ENVIRONMENTAL IMPACTS ON FLEXIBLE PAVEMENTS IN JEDDAH CITY

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ABSTRACT

Jeddah is a major metropolitan area on the Red Sea. It has witnessed a vast growth over recent years which was not matched with the construction of required drainage facilities. This paper deals with the effects of environmental conditions of high temperature and high ground table on the performance of flexible pavements as experienced in the city of Jeddah especially when combined with excessive traffic loads. Three conditions of ground water table levels have been assumed and analyzed, where the subgrade consisted of silty sand soil A computer program KENLAYER was used to conduct an elastic layer analysis to evaluate the fatigue and rutting criteria according to the Asphalt Institute design procedure. The results of the analysis clearly show the significant impacts of the prevailing environmental conditions, and illustrates the causes of rapid deterioration and premature failure of some existing flexible pavement.

KEYWORDS

Asphalt, environment, fatigue, flexible groundwater, impacts, Jeddah, pavement, rutting, temperature.

INTRODUCTION

Jeddah is the largest city on the Red Sea. It has witnessed a vast growth over recent years reaching an area of 2000 km^2 and with a population of 1.2 million. Water consumption exceeds 350,000 m^3/day. M.O.A.W. (1987). The high rate of development could not be matched with the construction of required waste water and storm water drainage facilities. Fifty percent of the city is yet to be hooked to centralized sewage treatment facilities. This, in addition to other factors such as leakage from water distribution system, surface irrigation, and sea intrusion, combined with the low horizontal and vertical hydraulic conductivity of the sub surface soils have caused the groundwater table to rise throughout Jeddah. A model was developed to estimate the rate of ground water rise in terms of the hydraulic conductivity and the rate of charge. It is estimated that the rate of rise of the groundwater table is about half a meter per year (Shihata, and Aburizaiza, 1988).

Flexible pavements have been used in most of the secondary streets, where the pavement structure was made of asphalt wearing surface, base course and crushed stone aggregate subbase with a total thickness typically in the range of 300-400 mm. The ground water table and especially in areas close to the sea is in the range 0.0-1.5 meters. Also, as the city is still in the development phase, the secondary streets are exposed to an appreciable heavy truck volumes. Other environmental conditions that will adversely affect the performance of flexible pavements are the annual rainfall and the moderately high air temperature and solar radiation. As the city is not fully covered with storm water facilities and because of the presence of undeveloped areas, rain water will percolate into the ground causing rise to the ground water table.

High air temperature combined with high intensity of solar radiation will increase the temperature of the asphalt layer/s thus reducing its stiffness. The effect of temperature on the dynamic modulus of typically used asphalt mixture was calculated. It was found in previous studies that increasing the mixture temperature from about 21°C to about 49°C, caused a reduction in the dynamic modulus of the mixture from 6.9 GPa to 0.49 GPa.

EXISTING PAVEMENT CONDITIONS

Visual inspection of the pavement surface condition indicates a relation between the condition of the pavement surface and the depth to the water table. It has been found that pavement surface deteriorates as the ground water table reaches the surface of the pavement. Pavement sections rebuilt with the typical pavement structure of 100-110 mm of asphalt surface and base course over a 200 mm of crushed aggregate subbase did not last more than 6 months to a year depending on traffic conditions.

The typical types of observed distresses are alligator cracks, rutting, shoving and pot holes. These types of distresses are typical of insufficient pavement structure for the prevailing traffic loads and environmental conditions.

Condition of a severely damaged street pavement is described in Figures 1 to 6. Fig. 1 shows the water table rising above ground surface and is in level with the surface of the street. Development of severe alligator cracks and rutting is shown in Fig. 2. The wet surface of the affected area is quite visible. With time; few months; the pavement surface starts to disintegrate, Fig. 3. Complete failure follows shortly thereafter, Fig. 4. Formation of salt crust at the surface of the disintegrated pavement indicates presence of high salt concentration in the groundwater.

The condition of the pavement surface was quantified using the Pavement Condition Index (PCI) (Shahin et al, 1988) which values lie in the range from 0 to 100. A value between 85-100 indicates an excellent pavement condition while a value below 40 means that the pavement needs major rehabilitation. The PCI was computed using the following equation.

$$PCI = 100 - CDV$$

Where

CDV = corrected deduct value.

Determination of the deduct values depends on the type of distress, its severity and its density. Then the deduct value was corrected for the number of existing distresses involved in calculating the deduct value. The pavement was divided into sampling units and the overall condition value of the PCI for the pavement was averaged over the sample units.

Distribution of the deduct values of three main distresses, namely, alligator cracks, rutting and shoving are presented in Fig. 5. The Figure shows the severe condition of the surveyed pavement section. The overall PCI of the section was below 10, reflecting a failure condition of the pavement surface.

THEORETICAL ANALYSIS

Evaluating the structural adequacy of the pavement structure under the prevailing traffic and environmental conditions is important as it helps predict the performance of proposed pavement designs and evaluates existing pavements. A typical flexible pavement structure was analyzed, and good agreement was obtained between predicted and observed results.

The computer program KENLAYER, (Huang, 1993) was used to calculate the tensile strain at the bottom of the asphalt layer and the compressive strain on the top of the subgrade. The backbone of the program is the solution for an elastic multi layer system under a circular loaded area. The solutions are super- imposed for multiple wheels, applied iteratively for nonlinear layers and collocated at various times for visco elastic layers.

In this analysis, the pavement structure was considered as an elastic multi layer system.The dynamic modulus $|E^*|$ was used to characterize the asphalt layers, four values of which were used; 8.28, 4.83, 2.07 and 0.55 GPa. Elastic (Resilient) Modulus was used to characterize both aggregate subbase layer and the subgrade. The resilient modulus of the aggregate was kept constant at 207 MPa ($30x10^3$ psi). The resilient modulus of the subgrade was estimated from Figures 7 and 8. The relation between the elastic modulus and the degree of saturation of the subgrade soil, basically silty sand is shown in Fig. 7 for different degrees of compaction (Shihata, et al, 1988). Fig. 8 shows measured degree of saturation with depth.

For the purpose of analysis in this paper, three levels of water table from the pavement surface were selected 0.0, -1.0 and -2.0 ms. The zone between the subgrade surface and the level of water table (partial saturation) was intuitively divided, based on the shape of the curve of Figure 8, into one or two sub zones depending on the groundwater level. Figure 9 shows the details of the three different pavement cross-sections.

Analysis was made for standard single axle load of 8.172 tons (18 kips) and the results are given in Tables 1 and 2. The theoretical maximum tensile strain values at the bottom of the asphalt layer are presented in Table 1 for different values of the dynamic modulus of the asphalt layer and for the three depths to the ground water table. Also the theoretical maximum compressive strain on top of the subgrade is given in Table 2. The maximum tensile strain at the bottom of the asphalt layer ε_t and the maximum compressive strain on top of the subgrade ε_c are frequently considered most critical for the design of flexible pavements. These two strains are used in the fatigue and permanent deformation failure criteria in the Asphalt Institute (AI) method.

Fatigue Criterion.

The fatigue equations developed by Asphalt Institute (AI 1982) are,

$$N_f = 0.00432C\,\varepsilon_t^{-3.291}\,|E^*|^{-0.854} \quad (1)$$

Where C is a correction factor expressed as $C = 10^M$ and

$$M = 4.84\left(\frac{V_b}{V_a + V_b} - 0.69\right)$$

for a mix with $V_a = 1.8$ % and $V_b = 11.16$ % $C = 6.733$

$$N_f = 0.02908\,\varepsilon_t^{-3.291}\,|E^*|^{-0.854} \quad (2)$$

Using the above equation would predict the number of repetitions that will result in fatigue cracking of 20% of the total area. The relation between N_f and depth to the ground water table is shown in Fig. 10 for different values of the dynamic modulus of the asphalt layer.

Permanent Deformation Criterion.

The allowable number of load repetitions to control permanent deformation (rutting) to no more than 12.7 mm is given by the following equation,

$$N_d = 1.365 \times 10^{-9}\,(\varepsilon_c)^{-4.477}$$

The relation between N_d and depth to ground water table is shown in Fig. 11.

Prediction of Pavement Condition.

To predict the behavior of the typical pavement structure that is used in secondary streets, truck traffic volumes and characteristics should be determined. Also the dynamic modulus of existing asphalt layers and its relation to temperature should be available. Knowing the above information and using Figs. 10 and 11, the design life of the pavement may be determined.

Traffic. Heavy truck traffic is composed mainly of construction dump trucks and fresh and waste water tank trucks. The observed daily traffic in some secondary streets in Jeddah with distressed pavements may be broken down to:-

Dump trucks.	
RB2	5 per day
RB3	15 per day
Tank trucks.	
RB2	20 per day
RB3	10 per day

Where RB2 and RB3 are the Ministry of Communications (MOC) designations of trucks with a single dual wheel and with a Tandem dual wheel rear axles respectively. The legal gross weight for RB2 is 19 tons and for RB3 is 26 tons. The weight on the front axle for both types of trucks is 6 tons. However, the legal gross loads of the MOC are not always observed. A study (Arora, et al, 1995) has found that 35 % the RB2 and 27 % of the RB3 truck traffic are violating the legal load limits. The 95 percentile illegal gross load of the RB2 is 25 tons and of the RB2 is 31 tons respectively. Applying the gross load violation to dump trucks, the traffic conversion to an equivalent standard axle load (ESAL) of 8.172 tons (18 kip) is given in Table 3. The numbers are calculated using the AASHTO (1986) conversions factors for a flexible pavement with a structural number SN of 3.0 and terminal present serviceability index $P_t = 2.5$. The total number of ESAL over several design periods and different annual growth factors is given in Table 4.

Dynamic Modulus of Asphalt Mixes. The formulas developed by Hwang and Witezak which were used in the DAMA computer program for the Asphalt Institute (Huang 1993) were applied here to calculate the dynamic modulus of a locally used asphalt mixture. The formulas are as follows:-

$$|E^*| = 100{,}000 \times 10^{\beta_1} \tag{3}$$

$$\beta_1 = \beta_3 + 0.000005\,\beta_2 - 0.00189\beta_2\, f^{-1.1}$$

$$\beta_2 = \beta_4^{0.5}\, T^{\beta_3}$$

$$\beta_3 = 0.553833 + 0.028829\ (P_{200}\, f^{-0.1703})$$

$$- 0.03476\ Va + 0.070377\lambda$$

$$+ 0.931757\ f^{-0.02774}$$

$$\lambda = 29508.2\ (P_{77^oF})^{-2.1939}$$

$$\beta_4 = 0.483\ V_b$$

$$\beta_5 = 1.3 + 0.49825 \log f$$

Where

β_1 - β_5 = temporary constants,
f = load frequency in Hz
$P_{77^\circ F}$ = asphalt penetration at 77°F (25°C)
P_{200} = % by weight of aggregate passing Sieve No. 200
T = mixture temp. in ° F
V_a = volume of air void %
V_b = volume of asphalt %

The asphalt mixture properties were $P_{77^\circ F} = 62$, $P_{200} = 6\%$, $V_a = 1.8\%$ and $V_b = 11.16\%$. Calculations were made for an $f = 8$ Hz and four mixture temperatures, 4.4° C (40°F), 1.1°C (70°F), 37.8°C (100°F) and 48.9°C (120°F). The calculated values of the dynamic modulus at the respective temperatures were 6.897 GPa (10^6 psi), 1.590 GPa (0.703×10^6 psi), 0.485 GPa (0.231×10^6 psi) and 0.55 GPa (0.08×10^6 psi).

Results.

The above theoretical analysis shows that the typical pavement structure which is used in the secondary streets is inadequate under the severe prevailing environmental conditions of high ground water table and moderately high temperature. Especially in the presence of excessively high truck loads. The presented analysis is conservative as it used the documented over loading conditions. The situation of high illegal loads is expected to be worse in urban areas where enforcement of the legal truck loads is limited. The analysis explains the occurrence of premature failure in severely affected areas where the ground water table is at the ground surface. N_d is limited to 47000 load repetitions if $|E^*|$ is equal to 0.55 GPa (i.e. asphalt temperature = 48.9°C) and the ground water table is at the surface. This translates to a design life of (4700/336) or 140 days or 4.7 months. This is typical of severely damaged areas where the service life of the pavement does not exceed six to nine months. However, the same pavement structure will have a design life of more than 15 years if the ground water table is kept lower than two meters.

CONCLUSIONS

The following conclusions may be reached:-

1. Presence of water in the pavement structure reduces drastically its design life.
2. Safer truck loads limits should be established for trucking serving effected areas.
3. Proper pavement structure should be designed to sustain the harsh prevailing environmental conditions.
4. Available analytical procedure may be used to successfully predict the behavior of flexible pavements under the prevailing environmental conditions.

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Table 1. Theoretical maximum tensile strain at the bottom of the surface layer $x10^{-3}$.

Dynamic Modulus of the Asphalt Layer (GPa)	Depth to the Ground Water Table		
	- 2.0 (ms)	- 1.0 (ms)	- 0.0 (ms)
8.28	0.1470	0.1631	0.1951
4.83	0.1994	0.2183	0.2580
2.07	0.2996	0.3176	0.3625
0.55	0.4282	0.4306	0.4353

Table 2. Theoretical maximum compressive strain on top of subgrade $x10^{-3}$.

Dynamic Modulus of the Asphalt Layer (GPa)	Depth to the Ground Water Table		
	- 2.0 (ms)	- 1.0 (ms)	- 0.0 (ms)
8.28	0.3163	0.4616	0.8696
4.83	0.3698	0.5437	1.038
2.07	0.4424	0.6566	1.278
0.55	0.5146	0.7747	1.583

Table 3. Traffic conversion to daily number of ESAL, $P_t = 2.5$ and SN = 3.

Vehicle Type	Max. Gross Weight Tons	Axel Type	Wt. of Axle, Tons (Kips)	Daily Number	Equivalance Factor	ESAL
RB2(L)*	19	$S^{(1)}$	8 (13.2)	23	0.331	7.61
		S	13 (28.6)	23	6.50	149.50
RB2(O)**	25	S	8 (17.6)	2	0.924	1.86
		S	17 (37.4)	2	21.13	42.26
RB3(L)	26	S	6 (13.2)	30	0.331	9.93
		$T^{(2)}$	20 (44.1)	30	3.02	90.60
RB3(O)	31	S	7 (15.4)	5	0.572	2.86
		T	24 (52.5)	5	6.389	31.95
					Total =	336.57

(L)* = Legal
(O)** = Over Loaded
$S^{(1)}$ = Single Axle
$T^{(2)}$ = Tandem Axle.

Table 4. Total number of ESAL (Millions) over several design periods.

Design Period (Years)	Annual Growth Rate %			
	0	2	5	10
5	0.615	0.640	0.680	0.752
10	1.230	1.347	1.547	1.961
15	1.845	2.127	2.654	3.908

Fig. 1 : An extreme condition high ground-water-table.

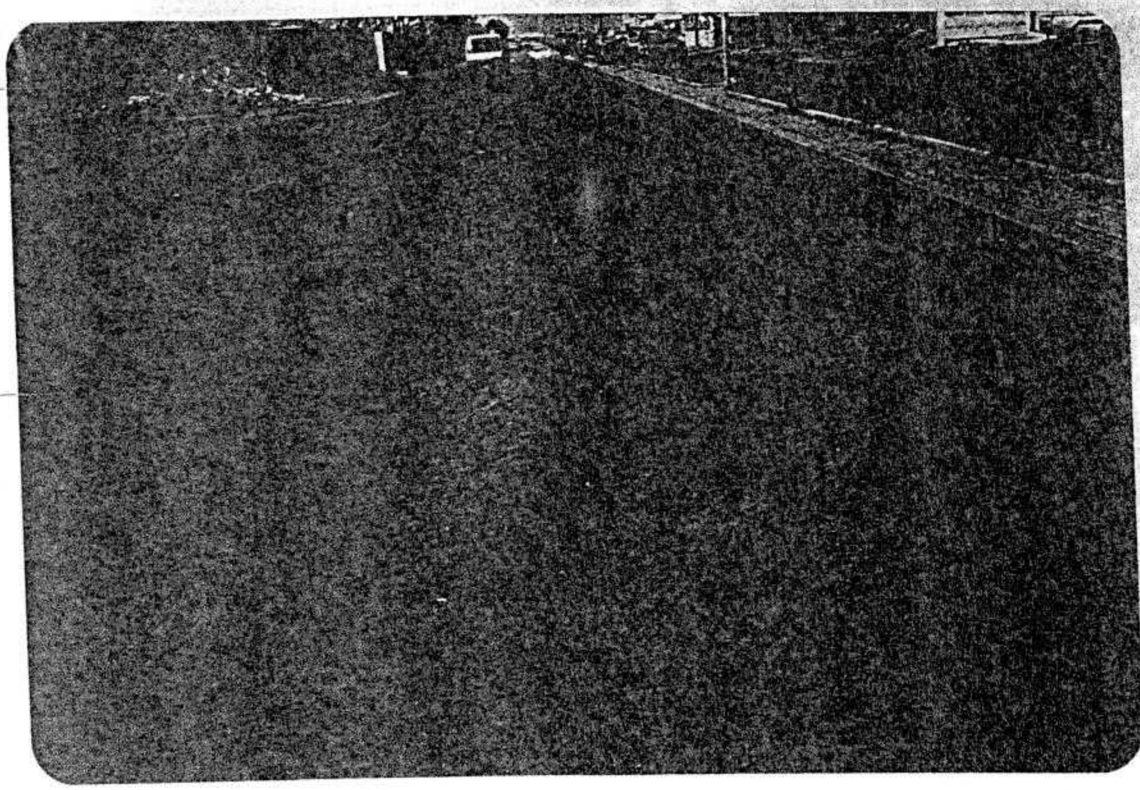

Fig. 2 : Severe aligator cracking and rutting in an affected area.

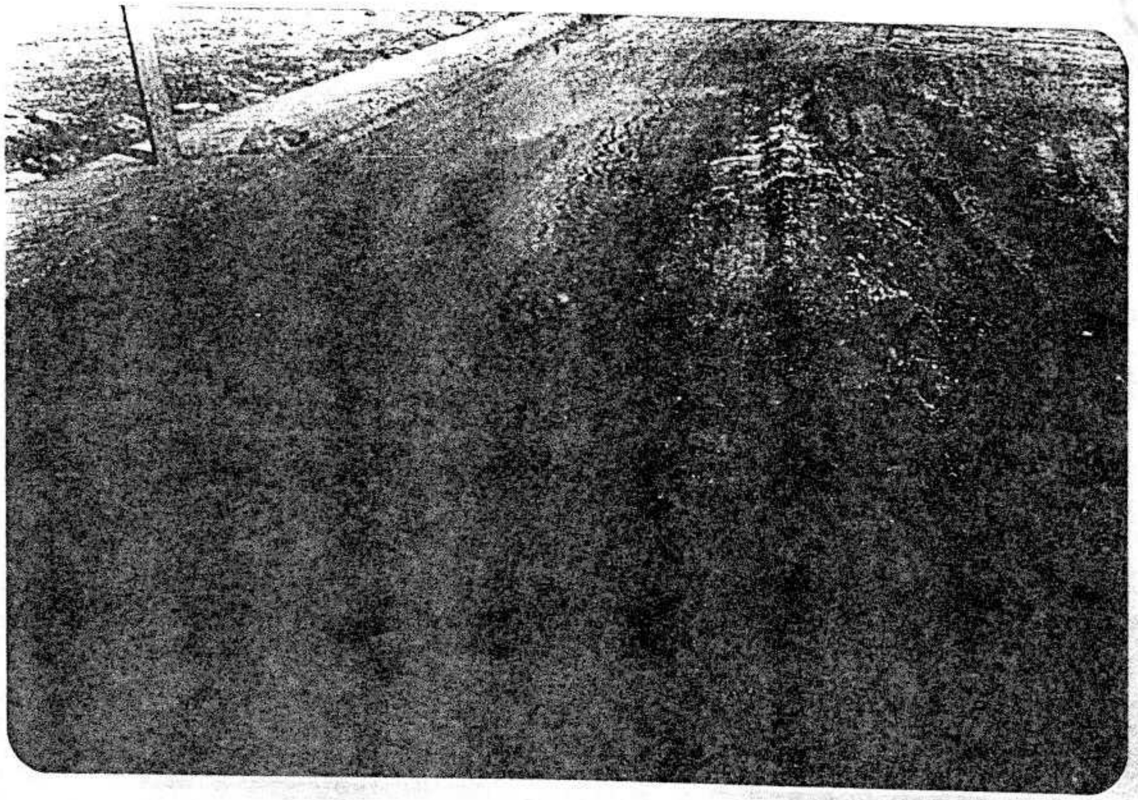

Fig. 3 : Initiation of pavement disintegration in an affected area.

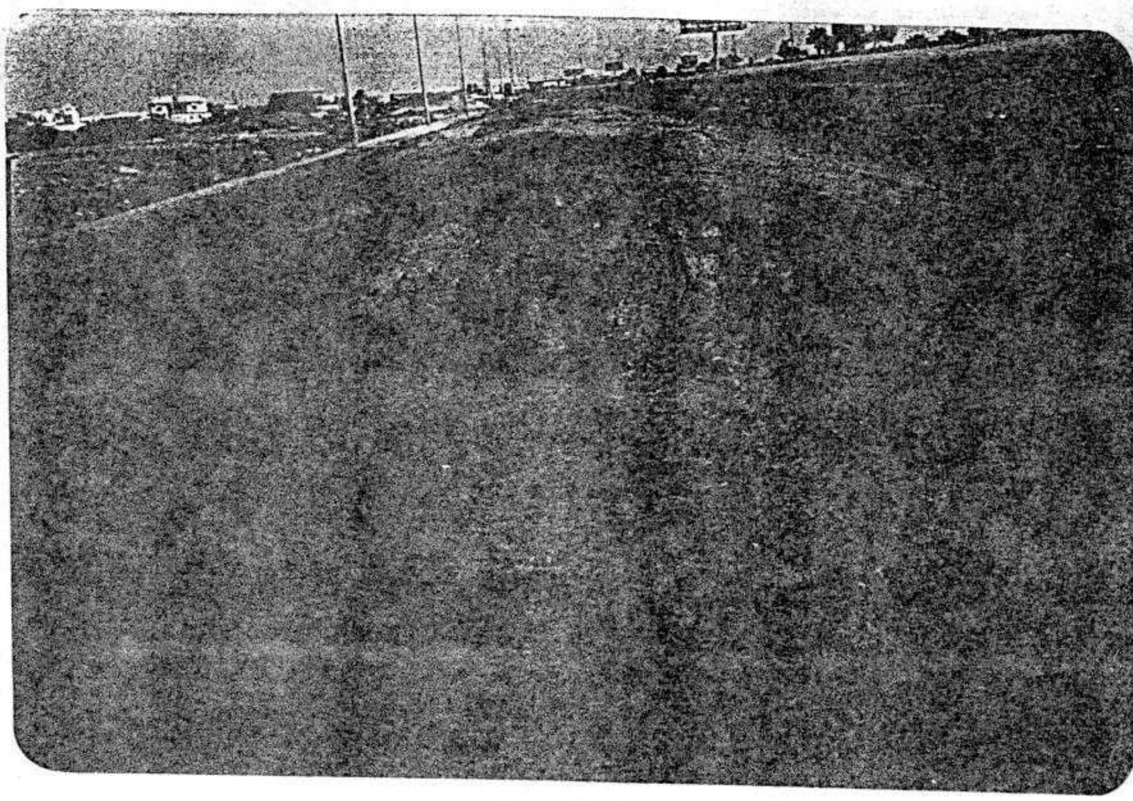

Fig. 4 : Disintegrated pavement.

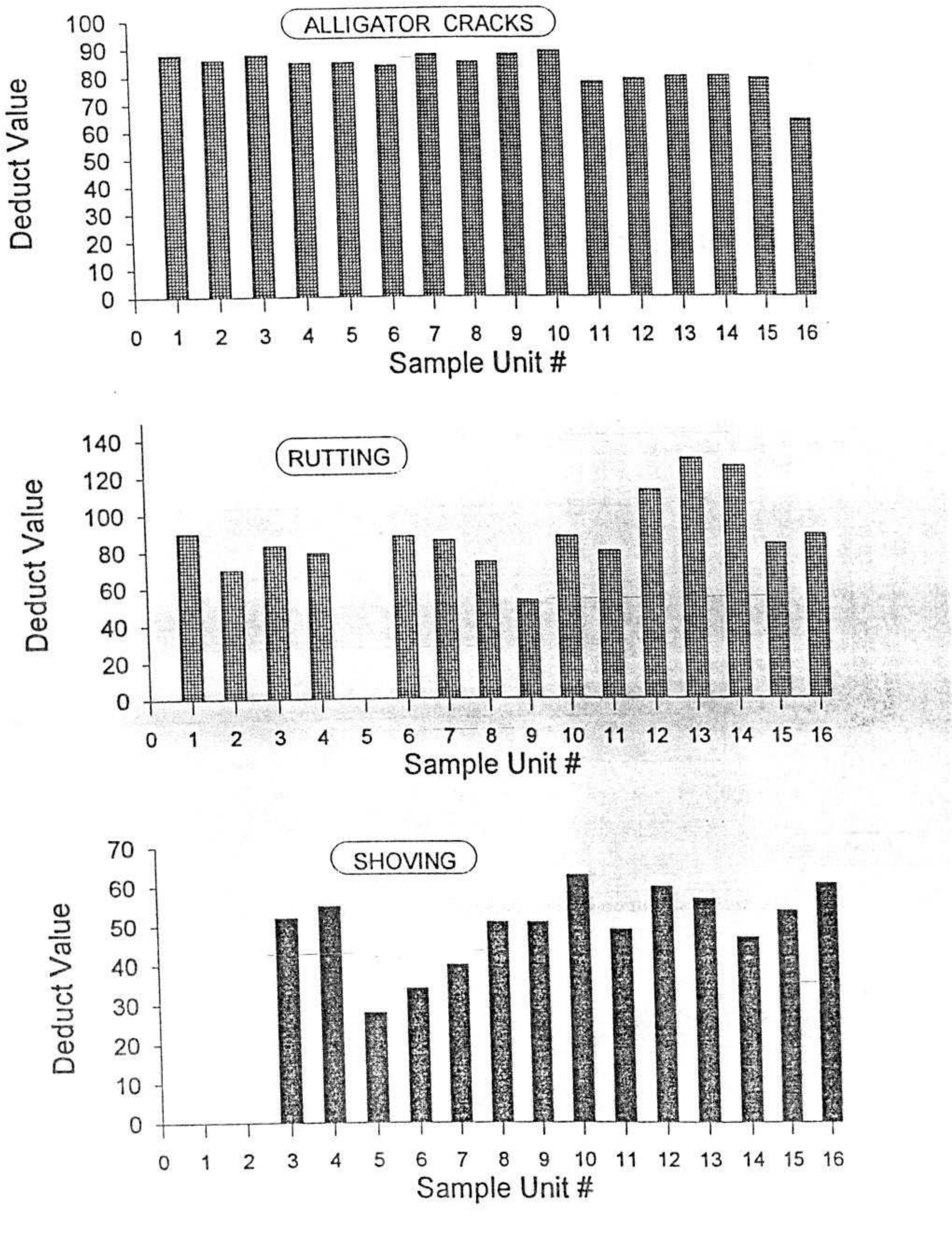

Fig. 5 : Distribution of deduct values of alligator cracks, rutting and showing over the sample units of a test site.

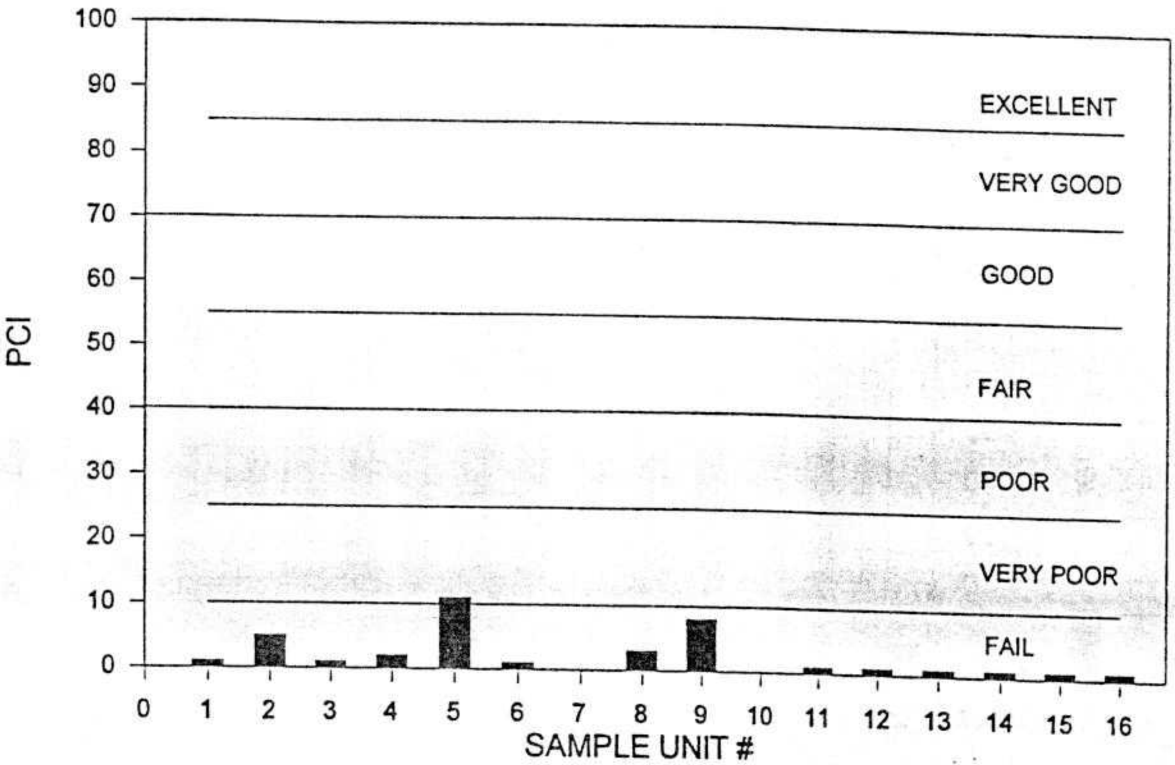

Fig. 6 : Distribution of the pavement condition Index PCI over the sample units of a test site.

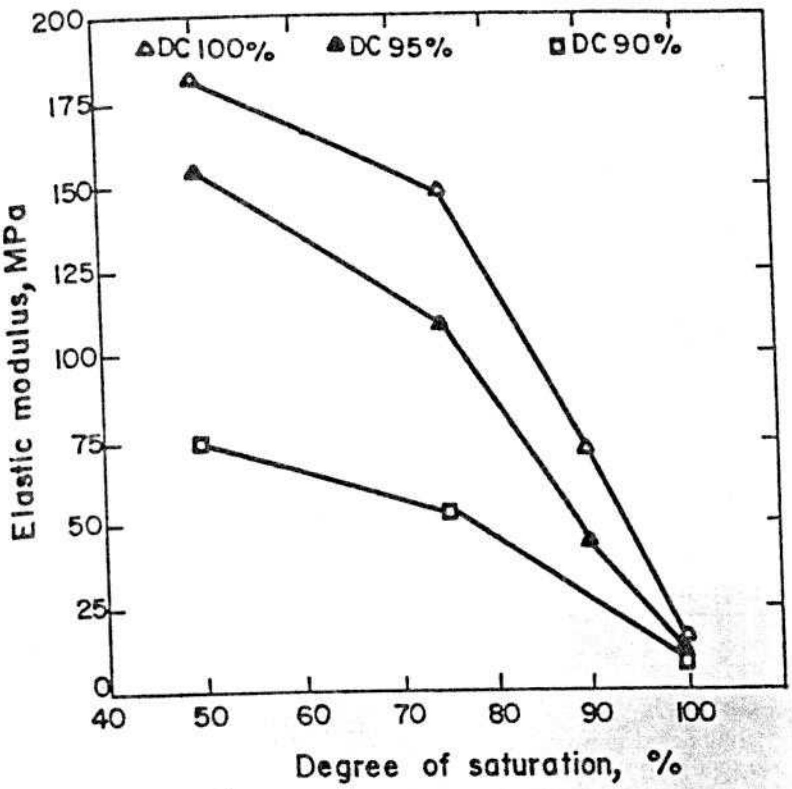

Fig. 7. Effect of degree of saturation on elastic modulus for different degrees of compaction and confining pressures.

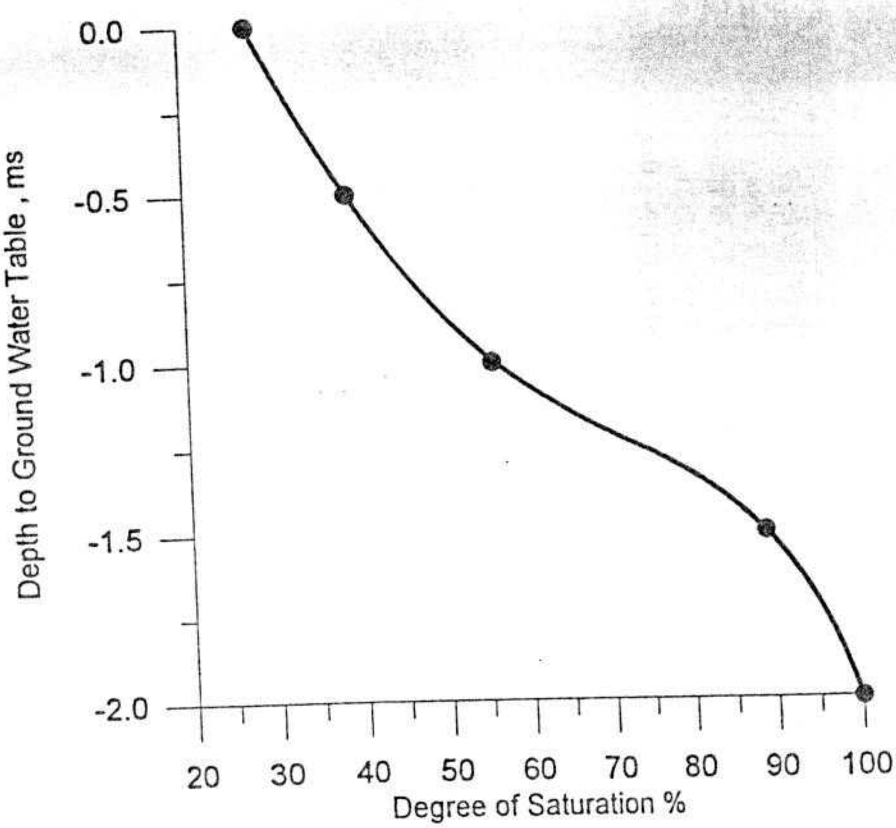

Fig. 8. Distribution of degree of saturation with depth

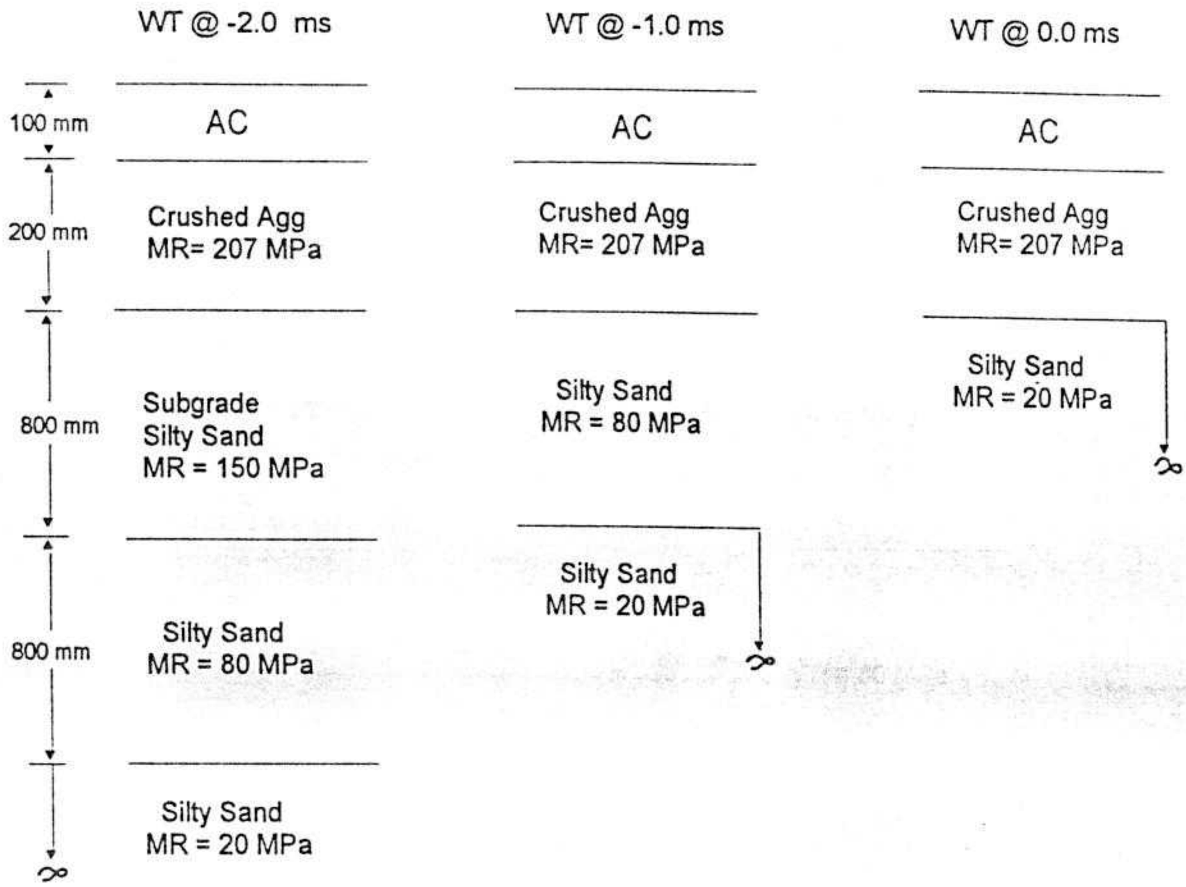

Fig. 9. Details of the pavement cross-sections for different depths to ground water table.

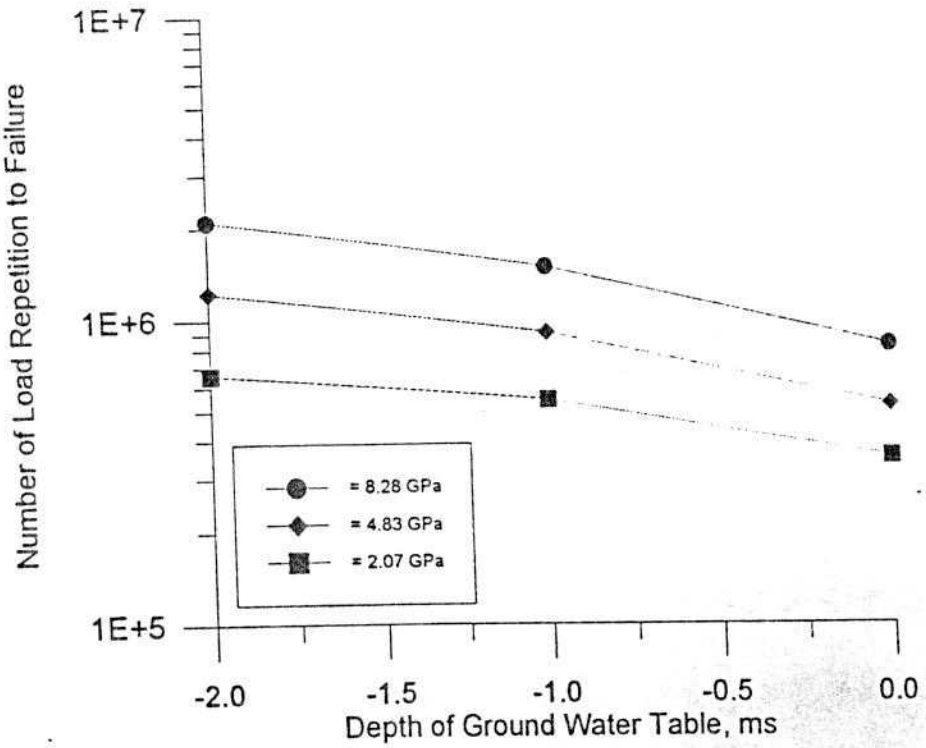

Fig. 10. Relationship between N f (fatigue cracking) and depth of ground water table for different values of $|E_1^*|$

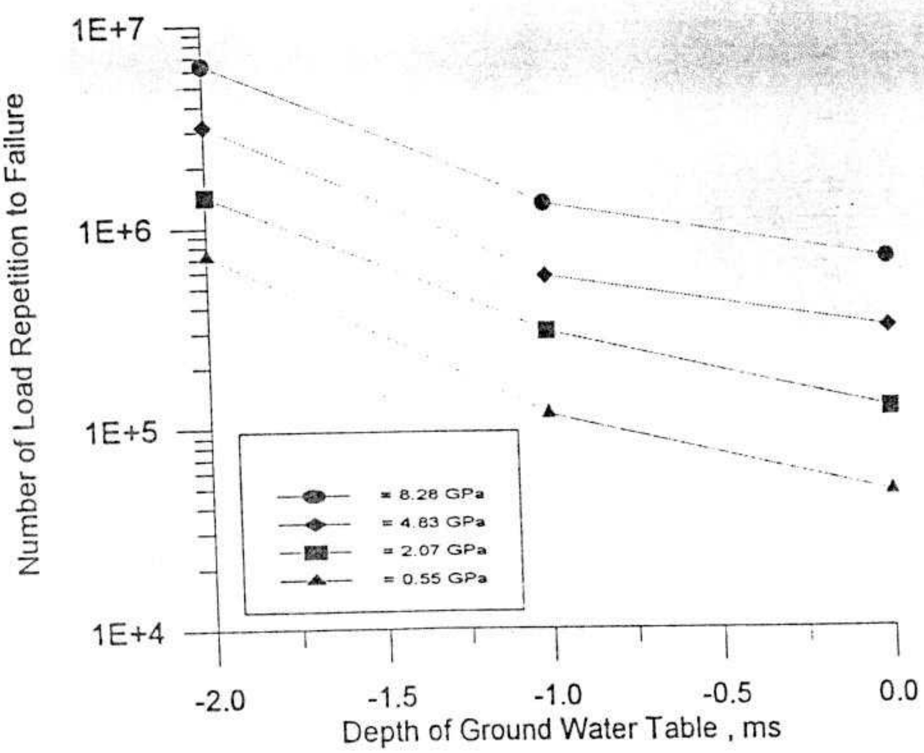

Fig. 11. Relation between Nd (Rutting) and depth of ground water table for different values of $|E_1^*|$