping is often thought to have caused distress in the form of extensive traffic-associated cracking in the treated layer.

APPENDIX B

THE PRISMATIC SOLIDS FINITE ELEMENT PROGRAM

A finite element computer program capable of handling prismatic solids was developed around 1969 and 1970 by E.L. Wilson and P.C. Pretorius (1970). The input requirements are essentially the same as for the other finite element programs that were developed by Wilson but there are some aspects of the input data that may constitute problems and these will be explained in this Appendix. It also contains a description of the input data.

It is assumed that the reader has some understanding of finite element analysis.

B.1 INPUT

B.1.1 Number of harmonics

Subroutine STIFF has a statement

$$TM = ZL*SIN\left[XHAR*PI*T(N)/ZL\right] \Big/ \left[XHAR*PI*T(N)\right] \quad \ldots\ldots\ldots\ldots\ldots \quad (B.1)$$

where T(N) is the loaded length in the Z-direction (see later)

PI = 3,141 2 when $\sin^{-1}$ is calculated in radians

= 180 when $\sin^{-1}$ is calculated in degrees

ZL = one half of the period length (see later)

XHAR = one less than the number of harmonics

TM = a parameter that should ideally be equal to zero. If T(N) or XHAR is zero then the parameter is not defined as above; if T(N) becomes zero then TM equals one and when XHAR becomes zero then TM becomes 0,5.

This equation is needed to calculate the number of harmonics (that is the number of terms in the Fourier series) that are required to represent the load accurately. To illustrate the use of the equation, assume T(N) as 150 mm and half of the period length as 2 400 mm. If TM should be zero, then (XHAR*PI*T(N)/ZL) should be zero since Sin 0° = Sin 180° = 0. Therefore

$$\frac{XHAR*T(N)}{ZL} \text{ should be 1 and } XHAR = \frac{ZL}{T(N)} = \frac{2\ 400}{150} = 16$$

Seventeen harmonics will be required since the number is given by XHAR + 1.

B.1.2 ZL-length

The ZL-length is half of the period length and the period length is the distance between two consecutive loads as indicated in Figure 4.1 (page 55).

For the analysis of pavement structures the distance between the loaded areas should be sufficient to ensure that there will be no interaction between two adjacent loaded areas and this means a long period length. The longer the period length the more the number of harmonics required to represent the load accurately but since this will be costly on computer time, the period length should not be made unnecessarily long. Using a stiff cement-treated layer, it is suggested that the period length should be of the order of 3 to 4 metres.

B.1.3 Material properties

Only one elastic modulus and one Poisson ratio can be specified for each layer of material. This implies homogeneous, isotropic, linear elastic materials.

B.1.4 Codes at nodal points

Care must be taken in the allocation of the boundary condition code numbers. A code of 0 indicates that the nodal point is free to move both vertically and horizontally, as is the case for all nodal points within the boundaries, and along the free surface. A code of 1 signifies freedom of movement in the Y-direction only (as for vertical boundaries and any vertical lines of symmetry) and one of 2 signifies freedom of movement in the X-direction only, while a code of 3 prohibits movement in both the X- and Y-directions. The presence of any cracks allows movement in a direction perpendicular to the crack.

B.1.5 Loaded length in Z-direction

The loaded length in the Z-direction is half of the total loaded length in the Z-direction. This is because of symmetry around the axis that goes through the centre of the loaded area (see Figure 4.1).

If the loaded area is rectangular it should be decided which side falls along the Z-axis and the loaded length in the Z-direction will again be half of the total load in the Z-direction.

B.1.6 Load application

The load on the structure is always applied as concentrated nodal point loads. A force working in the positive direction is given a + sign and one in the negative direction is designated negative, for example a force working downwards is negative.

If a total load of x kN is applied to a structure and it is allowable to use symmetry (around the y-axis), the load on the section of the structure under consideration in the finite element analysis is only $\frac{x}{2}$ kN. An example is shown in Figure B.1. If the load is specified as a pressure (load per area) the pressure remains the same on both sides of the axis, only the total load (kN) is halved.

If the load is applied as a uniformly distributed load, for example tyre or footing pressure, it must be converted and represented as concentrated line loads acting on the nearby nodal points. The length of these line loads are the loaded length in the Z-direction (section B.1.5). The concentrated forces on the nodal points are calculated from equation (B.2) which is

Nodal point force = (Applied pressure or stress) x (2 times loaded length in Z-direction) x (the effective width over which the stress acts) .... (B.2)

In this equation the term (2 x loaded length in the Z-direction) may be replaced by the <u>total</u> length in the Z-direction.

Equation (B.2) can best be explained by an example. Assume an applied stress of 520 kPa over an area of 280 x 280 mm and that in the finite element mesh this load will be carried on 5 nodal points (Figure B.2). Because of symmetry around the vertical axis (y) the distance between nodal points 1 and 5 is 140 mm and when equal spacing is assumed, the loads are 35 mm apart. The loaded length in the Z-direction is also 140 mm, it is the half of 280 mm. The concentrated (line) loads at the nodal points are therefore calculated as follows:

Nodal point 1 and 5 : (0,520)*(2*140)*(17,5) = 2 548 N

Nodal point 2 to 4 : (0,520)*(2x140)*(35) = 5 096 N

The total load at the 5 nodal points is 20,384 kN. (Note: it is about 50 per cent of the total applied load.)

B.1.6 Longitudinal distance

These distances are measured from the centre of the load along the Z-axis and any number of these distances can be fed in (all on separate cards). Stresses and displacements are printed at each plane so defined.

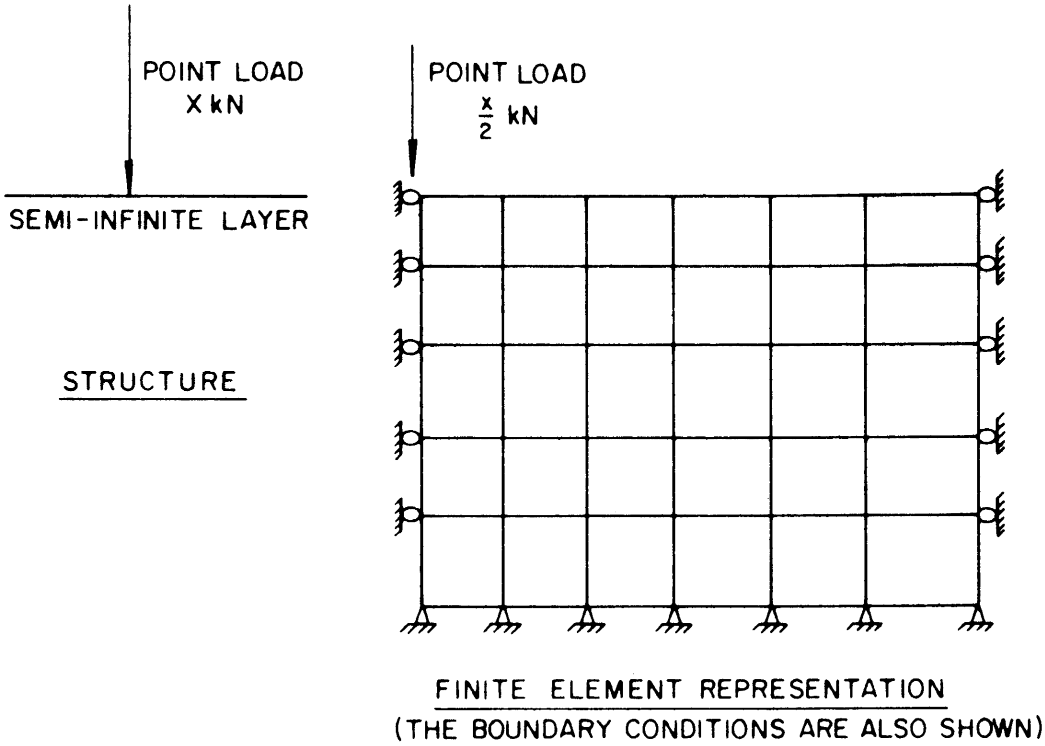


FIGURE B-1

THE LOADING OF AN AXISYMMETRIC STRUCTURE

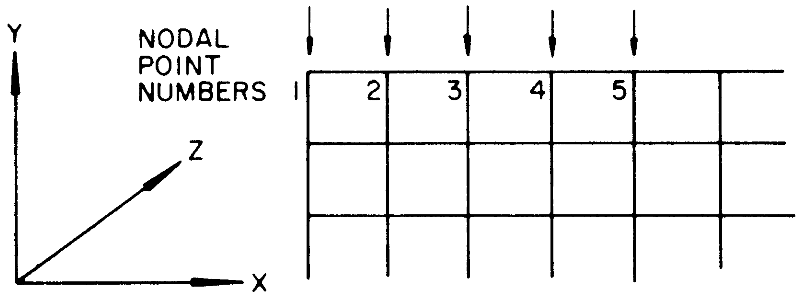


FIGURE B-2

CALCULATION OF CONCENTRATED

NODAL POINT LOADS

B.2 OUTPUT

The output contains the nodal point displacements in the X-, Y- and Z-directions for each harmonic. The contributions of each harmonic to the displacement at the various individual nodal points are totalled and the total displacement of each nodal point and the stresses in each element at the specified longitudinal distances, are printed. The stresses given are σ_{xx}, σ_{yy}, σ_{zz}, τ_{xy}, τ_{xz} and τ_{yz}. The normal stresses (σ_{xx}, σ_{yy} and σ_{zz}) are parallel to the X-, Y- and Z-axes respectively, and they act on planes perpendicular to these axes, called the x-, y- and z-planes. τ_{xy}, τ_{xz} and τ_{yz} are the shearing stresses. The first subscript associates the shearing stress with a plane which is perpendicular to the axis designated by the subscript, while the second subscript designates the direction of the shearing stress, for example τ_{xy} is a shear stress on the x-plane in the y-direction.

The sign convention in the program is the normal one, namely tensile stresses are positive and compressive stresses are negative.

B.3 DIMENSIONS FOR INPUT AND OUTPUT

The original program by Wilson and Pretorius was metricated by using scale factors in the input and output format specifications. The nodal point forces should be specified in N and this is then changed to mN by the scale factor. The elastic moduli should be specified in MPa and this is converted to kPa while all distances should be specified in millimetres. The output dimensions are micrometres for the nodal point displacements and kPa for the stresses. The dimensions to be used in the metricated version of the program are summarized in Table B.1.

TABLE B.1 : Input and output dimensions

INPUT	OUTPUT
Nodal point force - N	Stress - kPa
Elastic modulus - MPa	Displacements - micrometres
Distance - mm	

B.4 COMPUTER PROGRAM INPUT

The first step is to select a finite element representation of the two-dimensional cross-section of the body. Elements and nodal points are then numbered in two numerical sequences, each starting with one. The following group of punched cards numerically defines the two-dimensional structure to be analyzed:

(i) Identification card - (18A4)

Columns 1 - 72 This card contains the heading or other relevant information which is to be printed with the results

(ii) Control card - (415, F10.2)

Columns	1 - 5	Number of nodal points (450 max)
	6 - 10	Number of elements (400 max)
	11 - 15	Number of different materials (12 max)
	16 - 20	Number of harmonics
	21 - 30	ZL - length

The ZL-length is half of the period length. The period length is the length to the next load.

(iii) Material property information (I5, 2F10.0)

One card for each material:

Columns	1 - 5	Material identification - any number from 1 to 12
	6 - 15	Elastic modulus (MPa)
	16 - 25	Poisson ratio

(iv) Nodal point data - (I5, F5.0, 5F10.0)

One card for each nodal point with the following information:

Columns	1 - 5	Nodal point number
	6 - 10	Code number
	11 - 20	X-ordinate (mm) (usually horizontal)
	21 - 30	Y-ordinate (mm) (usually vertical)
	31 - 40	UX
	41 - 50	UY
	51 - 60	Loaded length in Z-direction (i.e. half of the total length of the load). (If the nodal point is not loaded the value is zero.)

If the number in column 10 (code number) is

0, UX is specified X-load
UY is specified Y-load

NB. Load in Newton (N)

1, UX is specified X-displacement
UY is specified Y-load

2, UX is specified X-load
UY is specified Y-displacement

3, UX is specified X-displacement
UY is specified Y-displacement

All loads are total forces acting at the nodal point. Loaded length is half the total loaded length in the Z-direction. Nodal point cards must be in numerical sequence and the first and last nodal points must have cards. If cards are omitted, the omitted nodal points are generated at equal intervals along a straight line between the defined nodal points. The boundary code (column 10), UX, UY, and loaded length for the generated nodal points are all set equal to zero.

(v) Element properties: (6I5)

One card for each element.

Columns	1 - 5	Element number
	6 - 10	Nodal point I
	11 - 15	Nodal point J
	16 - 20	Nodal point K
	21 - 25	Nodal point L
	26 - 30	Material identification.

NOTE: (a) The nodal points I, J, K and L defining the element must be ordered counter-clockwise. The maximum difference between nodal point numbers defining any one element is 17.

(b) Element cards must be in numerical sequence. If cards are omitted, the information for the omitted elements is generated by incrementing by one the preceding, I, J, K and L. The material identification number for the generated elements is set equal to the value on the first card.

(c) No provision was made for triangular elements.

(vi) Longitudinal distance: (F10.0)

Column 1 - 10 ZZ - length.

This distance defines the cross-sections in the longitudinal (Z) direction where stresses (kPa) and strains are to be printed. Nodal point displacements and element stresses for the defined finite element mesh are obtained.

APPENDIX C

CALCULATION OF THERMAL CONDUCTIVITIES

Williamson (1972c) discussed various theories to calculate the thermal conductivity of composite materials, such as crusher-runs and asphaltic concretes, and concluded that "...the geometric mean equation is capable of undertaking such calculations to an accuracy of about 90 per cent...". The equation is

$$k_{mix} = (k_{agg})^m \cdot (k_{bind})^n \cdot (k_{void})^p \cdot (k_{water})^q \text{ ...... (C.1)}$$

where
k_{mix} = thermal conductivity of the composite material
k_{agg} = thermal conductivity of the aggregate
k_{bind} = thermal conductivity of the binder: cement, lime or bitumen. Taken as 0,002 7 cal/cm.s.^{o}C for cement
k_{void} = thermal conductivity of air. Taken as 0,000 063 cal/cm.s.^{o}C
k_{water} = thermal conductivity of water. Taken as 0,001 5 cal/cm.s.^{o}C
m,n,p & q = percentage of unity for the various phases in the material, e.g. 0,9 and 0,04.

C.1 CRUSHER-RUN

Two rock types were considered for the crusher-run, quartzite and granite. Bullard (1939) gave the thermal conductivities of the rocks as about 0,016 and 0,006 5 cal/cm.s.^{o}C and the solid densities (specific weights) as 2,69 and 2,62 g/cc respectively.

The specifications for crusher-run basecourses call for compaction to 88 per cent of solid density. The remaining 12 per cent of the volume is taken up by air voids and water and these were assumed to be 8 and 4 per cent respectively. The moisture content may change during the day and the year, but 4 per cent moisture is a reasonable average value. The percentage binder equals zero, since an untreated crusher-run was considered.

Quartzite: $k_{mix} = (0{,}016)^{0,88} \cdot (0{,}000\ 063)^{0,08} \cdot (0{,}001\ 5)^{0,04}$

$= 0{,}009\ 3$ cal/cm.s.^{o}C

Granite : $k_{mix} = (0{,}006\ 5)^{0,88} \cdot (0{,}000\ 063)^{0,08} \cdot (0{,}001\ 5)^{0,04}$

$= 0{,}004\ 2$ cal/cm.s.^{o}C

Often a lower density is achieved in practice and, assuming the same moisture content, the void ratio would increase. To investigate the effect of a change in density 82 per cent of solid density was assumed:

Quartzite: $k_{mix} = (0{,}016)^{0{,}82} \cdot (0{,}000\ 063)^{0{,}14} \cdot (0{,}001\ 5)^{0{,}04}$
$= 0{,}006\ 7$ cal/cm.s.°C

Granite : $k_{mix} = (0{,}006\ 5)^{0{,}82} \cdot (0{,}000\ 063)^{0{,}14} \cdot (0{,}001\ 5)^{0{,}04}$
$= 0{,}003\ 2$ cal/cm.s.°C

In the previous calculations only two densities were considered. To study the full spectrum of densities and to evaluate the effect of small changes in water content and void ratio, Figure C.1 was prepared. In preparing the figure it was assumed that the sum of the percentages of solid density, void ratio and water content should equal 100 per cent. The figure shows the density and rock type to be important but the water content and the void ratio has a relatively minor effect. The reason for this is that both air and water have relatively low thermal conductivities.

C.2 BITUMINOUS MATERIALS

Williamson (1972) reported the thermal conductivity of an asphaltic concrete with quartzitic aggregate as 0,007 1. The bitumen content was about 5 per cent and the void ratio was about 11 per cent. Saal et al (1940) reported the thermal conductivity of bitumen as about 0,000 4. When a dry mixture is assumed, that is water content equals zero, the percentage of solid density of the aggregate (m) can be calculated from equation (C.1) as 0,84 that is 84 per cent of solid density. The applicability of the equation was again confirmed by these calculations since the volume percentages totalled a hundred.

The void ratio of the abovementioned mixture was high since the specifications usually call for it to be between 2 and 6 per cent. A more practical mix would be one with only 5 per cent voids and hence a higher percentage of solid density for the aggregate. The thermal conductivity of such a mix was calculated as

$$k_{mix} = (0{,}016)^{0{,}9} \cdot (0{,}000\ 4)^{0{,}05} \cdot (0{,}000\ 063)^{0{,}05}$$
$$= 0{,}01 \text{ cal/cm.s.}^{\circ}\text{C}$$

When applying the equation to the same mixture, but with a granitic aggregate, the conductivity was calculated as 0,004 5 cal/cm.s.°C.

To reduce the number of variables the average values for bituminous materials quoted by Williamson (1972) will be used in the analyses. These are 0,007 cal/cm.s.°C and 2,2 g/cc.

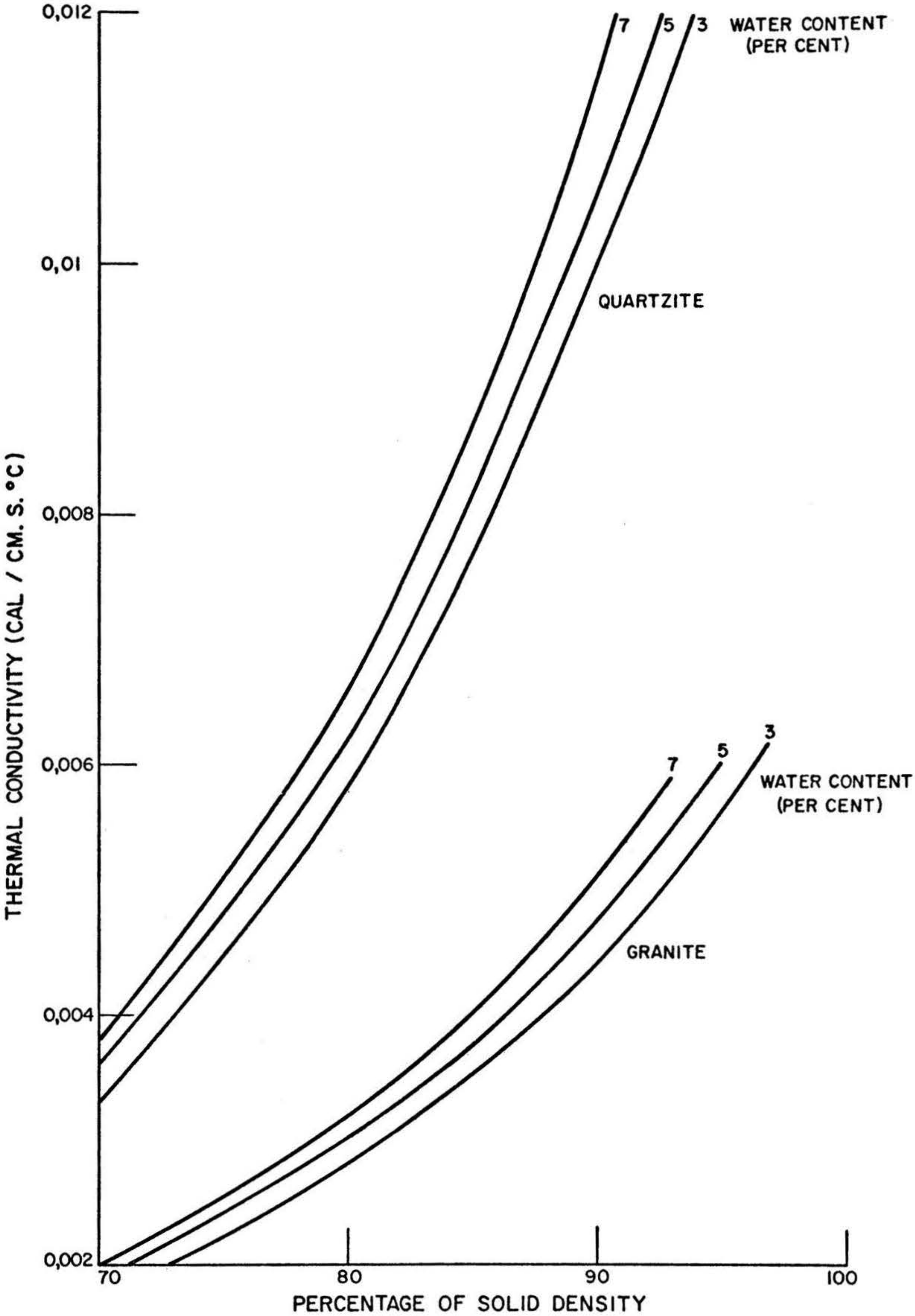


FIGURE C-1

EFFECT OF DENSITY, WATER CONTENT AND ROCK TYPE ON THE THERMAL CONDUCTIVITY OF CRUSHER-RUN

C.3 CONCLUSIONS

(a) The thermal conductivity of quartzitic and granitic crusher-run basecourses should be taken as 0,009 3 and 0,004 2 cal/cm.s.^{o}C when compacted to 2,36 and 2,31 g/cc respectively.

(b) At lower densities (2,2 and 2,14 g/cc) the conductivities should be reduced to 0,006 7 and 0,003 2 cal/cm.s.^{o}C.

(c) The effect of changes in void ratio and water content seems to be fairly small and for the sake of minimizing the number of variables, only 4 per cent moisture was considered.

(d) The thermal conductivity of an asphaltic concrete made with quartzitic and granitic aggregates was calculated as 0,010 and 0,004 5 cal/cm.s.^{o}C respectively. Both the void ratio and bitumen content were fixed at 5 per cent. In Chapter 5 an average value was used, namely 0,007 cal/cm.s.^{o}C.

APPENDIX D

DATA REQUIRED TO ANALYSE THE PAVEMENTS OF ROADS S12 AND N4/1

To model the pavement for the computer program it was subdivided into 21 nodes; one 25 mm node for the sufacing, four 25 mm nodes for each of the next four layers, and an additional four 75 mm nodes for the selected subgrade. The other information was described in Chapter 5, but the material properties were changed according to Table D.1.

TABLE D.1 : Material properties

PROPERTY	BITUMINOUS MATERIAL	CEMENT-TREATED CRUSHER-RUN (QUARTZITE)	CRUSHER-RUN (QUARTZITE)	CEMENT-TREATED NATURAL GRAVEL	SUBGRADE
Conductivity	0,010	0,010 8	0,009 3	0,005	0,002 5
Specific heat	0,2	0,2	0,2	0,2	0,19
Density (g/cc)	2,3	2,36	2,36	2,0	1,85
Elastic modulus (MPa)	3 000	18 500	500	4 000	150

The tensile strength and coefficient of linear expansion of the cement-treated crusher-run were 690 kPa and $8.10^{-6}/^{o}C$ respectively (Otte, 1974, and Williamson, 1972).

The thermal conductivity of the cement-treated quartzitic crusher-run was calculated according to equation (C.1) given in Appendix C

$$k_{mix} = (0,016)^{0,88} . (0,002\ 7)^{0,04} . (0,000\ 063)^{0,04} . (0.001\ 5)^{0,04}$$
$$= 0,010\ 8\ \text{cal/cm.s.}^{o}C$$

In this calculation compaction to 88 per cent of solid density was assumed and 4 per cent for each of the other three components.

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