it does not, the limitations of the models should be identified. Mechanistic variables such as stress, strain, or stress-and-strength ratio should be considered, since this may greatly increase the reliability of the model. The stepwise regression procedure is believed to give the best selection of independent variables.

3. The functional form of the model should be carefully selected to represent the physical real-world situation as closely as possible. This will lead to a model that considers the appropriate shape, nonlinearity, and interactions of variables; meets boundary conditions; and also gives reasonable sensitivity of the variables. Such selection requires extensive knowledge of the problem and the available data.

4. Various statistical criteria should be used to assess the precision of the model. The model should explain a high percentage of the total variation about regression; the standard error should be less than a practical value for usefulness; there should be no discernible patterns in the residuals; the model should not suffer from significant lack of fit; and all estimated coefficients should be significant with, say, $\alpha \leq 0.05$. Detailed explanation of regression-model development and testing may be found in the literature (11-15).

5. Significant progress can be made in pavement technology if agencies will begin the development of in-service pavement data bases from which reliable predictive models can be developed and used for pavement management purposes.

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Characterization of Bitumen-Treated Sand for Desert Road Construction

GURDEV SINGH AND SHAFIQ KHALIL HAMDANI

This paper summarizes the findings of an experimental program designed to permit evaluation of the accumulation of permanent deformation in bitumen-treated sand layers by applying the more rational methods of pavement analysis and design. The primary part of the work consists of the characterization of the cumulative deformation response of bitumen-sand specimens tested under simulated conditions of temperature and dynamic stress. Results have been analyzed by using multiple regression analysis, and predictive relationships of rut depth are formulated therefrom.

The developing economies of many countries in the Middle East have resulted in an increasing demand

Table 1. Growth in number of motor vehicles in some Middle Eastern countries.

Country	Code	Units (000s) 1966	1970	1975
Algeria	A	103.4	142.8	180.0[a]
	B	68.3	81.6	95.0[a]
Egypt	A	105.3	130.7	215.5
	B	27.5	30.1	46.3
Iran	A	142.4	278.2	589.2[a]
	B	49.4	73.5	111.2[a]
Kuwait	A	69.6	112.9	203.7
	B	25.3	36.8	68.5
Lebanon	A	105.4	136.0	220.2[a]
	B	14.1	16.6	23.4[a]
Libyan Arab Republic	A	53.0	100.1	263.1
	B	25.2	45.4	131.3
Morocco	A	168.6	222.5	320.1
	B	68.0	83.9	127.2
Tunisia	A	53.7	66.4	102.6
	B	31.5	37.2	67.0

Note: A = passenger cars; B = commercial vehicles.
[a]Statistic for 1974.

for the transportation of passengers and goods in general. This increasing demand for road transport is exerting an urgent need for the construction of many miles of both high-standard surfaced roads and secondary, low- to medium-volume desert roads; see Table 1 (1).

Most countries in this region either border or lie completely within areas whose climate is categorized as desert or semidesert, and a significant proportion of the total required mileage is projected to run through desert land where little or no coarse hard aggregates or gravel are readily available for conventional road construction. The surface soil consists largely of only windblown or other sand deposits. The problem of how to build such roads economically is therefore becoming evident.

One of the important items influencing the economy of road projects is the cost of aggregates. Aggregates constitute 95-100 percent of the material in the base layers and subbases (2), and the availability, or lack, of economically exploitable sources of suitable aggregate has a great impact on the total cost of road projects.

Stabilization of windblown and other sand deposits by using bituminous products has been tried in many countries all over the world, and the literature reveals many successful experimental field trials that emphasize the potential of this composite in road construction (3-5). The inherent lack of internal stability of these mixes, however, coupled with excessive temperature susceptibility, makes surface rutting a major cause of failure in desert roads. Unfortunately, the design subsystem of this type of damage has received little attention compared with fatigue and thermal-cracking failure (6). In addition, more rational methods of design against rutting (such as pseudoelastic and linear viscoelastic designs) have been rendered inapplicable by the lack of suitable characterization of the mechanical response of the materials considered in the design. Accordingly, less reliable empirical methods for mixture and thickness design have been and are still being widely used in the construction of bitumen-sand roads.

In this work, the systems approach has been adopted to investigate the potential of using bitumen-treated, poorly graded sand (like that encountered in real desert-road projects) as a structural component in pavement systems. The approach consists of simulative tests in which a temperature-controlled triaxial cell capable of applying repetitive and independent stresses in the axial and the radial directions was used to determine the pattern in which the irrecoverable component of the dynamic strain accumulates under different testing conditions.

METHODOLOGY

A general outline of research activities is shown in Figure 1. The primary part is represented by cells 11 to 15; other cells represent the necessary activities of preparatory or complementary nature.

EXPERIMENTAL PROGRAMS

The work involved the design and implementation of two types of experimental programs. The first consists of four preparatory investigations intended to provide necessary data for a detailed design of the two primary studies.

Preparatory Investigations

1. Determination of the compactibility or the compaction-density relationships for a range of bitumen-sand mixtures--The gyratory testing machine (GTM) was used to apply two different compactive efforts to 11 mixes that ranged in bitumen content from 2 percent to 13 percent (in 1 percent increments). The test program was replicated according to the 1975 ASTM standard D3387-74T so that each treatment was represented by three tests. Unit weights corresponding to the lower compactive effort (7) were adopted as molding densities for the preparation of the specimens for the subsequent study of mixture design.

2. Mixture-design study to determine the optimum amount of bitumen to be mixed with the sand--The cylindrical specimens tested were 51 mm in diameter and 102 mm long. These were compacted in a constant-volume mold (British Standard 1924: 1975) to initial densities corresponding to bitumen contents of 3, 5, 7, 9, and 11 percent, as determined above. The temperature-controlled dynamic triaxial apparatus was used to apply repeated uniaxial stresses, and the criterion adopted was the resistance of the tested samples to the cumulative permanent distortion.

3. Determination by direct testing of the resilient modulus and Poisson's ratio of the optimum mixture chosen--At this stage, measurements of variations in these parameters with stress repetitions were considered unnecessary. The measurement of the dynamic response at each testing condition was, therefore, made only once and then only after a conditioning stage of 100 repetitions. A range of temperature and stress conditions likely to exist in real pavements was included in the test program. The duration of the repeated stress pulses was varied at two levels, 0.1 s and 0.2 s. If an element is considered to be 200 mm beneath pavement surface, these durations correspond approximately to wheel speeds of 26 km/h and 16 km/h, respectively (8). Stress amplitudes, on the other hand, were set to result in ratios of σ_3/σ_1 between 0.0 and 0.5, thus simulating only those combinations of stress that occur in the compression zone of a pavement layer. Stress-strain response was recorded on an ultraviolet (UV) trace that was subsequently used to calculate the resilient constants.

4. Structural analysis of typical desert-road cross sections to define the stress profiles and combinations likely to exist in compacted layers of

the optimum mixture selected--The program consisted of analyzing 27 systems in which the treated sand acted either as the top layer or as a base under 100 mm of bituminous concrete surfacing. The subgrade in all the systems was assumed to be untreated and densely compacted sand. Resilient moduli and Poisson's ratios for the bitumen-sand layer were chosen from results of the investigation described above, and stiffness moduli for the bituminous concrete surfacing were selected by using van der Poel's nomograph (9), assuming certain temperature extremes (10). Values for the resilient modulus of the dense sand subgrade were derived from two sources: (a) experimental results reported by other investigators (11,12) and (b) by measuring the California bearing ratio (CBR) and using it in the correlation: E_{dyn} (kN/m²) = (5 to 20)10^3 x CBR(%), suggested by Huekelom and Foster (13).

The multilayer elastic analysis was facilitated by using Shell's computer program, Bitumen Structures Analysis in Roads (BISAR).

Primary Investigation

The selection of constitutive equations that adequately model the response of paving materials to the loading and environmental conditions can be a very complex task. Simulation is a suitable technique for solving such complex problems. It is,

Figure 1. Outline of research activities.

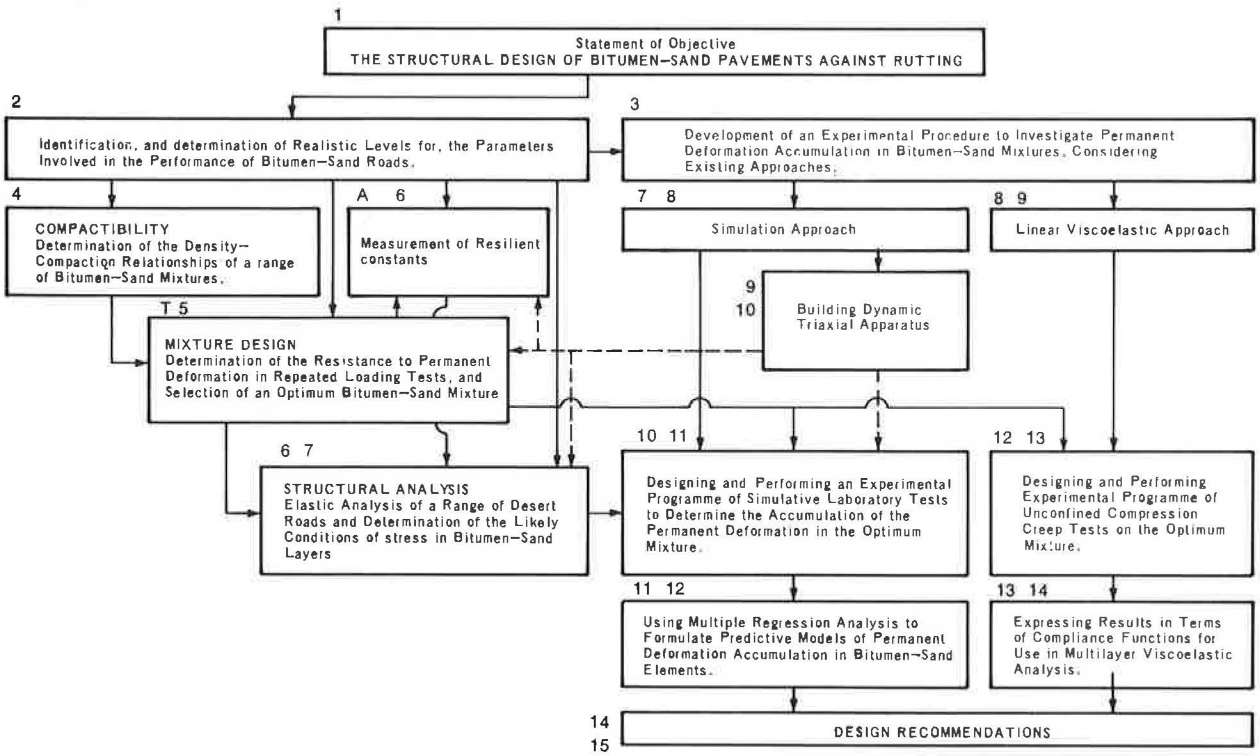
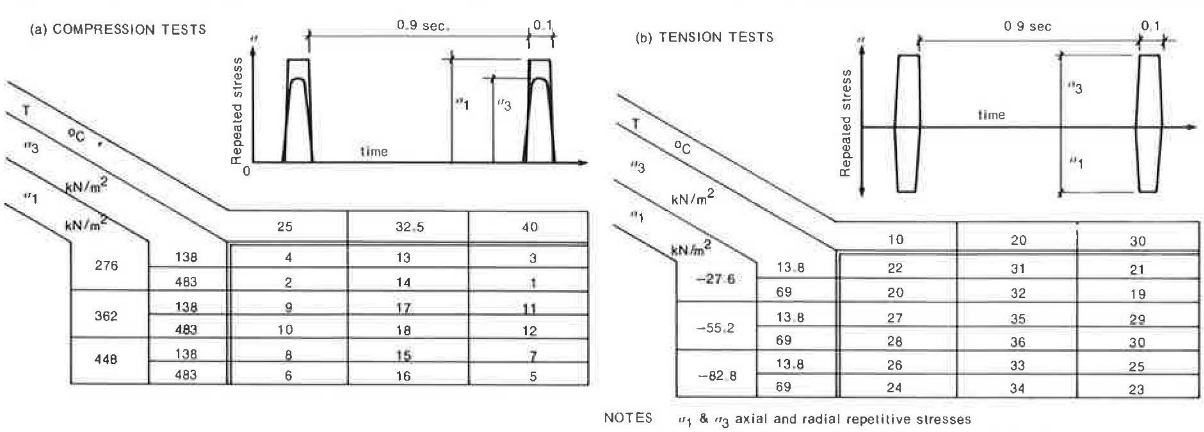


Figure 2. Experimental program for the simulation of the permanent deformation accumulation in bitumen-sand layers under repetitive triaxial stresses.



(a) Compression tests

σ3 (kN/m²)	σ1 (kN/m²)	T = 25 °C	T = 32.5 °C	T = 40 °C
276	138	4	13	3
	483	2	14	1
362	138	9	17	11
	483	10	18	12
448	138	8	15	7
	483	6	16	5

(b) Tension tests

σ3 (kN/m²)	σ1 (kN/m²)	T = 10 °C	T = 20 °C	T = 30 °C
−27.6	13.8	22	31	21
	69	20	32	19
−55.2	13.8	27	35	29
	69	28	36	30
−82.8	13.8	26	33	25
	69	24	34	23

NOTES σ_1 & σ_3 axial and radial repetitive stresses
Figures in cells are to identify the corresponding treatments.
Mixture tested : optimum bitumen–sand (7% B.C.)
Each treatment is represented by 4 tests.

Figure 3. Specified gradation of the sand used and typical gradations in desert areas.

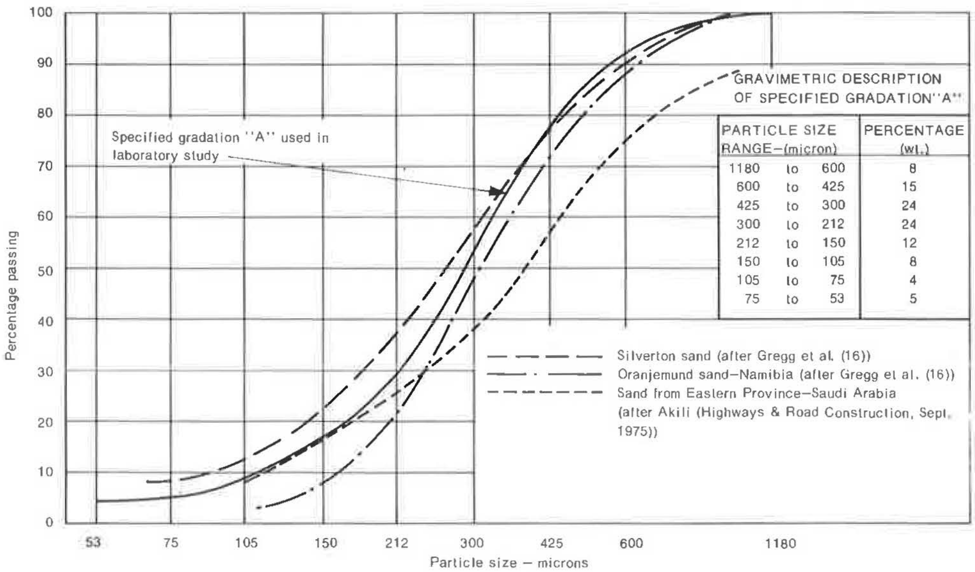


Figure 4. General schematic diagram of equipment.

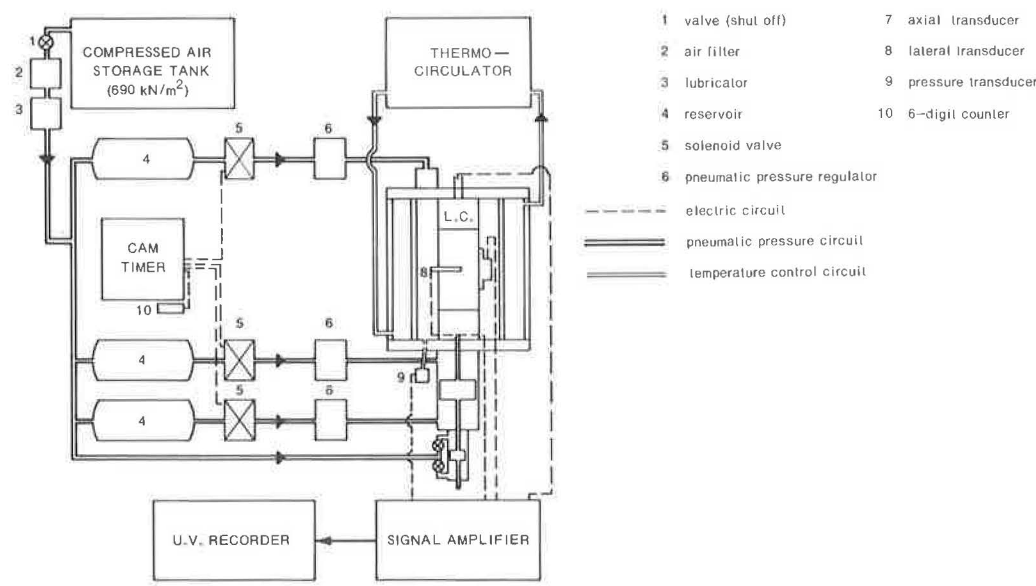
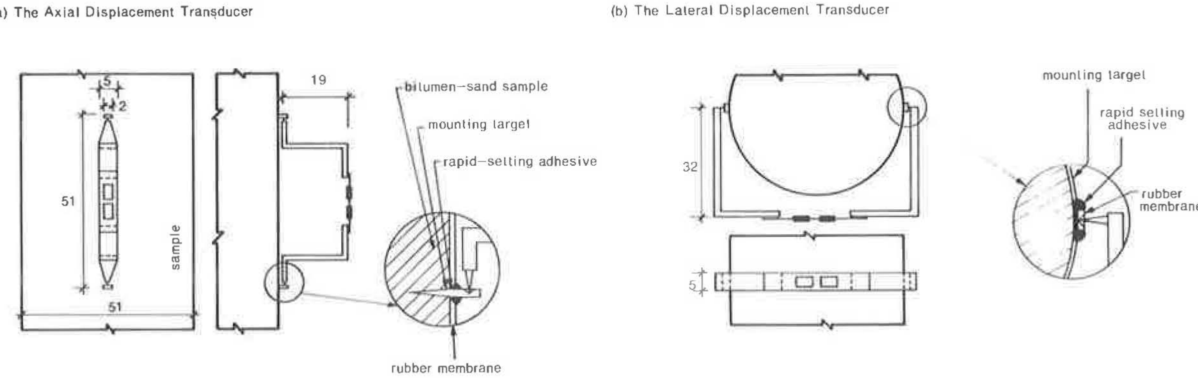


Figure 5. Transducers for load and displacement measurements in the dynamic triaxial apparatus.



however, not necessary to include most of the actual features of the problem considered, since few are vital to the particular aspect under study (14). The extremely arid environment of hot desert implied that moisture content of samples could be excluded as a test variable. Also reduced to constants are factors of gradation and surface characteristics of the sand. Bulk density and bitumen content of tested samples were maintained at 1857 kg/m^3 and 7 percent, respectively.

The experimental program is shown in Figure 2. Amplitudes for vertical and horizontal stress were selected with consideration of actual stress profiles in bitumen-treated sand layers produced in the previous investigation of stress analysis and with a provision that stresses should be repeated at least 100 000 times in the compression tests and 30 000 times in the tension tests before permanent distortion in the tested sample should reach 10 percent extension or contraction. Stresses in the tension tests were also kept relatively low to limit the number of samples that tended to fracture prematurely.

MATERIALS AND EQUIPMENT

Materials

The materials procured for preparing test specimens consisted of poorly graded quartzitic sand from Leighton Buzzard (United Kingdom), 70/80-penetration-grade bitumen, and solvent naphtha. The sand was the only aggregate used in preparing the mixtures. Its type and gradation were selected to approximate those of windblown sand often encountered in desert-road construction. Figure 3 shows typical gradation curves for sands of this type (15), together with the distribution curve adopted for this work. The shape of the particles was classified as rounded to irregular and the surface texture as smooth. The percentage of fines was fixed at 5 percent. Possible variability because of unspecified gradation of this proportion of fines was eliminated by sieving out all dust particles smaller than 53 µm.

A rapid-curing cutback was prepared by diluting the refinery bitumen by 40 percent of its volume by solvent naphtha. The proportion of solvent was arrived at after a few preliminary trials to allow

Figure 6. Compactibility of bitumen-sand mixtures in the gyratory testing machine.

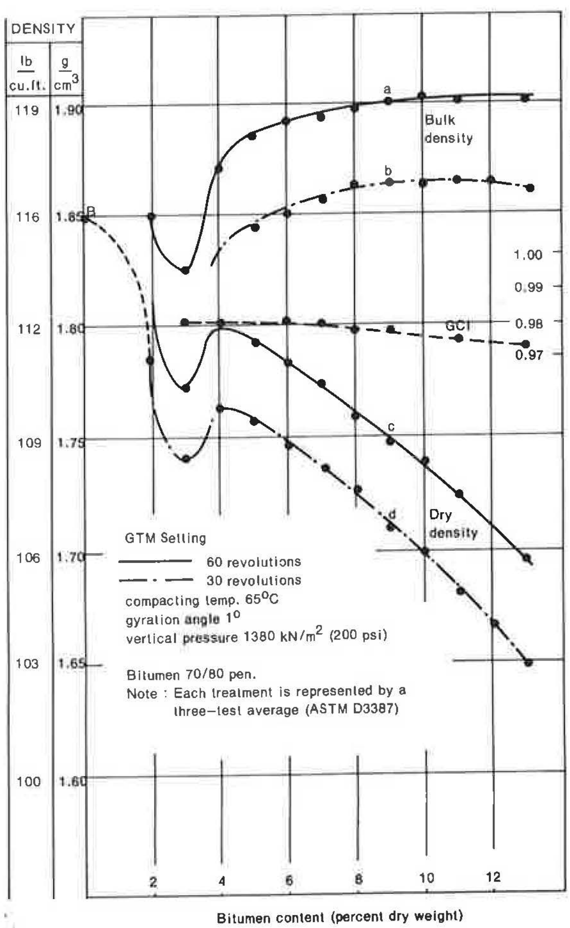
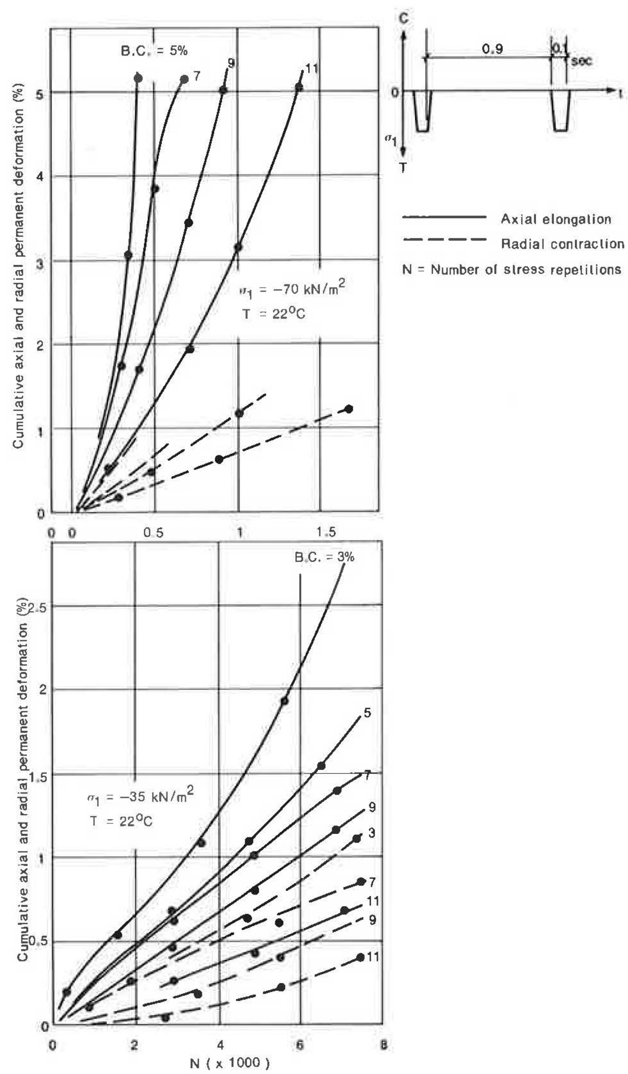


Figure 7. Accumulation of permanent deformation in bitumen-sand mixtures under repeated uniaxial stress–tension.



adequate manual mixing with the minimum of preheating.

Equipment

The triaxial cell fabricated and used here is capable of controlling the temperature and of pulsing the axial and radial stresses independently. A Perspex cylinder was placed around the pressure chamber to form an annular cavity through which water, at the predetermined temperature, was circulated. The pressure chamber was filled with a relatively incompressible fluid that served as a heating and a lateral-pressurizing medium. Amplitudes of axial and radial pressure pulses were controlled by pneumatic pressure regulators connected to the air-supply line. Durations and synchronization of pulses were ensured by using three solenoid valves connected to the pressure lines and controlled by an electric cam timer. A schematic diagram of the equipment is shown in Figure 4.

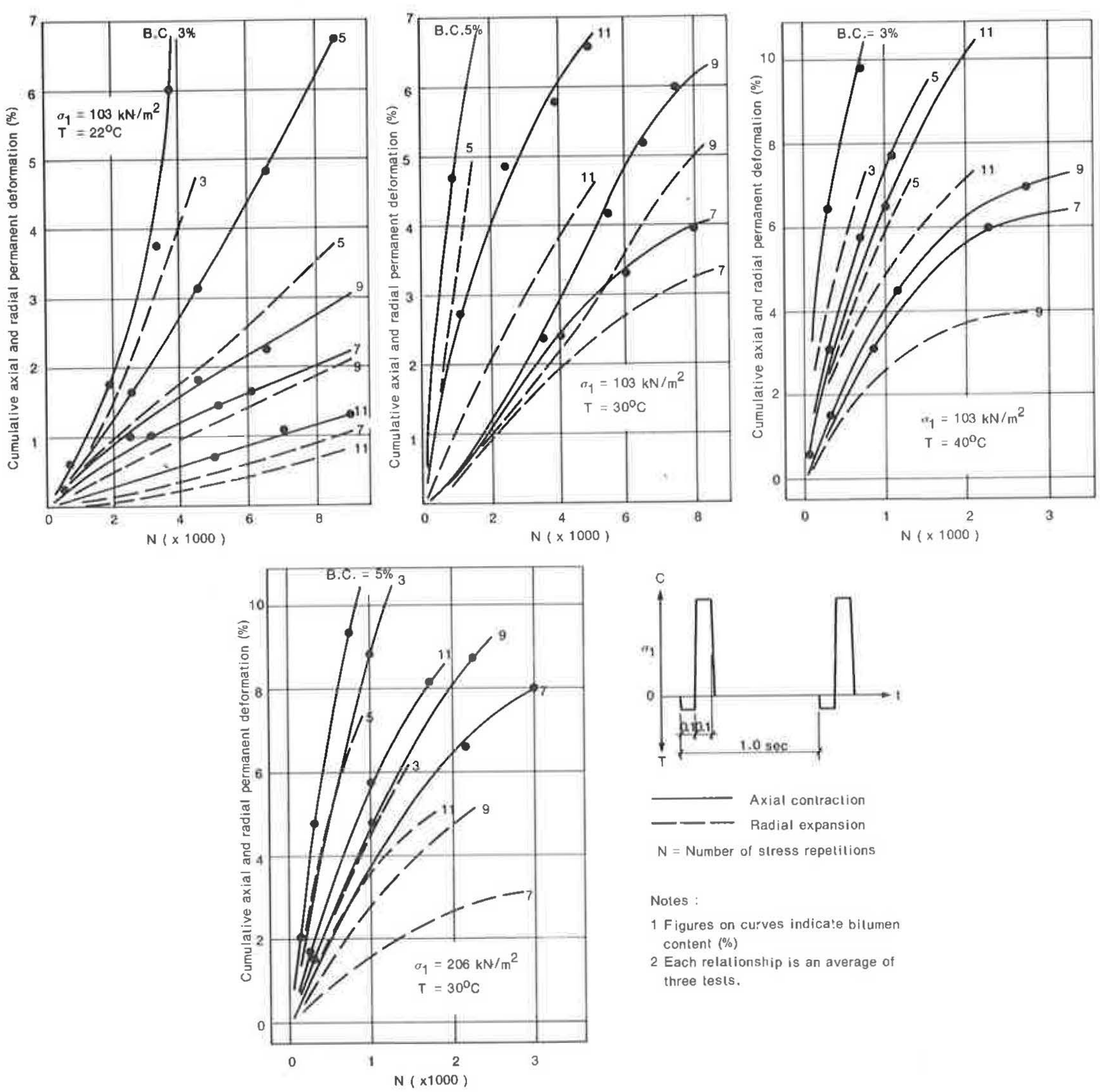
The resilient and the cumulative permanent deformation in the sample were measured by using lightweight transducers made of rigid aluminum arms connected to central pieces of thin brass plates, as shown in Figure 5. Strain gauges were bonded to these plates to form full-bridge circuits.

Axial stress was measured inside the pressure chamber by using a load transducer bearing directly on the specimen. It was manufactured so that the measurement was independent of chamber pressure (16). Finally, confining pressure was measured by using an ordinary commercial transducer.

RESULTS AND DISCUSSION

Results of the GTM compaction are plotted in Figure 6 as bitumen content versus density relationships. It can be seen that, for most of the range, dry density decreases markedly whereas bulk density increases slightly with binder content. This indicates that the reduction in mix density resulting from particle separation caused by the addition of bitumen is a little more than compensated for by the weight of the added binder. In the kneading-compaction process, the high porosity of sand seems to allow a larger proportion of the added binder to occupy existing voids rather than to force particles apart. This results in the absence of a definite optimum amount of bitumen for

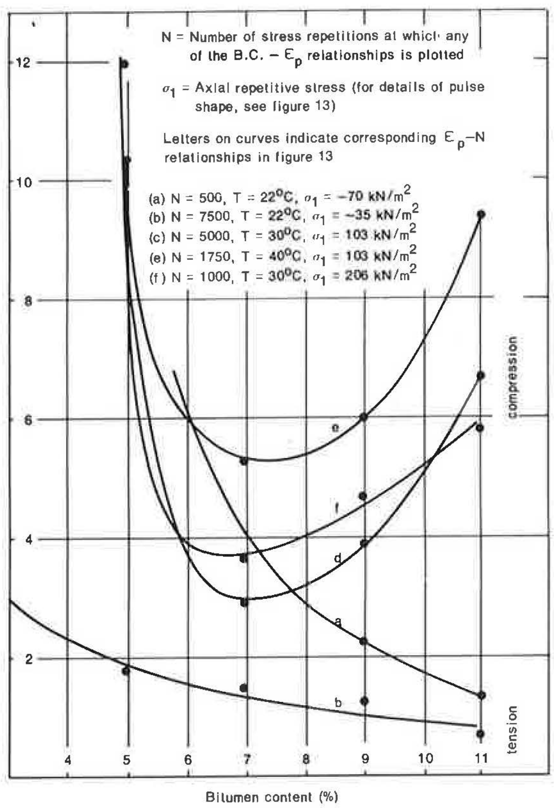
Figure 8. Accumulation of permanent deformation in bitumen-sand mixtures under repeated uniaxial stress—compression.



maximum bulk density, which is regarded as a characteristic property of the compactibility of the mixes used.

Results of the experimental program of mixture design are presented in Figures 7, 8, and 9. It is obvious that, in general, repeated tension tests resulted in an increasing rate of permanent deformation, whereas compression tests produced a decreasing rate with stress repetition, probably because of the slight densification and increase in sample stiffness effected in the compression tests compared with the weakening of tension samples caused by initiation of microcracks in the fatigued films of binder (6). Comparison of the five mixes in Figure 9 shows the resulting percentages of permanent distortion caused by the same number of stress cycles. The effect of bitumen content on the resistance to cumulative distortion appears to differ in the tension and compression tests: Although in repeated tension the resistance continuously increased, it is seen to reach a maximum at about 6.5-7.5 percent bitumen content in most of the repeated compression tests. The optimum amount of bitumen in these tests corresponds, therefore, to the critical mix condition at which the highest mobilization of the combination of cohesion and friction occurs. The results thus seem to point to the use of richer mixes in the lower portions and about 7 percent binder in the upper portions of pavement layers for an optimum performance against rutting.

Figure 9. Bitumen content versus permanent deformation accumulation in the design of bitumen-sand mixtures.



Experimental values of the resilient modulus M_r and Poisson's ratio ν_r for the selected design mix (7 percent bitumen content and 1857 kg/m³ bulk density) are shown in Figure 10. Although the effect of temperature on these values is marked, the effects of stress amplitude and duration appear to have inconsistent trends, as indicated by the shaded areas. These figures were used to select realistic values of elastic constants that corresponded to extreme layer conditions in order to determine the stress profiles.

It was evident from the relative values of layer moduli in the desert pavements analyzed that the general stress patterns in these systems would differ significantly from those in conventional cross sections. In the latter type, the ratio of the base to subgrade stiffness can be as high as 20 or more. For a desert road that consists of a bituminized sand layer on dense and untreated sand subgrade, this ratio would be only about 4. This ratio occurs when the binder is 70/80 penetration grade, the treated sand layer is relatively cold, and the subgrade is at its weakest condition.

Results of the stress analysis program are shown in Figures 11 and 12. These show the range of variation in the bitumen-sand layer of the vertical and horizontal stresses with depth and with consideration of possible extremes in the properties of the layers under real service conditions. It is clear that the influence of these properties becomes less pronounced when the thickness of the treated-sand layer is increased. The reduction in

Figure 10. Resilient parameters of the optimum bitumen-sand mixture.

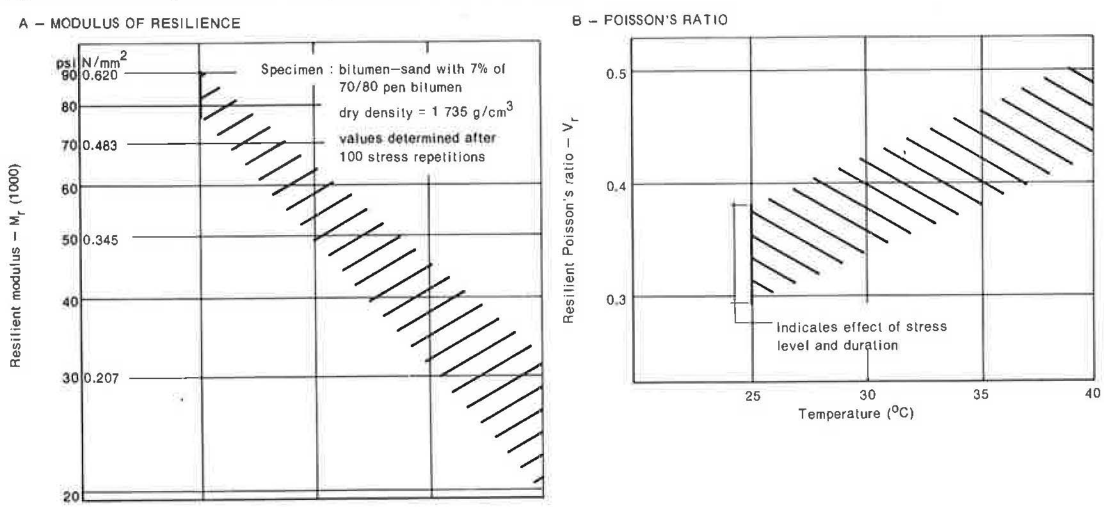


Figure 11. Range of stresses in the bituminized sand layer of two-layer pavement systems.

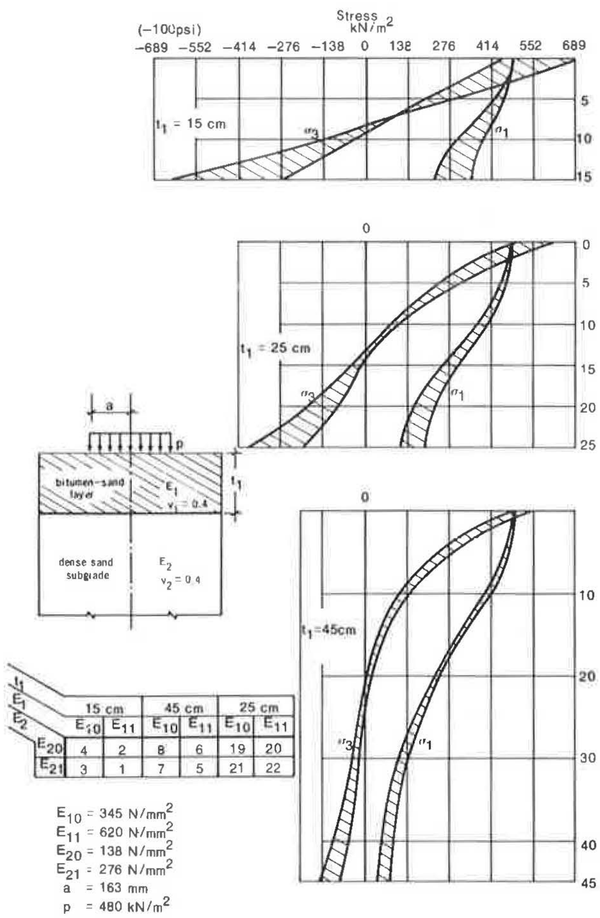
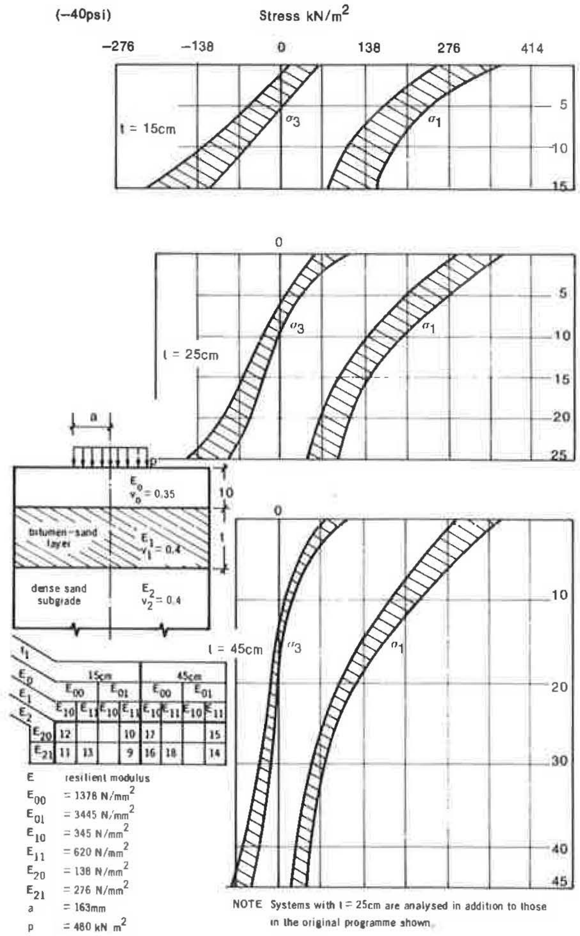


Figure 12. Range of stresses in the bituminized sand layer of three-layer pavement systems.



the horizontal tensile stress range at the bottom amounts to about 80 percent for an increase in thickness from 150 to 450 mm (Figure 11). Corresponding decrease in the vertical compressive stress at the same location is around 67 percent.

Figure 13 shows the relationships corresponding to all treatments of the program on one semilogarithmic plot that proved useful in further analysis. Although they are nonlinear, a significant portion of the relationships in this figure can be approximated by straight-line segments, i.e., where N is greater than 1000. The least-squares technique was, therefore, applied to perform such an approximation by using the original four-test data in each treatment. In Figure 14, the resulting straight-line equations are listed in terms of the slope $S_c = \epsilon_p/\log N$ and the intercept with N = 1000 ordinate, I_c. The formulation of equations for predicting these two dependent variables, when temperature and stress conditions are given, would allow the estimation of the amount of distortion accumulating in an element of any thickness.

Such equations were derived here by using multilinear regression analysis of the experimental data in Figure 14. The slope (S_c) or the intercept (I_c) represented the dependent variable, while factors of temperature (T) and stress (σ_1 and σ_3) were input, in different combinations, as independent variables. The combination terms, which represented potential interaction effects, included such terms as $(\sigma_1-\sigma_3)$, $(\sigma_1-\sigma_3)T$, $\sigma_1 T$, $\sigma_3 T$, $\sigma_1\sigma_3$, and others. The facility of stepwise multiple regression provided by the Statistical Package for the Social Sciences (17) allowed the choice of the fewest terms with the highest predictive power of the dependent variable. The equations finally selected are included in Figure 15, together with their characterizing statistics. The figure also includes selected equations for predicting S_t and I_t associated with the tension-test results. These were derived in the same way as S_c and I_c but from an ordinary plot of ϵ_p versus N, as shown in Figures 16 and 17.

In any of the four equations selected, the term for the interaction between deviatoric stress and temperature proved sufficient to predict the dependent variable to an acceptable level. Values of the squared multiple correlation coefficient (R^2) indicate that at least 82 percent of the variance in S or I is being accounted for by the equations selected. This reflects a simplicity in the distortion response that could be related to the very nature of the mixture used. Unlike well-graded aggregates in conventional mixes, the rounded shape and smooth texture of the stabilized sand particles produced a minimum degree of interlocking and, consequently, the least interruption to the function of the binder film in between. Minimum interlocking is also encouraged by the absence of large-sized aggregates, which implied that load transmitted between any two adjacent particles would be relatively very small. It is the presence of the

Figure 13. Results of the experimental program of repeated-load triaxial tests (compression series).

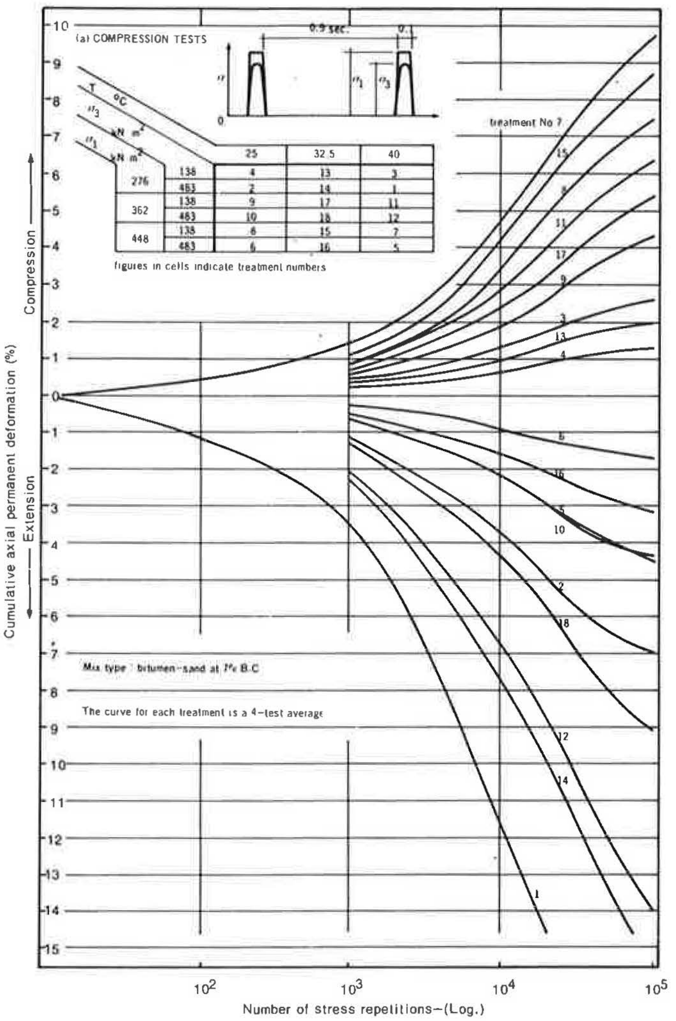


Figure 14. Characteristics of the relationships between ϵ_p and log N approximated to linearity (compression tests: N > 1000).

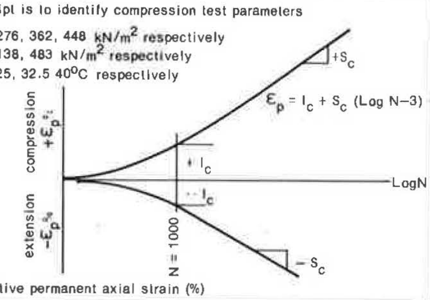
TREATMENT No	REPEATED STRESS AMPLITUDE		TEMPERATURE °C	I_c* INTERCEPT WITH N = 1000 ORDINATE (ϵ_p %)	S_c GRADIENT $\frac{\epsilon_p\%}{\text{Log N}}$
	AXIAL σ_1	RADIAL σ_3			
1	σ_1''	σ_3''	T'''	−3.16	−8.45
2	σ_1'	σ_3''	T'	−0.95	−3.06
3	σ_1'	σ_3'	T'''	0.30	1.12
4	σ_1'	σ_3'	T''	0.15	0.57
5	σ_1'''	σ_3''	T''	−0.54	−1.99
6	σ_1''	σ_3''	T'	−0.18	−0.77
7	σ_1'''	σ_3'	T'''	1.05	4.16
8	σ_1'''	σ_3'	T''	0.42	3.53
9	σ_1''	σ_3'	T''	0.27	1.96
10	σ_1''	σ_3''	T''	−0.49	−1.95
11	σ_1''	σ_3'	T'''	0.51	2.86
12	σ_1''	σ_3''	T'''	−1.49	−5.97
13	σ_1'	σ_3'	T''	0.22	0.88
14	σ_1''	σ_3''	T''	−1.68	−6.78
15	σ_1'''	σ_3'	T''	0.64	3.99
16	σ_1'''	σ_3''	T''	−0.36	−1.37
17	σ_1''	σ_3'	T'''	0.36	2.42
18	σ_1''	σ_3''	T''	−0.95	−3.91

* The c subscript is to identify compression test parameters

$\sigma_1', \sigma_1'', \sigma_1'''$ = 276, 362, 448 kN/m² respectively

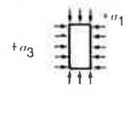
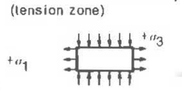
σ', σ'' = 138, 483 kN/m² respectively

T', T'', T''' = 25, 32.5 40°C respectively



ϵ_p% = cumulative permanent axial strain (%)

Figure 15. Selected predictive equations and their characteristics.

Repeated Stress Pattern (in the Triaxial Test)	Predictive Equation Selected	Characteristics: STD. ERROR B	BETA	STANDARD ERROR	R^2	F
Triaxial Compression (compression zone) 	$I_c = -0.57438 + 0.00015\ (\sigma_1 - \sigma_3)\ T$	0.00002	0.91	0.4427	0.82	75
	$S_c = -1.67194 + 0.00057\ (\sigma_1 - \sigma_3)\ T$	0.00004	0.96	1.0813	0.92	193
Biaxial Compression σ_3, with Uniaxial Tension σ_1 (tension zone) 	$I_t = 0.21447 + 0.00072\ (\sigma_1 + \sigma_3)\ T$	0.00006	0.94	0.2882	0.89	135
	$S_t = -1.45665 + 0.00250\ (\sigma_1 + \sigma_3)\ T$	0.00014	0.97	0.6758	0.94	300

Notes – In the above equations, temperature T, and stress σ_1 and σ_3, should be in °C and kN/m² units.

– Signs of the resulting parameters I or S are significant for I_c and S_c a plus sign indicates shortening, a minus sign indicates elongation. For I_t and S_t, a positive sign should normally be expected, indicating permanent compression.

Figure 16. Results of the experimental program of repeated-load triaxial tests (tension series).

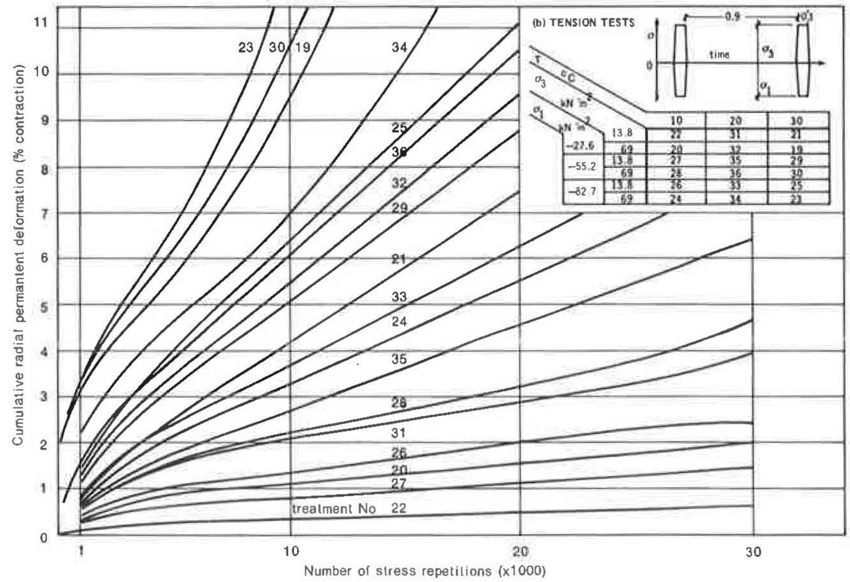
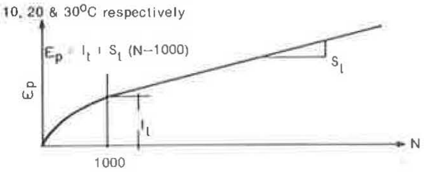


Figure 17. Characteristics of the relationships between ϵ_p and N approximated to linearity (tension tests: N > 1000).

TREATMENT No	REPEATED STRESS AMPLITUDE AXIAL σ_1	REPEATED STRESS AMPLITUDE RADIAL σ_3	TEMPERATURE °C	I_t* INTERCEPT WITH N=1000 ORDINATE (ϵ_p%)	S_t GRADIENT $\frac{\epsilon_p\%}{N}$ (10^{-4})
19	σ_1'	σ_3''	T'''	2.93	6.9
20	σ_1'	σ_3''	T''	0.69	0.4
21	σ_1'	σ_3'	T'''	1.47	3.0
22	σ_1'	σ_3'	T'	0.23	0.1
23	σ_1''	σ_3''	T'''	3.07	10.3
24	σ_1'''	σ_3''	T'	1.17	2.3
25	σ_1'''	σ_3'	T'''	2.12	4 7
26	σ_1'''	σ_3'	T'	0.85	0.5
27	σ_1''	σ_3'	T'	0 52	0.3
28	σ_1''	σ_3''	T'	1 08	1 2
29	σ_1''	σ_3'	T''	1 80	3 7
30	σ_1''	σ_3''	T'''	3 08	8 3
31	σ_1'	σ_3'	T''	1 18	0.9
32	σ_1'	σ_3''	T''	1 87	4.0
33	σ_1'''	σ_3'	T''	1.28	2.7
34	σ_1'''	σ_3''	T''	2 26	5.4
35	σ_1''	σ_3'	T''	1 09	1 8
36	σ_1''	σ_3''	T''	2 09	4 4

* The t subscript is to identify tension test parameters
$\sigma_1', \sigma_1'', \sigma_1'''$ = 27.6, 55 & 83 kN/m^2 respectively (tension)
σ_3', σ_3'' = 13.8 & 69 kN/m^2 respectively
T', T'', T''' = 10, 20 & 30°C respectively



ϵ_p = cumulative permanent radial strain (contraction)

aggregate phase and the complexity of its structure that contribute to the complexity of the mixture (18,19).

The relatively large sample size adopted in the experimental phase (four specimens per treatment) has helped in producing more accurate estimates of the real response. It limited the variance associated with the average response in each treatment, which had the effect of reducing inconsistencies in the input data to the regression analysis. [It is interesting to note that Shen and Smith (20), in their work on chemically stabilized fine sand, observed a simplicity of response similar to the one reported here.]

The plausibility of the formulated predictive equations (Figure 15) was finally demonstrated by a numerical example. Here the equations were used to estimate the component of surface-rut depth caused in the bitumen-sand layer of two desert pavement cross sections. Certain assumptions regarding traffic and material variables were made, and the geometries of the sections were chosen to allow observation of the effects of changing the thickness of the layer on the value of the resulting rut component at relatively high average temperature. Computation and other details are included in Figures 18 and 19. It is useful to note that because of the lack of complete simulation in the tests of the mode of tensile stresses in the pavement, as well as because of the assumptions written into the BISAR program, the results reported here are overestimates of the total permanent strain in the tensile zone.

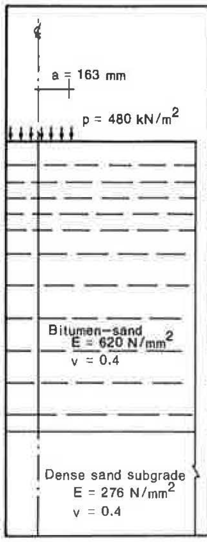
CONCLUSIONS

1. For a type of sand similar in properties to that encountered in desert road construction, design bitumen content for optimum performance under repeated uniaxial compressive stresses lies between 6 percent and 8 percent; under repeated uniaxial tension, no optimum value exists within the range of testing conditions adopted.

2. Stress pulse duration between 0.1 s and 0.2 s has no clear trend in its effect on the resilient modulus of the optimum mix in the triaxial mode of testing.

3. The permanent deformation response of the optimum mix under repeated triaxial stresses was investigated, the results were analyzed by multiple linear regression, and predictive relationships for distortion accumulation were formulated. The response correlated highly significantly with the term $(\sigma_1-\sigma_3)T$, which represents the interactive effect among the main factors of axial stress σ_1, lateral stress σ_3, and T. This term

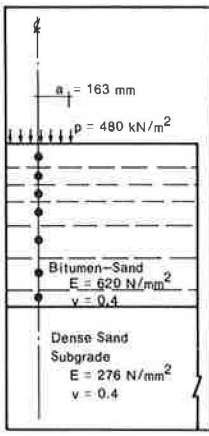
Figure 18. Example of prediction of permanent deformation in a 45-cm bitumen-sand base.



Repeated Stresses (kN/m²) σ_1	σ_3	T	N	Solutions Using Equations In Table 3: ϵ_p at N = 1000, I_c (%)	I_t (%)	ϵ_p rate after N = 1000, S_c (%/Log N)	S_t ($\frac{\%}{N}$ (10⁻⁴))	Results Using Equations In Table 3: Total Vertical Permanent Deformation In The Element At N = 7000, ϵ_{pc} (%)	ϵ_{pc} (mm)	ϵ_{pt} (%)	ϵ_{pt} (mm)
479	358	25 °C	7000	−0.121		0.052		−0.07	−0.03		
469	260			0.209		1.306		1.31	0.33		
443	183			0.401		2.033		2.12	0.52		
406	125			1 222		2.318		3.18	0.79		
364	83			0.479		2.332		2.45	0.61		
320	54			0.423		2.118		2.21	0.82		
240	17			0.262		1.506		1.53	0.76		
176	−3				3.436		9.731			9.27	4.63
129	−19				2.878		7.793			7.55	3.77
94	−36				2.554		6.668			6.55	3.27
71	−58				2.536		6.606			6.49	3.25
60	−89				2.896		7.856			7.61	1.90

Total Deformation In The Compression Zone = 3.80
Total Deformation In The Tension Zone = 16.82
Total Contribution To Surface Rut Depth = 3.80 + 16.82 = 20.62mm

Figure 19. Example of prediction of permanent deformation in a 25-cm bitumen-sand base.



Repeated Stresses (kN/m²) σ_1	σ_3	T	N	Solutions Using Equations In Table 3: ϵ_p at N = 1000, I_c (%)	I_t (%)	ϵ_p rate for N >1000, S_c (% /Log N)	S_t ($\frac{\%}{N}$ (10⁻⁴))	Results Using Equations In Table 3: Total Vertical Permanent Deformation In The Element At N = 7000, ϵ_{pc} (%)	ϵ_{pc} (mm)	ϵ_{pt} (%)	ϵ_{pt} (mm)
477	398	25°C	7000	−0.267		−0.503		−0.69	−0.26		
460	274			0.123		0.978		0.95	0.23		
427	174			0.374		1.933		2.01	0.50		
382	94			0.505		2.432		2.56	0.96		
280	−26			5.722	5.722		17.668			16.32	8.16
196	−132				6.118		19.043			17.54	8.77
159	−273				7.990		25.543			23.31	5.82

Total Deformation In The Compression Zone = 1.43
Total Deformation In The Tension Zone = 22 75
Total Contribution To Surface Rut Depth = 1.43 + 22.75 = 24.18 mm

explained the major part of treatment-to-treatment variation in the experimental results.

4. Application of the predictive relationships derived in the study produced plausible solutions, but verification against observations of real performance remains to be done and is considered essential before reliable use in real design problems can be made.

5. The solutions provided by the predictive models indicated that (a) most of the permanent deformation occurs in the tension zone and (b) increasing the thickness of the treated sand layer has the effect of reducing its contribution to the total rut depth in the pavement system.

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