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Reliability Analysis of Flexible Pavement Using Crude Monte Carlo Simulation

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ABSTRACT

Flexible pavement design process is influenced by many parameters such as (traffic characterization, environmental conditions and structure materials…etc.). Several attempts have been carried out to add reliability concept to the mechanistic-empirical (M-E) design of pavements. In pavement structural design, it is common to consider the design input variables as fixed or deterministic. Also, the current design methodology used in many countries such as Egypt is ignoring the effect of temperature variation (despite its importance) on the pavement design. By using Minitab software this research aimed to assess the effect of variations in design parameters on pavement reliability and also predict the pavement reliability due to variation in pavement temperature using Monte Carlo simulation method (MCs) considering rutting and fatigue failures. Moreover, a comparison was performed between regressions models represented from different pavement agencies to recommend the most efficient one for Egyptian temperature. The results obtained that, considering design parameters variations (without temperature); the reliability based on Shell Research agency (86.57%) was the nearest one to the current design methodology in Egypt (91.0%). After adding temperature variations, the reliability was clearly affected but the regression model of Shell Research agency was still the most appropriate one to all Egyptian temperature zones as it achieved the lowest error mean (0.04) and the lowest error standard deviation (0.004). Moreover, the relation between air temperature and reliability was considered to confirm the first-order reliability method (FORM) results.

Keywords: *Reliability; Crude Monte Carlo; Minitab; rutting and fatigue pavement life; Egyptian climatic.*

1. Introduction

In structural pavement design methodology according to the Egyptian Code for urban and rural pavements works (ECP, 2008) [1] and also the American Association of State Highway and Transportation Officials (AASHTO, 1993) [2], it is common to consider the input variables as fixed or predefined. There are exceptions for some variables, such as modulus of the supporting layers. However, they are still considered to be deterministic or fixed [3]. Recently many studies have focused on converting the design steps of flexible pavement from empirical to mechanistic process. By utilizing new probabilistic concepts such as reliability analysis in pavement design [4]. A field observation for evaluation of pavement surface conditions of Egyptian road's network showed that rutting and fatigue cracking are considered the most important distresses surveyed that determining the pavement life [5].

Calculating pavement layers thickness (that depending on rutting and fatigue) is considered as an uphill mission. The complication in asphalt pavement design is increased by adding traffic flows, material properties and pavement attitude under various climatic cases [4].

The appearance of each rutting or fatigue means the pavement fail. Moreover, the rutting and fatigue patterns perhaps related to popular variables. There is a probability of appearance of fatigue and rutting in the same time, which cannot be considered in reliability ingredients [6]. So reliability analysis steps is based on sampling methods, deterioration patterns, and transfer tasks were suggested by many recent studies [7; 8]. The Crude Monte Carlo method is a probabilistic technique based on generating a large number of random samples. Simulations are particularly useful in the design phases of product development because they unravel the uncertainty or variability of a complex system.

2. Aim and Research Significance

The previous researches well discussed the quality of flexible pavements versus the failure ways such as rutting and fatigue separately. But they and the ECP 2008 design guide neglected the variation in design parameters and its effect into the predicted reliability of the flexible pavement and also ignoring the impact of the temperature fluctuation on the reliability.

Thus, in this paper, the reliability analysis that relies especially on Crude Monte Carlo simulation (CMCs) implemented in Minitab software to study the predicted reliability of a four-layer flexible pavement from ECP 2008 considering two ingredients failure patterns (rutting and fatigue) in the same time.

Thus the main objectives of this study could be summarized into:

- Evaluating the effect of variation in design parameters such as (traffic characterization and structure materials) on the pavement reliability considering five different agencies that calculating pavement deterioration patterns (rutting and fatigue) to determine the closest agency to the Egyptian design methodology.
- Studying the effect of adding temperature as a design parameter on the pavement reliability all over Egypt and determining the most appropriate regression model to ECP.

3. Design Life

Each pavement is designed to withstand a certain number of years (design life). The design life can be defined as the time from original construction to a terminal condition for a pavement structure. A terminal condition refers to a state where the pavement needs reconstruction [9].

Pavement is designed to serve a certain number of years (design life) in a good condition. With the continuous increase in weights of traffic loads, the detrimental effect of traffic and environment results in a continuous decrease of the pavement's level of service [10]. Several fatigue and rutting models have been established to link the asphalt modulus and/or the measured strains to the number of load repetitions to pavement failure. The most fatigue and rutting models have been developed take the following form [9]:

$$N_f = f_1 \times \varepsilon_t{}^{-f_2} \times E_1{}^{-f_3} \quad (1)$$

$$N_r = f_4 \times \varepsilon_v{}^{-f_5} \quad (2)$$

Where:

N_f : is the allowable number of load repetitions to prevent fatigue cracking from reaching a certain limit (10–20% of the pavement surface area);

N_r : is the allowable number of load repetitions to prevent rutting from reaching a certain limit (0.5 in.);

ε_t : is the maximum tensile horizontal strain on the bottom of the asphalt layer;

ε_v : is the maximum compressive vertical strain on the surface of subgrade;

E_1 : is the elastic modulus of the asphalt layer;

f1, f2, f3, f4, f5 are the regression coefficients as shown in Tables 1 and 2.

Ameri et al. [11] concluded that the tensile horizontal strain on the bottom of the asphalt layer (ε_t) and the compressive vertical strain on the surface of subgrade (ε_v) values as following:

Table 1. Fatigue regression coefficients by different organizations [9].

.No	Organization	f_1	f_2	f_3
1	Asphalt Institute	0.0795	3.291	0.854
2	Shell Research	0.0685	5.671	2.363
3	US Army Corps of Engineers	497.156	5	2.66
4	Belgian Road Research Center	14-E4.92	4.76	0
5	Transport and Road Research Laboratory	10-E1.66	4.32	0

Table 2. Rutting regression coefficients by different organizations [9].

.No	Organization	f_4	f_5
1	Asphalt Institute	09-E1.365	4.477
2	Shell Research	07-E6.15	4
3	US Army Corps of Engineers	15-E1.81	6.527
4	Belgian Road Research Center	09-E3.05	4.35
5	Transport and Road Research Laboratory	06-E1.13	3.75

$$\varepsilon_t = 0.259421 \times 0.93637^{h_1\, logE_1} \times 0.999999^{E_1/logE_1} \times 1.346352^{h_1} \times 1.004334^{\mathrm{Tp}} \times 1.059582^{W_{load}} \times 0.22101^{logE_2} \times 0.996338^{h_2} \quad (3)$$

$$\varepsilon_v = 0.005897 \times 0.997936^{E_4\backslash logE_4} \times 0.992823^{h_2} \times 0.999987^{E_3} \times 0.969754^{logE_1 \times h_1} \times 1.0004^{E_4} \times 0.990023^{h_3} \times 1.09869^{W_{load}} \quad (4)$$

Where:-

h_1 : is asphalt thickness (cm); E_1: asphalt elastic module (psi); h_2: base thickness (cm); E_1: base elastic module (psi); h_3: subbase thickness (cm); E_3: subbase elastic module (psi); E_4: subgrade elastic module (psi); Tp :tire pressure (psi); and, W_{load}: is axle load (ton).

While the empirical design equation in ECP, 2008 & AASHTO, 1993 take the following form

$$\log_{10} W_{18} = Z_r \times S_0 + 9.36 \times \log_{10}(SN + 1) - 0.2 + \frac{\log_{10}\frac{PSI}{4.2-1.5}}{0.4+\frac{1094}{(SN+1)^{5.19}}} + 2.32 \times \log_{10} M_R - 8.07 \quad (5)$$

Where:-

W_{18}: Equivalent single axle loads (ESALs); Z_r: Standard normal deviate; S_0: Standard error; SN: Structural number; Δ PSI: Change in serviceability; M_R: Effective subgrade resilient modulus.

3. Pavement Design Parameters

3.1 Traffic Conditions

According to AASHTO 1993 design methodology, all axles converted to 18-kip equivalent single axle loads (ESALs) as a method of capturing cumulative loading. In M-E pavement design guide, obtaining axle load vision for the different vehicle classes, weight-in-motion (WIM) stations are required [12]. Unfortunately, WIM stations is not used in Egypt yet. The case study for our research is a design example from ECP 2008 as a mean value of all parameter with an appropriate coefficient of variation collected from previous studies as shown in Table 3.

3.2 Environmental Effect

The environmental factors have a major influence in pavement performance. The temperature of the asphalt concrete is one of the most important environmental factors that influences flexible pavement performance. The possibility hazard of temperature change raises attention in how it may affect the deterioration rates (deflection, strain and stress distributions) in flexible pavement and how pavement service life would be changed as a result [13]. Figures 1 and 2 show the minimum, average, and maximum air temperature as well as the monthly standard deviation (S.D) in many Egyptian cities during January and August, respectively [14]. The following Equation 6 shows the relation between air temperature and pavement temperature [15].

$$T_p = 1.118 \times T_{air} - 0.23 \times h + 4.1 \quad (6)$$

Where:-

T_p: is the asphalt layer temperature (°C) at depth h (cm) from the surface,

T_{air}: is the air temperature (°C) at the surface of pavement.

The following Equation illustrates the dependency relations between pavement temperature and asphalt concrete modulus [16].

$$E_1 = 16693.4 \times e\left[\frac{(T_p+26.2)^2}{-1459.7}\right] \quad (7)$$

Where:

E_1: is the modulus of hot mix asphalt concrete (MPa);

T_p : is the average of the asphalt layer temperature (°C).

3.3 Pavement Materials

As the cost of designing and building new highway pavements increases, the number of new construction and major rehabilitation projects decreases, the importance of ensuring that a given pavement design performs as expected in the field becomes vital [3]. The materials used in different layers have an obvious impact on the predicted performance of the pavement. Therefore it is extremely important to identify material properties and its variation accurately to characterize the pavement material thus the pavement behavior. Unfortunately there is not any previous studies that investigated the variation of pavement materials in Egypt. So the information of the variability and the coefficients of variations (C.O.V) in different design parameters were collected from previous studies and summarized in Table (3).

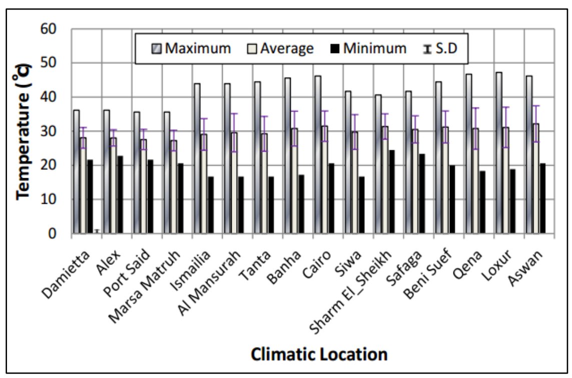


Figure 1. The Egyptian air temperatures during August [14].

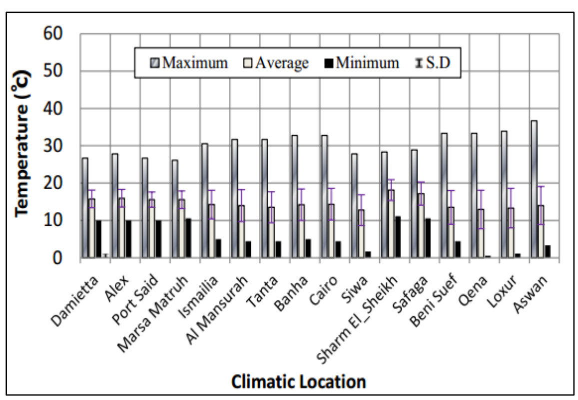


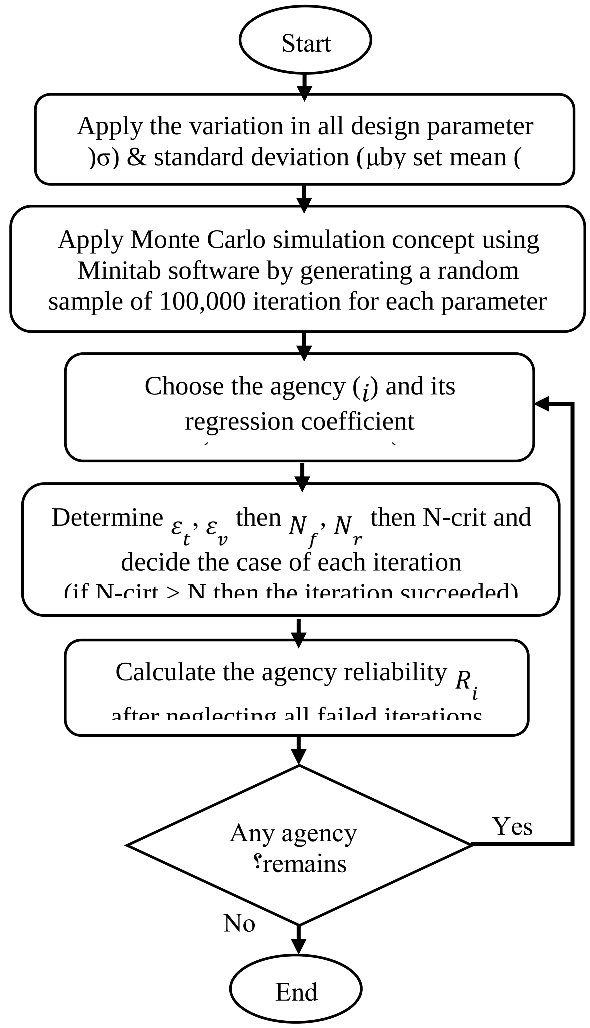
Figure 2. The Egyptian air temperatures during January [14]

Table 3. Coefficients of variations (COV) of different design parameters.

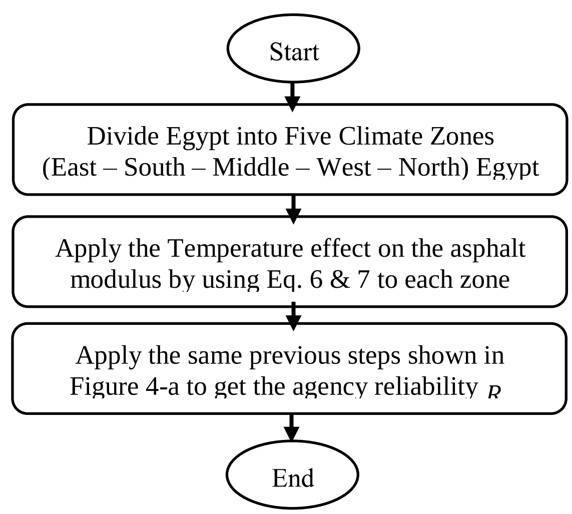
Parameter	Notation	COV	Refrence
Wheel loads	W_s	%0.13	[17]
	T_p	%3.77	[17]
	N	%42	[16]
		%20	[6]
Asphalt Layer	h_1	%20	[17]
		%5	[18]
		%15-3	[19]
		%10	[16]
		%10.5	[3]
		%7.5	[17]
	E_1	%20 – 10	[20]
		%20	[18]
		%25	[16]
Granular layer (base-base & sub)	h_2 ‘h_3	%15 – 10	[20]
		%15 – 8	[18]
		%20-10	[19]
		%10.3	[3]
		%10.5	[17]
	E_2 ‘E_3	%20 – 8	[20]
		%30	[18]
		%15	[16]
		%10.1	[3]
		%20	[17]
grade-Sub	E_4	%30 – 10	[20]
		%40	[18]
		%35	[16]
		%9.3	[3]
		%22	[17]

4. Methodology

Analysis of reliability was achieved in this paper utilizing Crude Monte Carlo simulation technics (MCs) to demonstrate the probabilities of pavement survival considering the rutting and fatigue life. A 4-layer flexible pavement section from ECP (2008) were used as a case study in Egypt. Nonlinear regression relations for fatigue and rutting strains (Equations 1, 2, 3 and 4 for all agencies) were used for calculating the allowable number of axle that the pavement can survive then calculating the reliability by the aid of Minitab software to clarify the effect of considering variation of design parameters on the predicted reliability. Thereafter, a comparison between the five agencies (five different regression equations) to determine the most efficient one for Egyptian temperature and ECP (2008) that depending on the existing AASHTO (1993) design method. Figure 3 illustrates the procedure of the reliability analysis due to (a) design input variance and (b) adding temperature variance using Crude Monte Carlo simulation technics by Minitab software.



(a) Variations in design parameters.



(b) Adding temperature variation.

Figure 3. Flowchart for reliability analysis steps using Crude Monte Carlo simulation.

5. Simulation Concept

Simulation techniques consist of randomly sampling the variables that affect the performance of the pavement structure a large number of times and analyzing the outcomes or results. Based on these results, probabilistic response properties can be estimated. The most widely applicable simulation technique is Crude Monte Carlo Simulation [3].

An important concern with Crude Monte Carlo simulation is that solving a large number of deterministic instances of the performance or limit failure state function is required. Additionally, it has been shown that generally, in order to obtain reliable results the number of iterations needs to be in the order of thousands [21].

Crude Monte Carlo consists of generating N random data points for each random variable based on the distribution of the random variables included in the analysis, estimating the value of the failure function for each vector of random variables, and counting the number of failures that are observed within the N samples. The probability of failure is given by:

$$P_f = E[1g(x) \leq 0] \cong \frac{\sum_i 1(1g(x) \leq 0)}{N} \quad (8)$$

Where:

P_f : is the probability of failure;

$1(g(x) \leq 0)$ is an indicator function that is equal to 1 if $g(x) \leq 0$ or 0 otherwise. Finally, the simulation is repeated several times to determine the variability of the estimate.

Alsherri and George [22] used Crude Monte Carlo simulation to solve the AASHTO design equations under the assumption that all the input variables are probabilistic, independent and normally distributed. Crude Monte Carlo simulation has also been used by Prozzi et al. [12] to evaluate the reliability of pavement designs using the AASHTO Design Guide under various traffic levels. A simple reliability analysis based on Monte Carlo simulation with variance reduction was also initially suggested by Timm et al. [23] and implemented by Chadbourn [24] for the mechanistic-empirical (ME) pavement design procedure MnPave (MnDOT Flexible Pavement Design: Mechanistic-Empirical Method). The reliability analysis was used on the fatigue cracking and rutting transfer functions where the required inputs for the program are thickness (μ, CV), elastic modulus (E), and Poisson's ration (ν). Because of the computing and time constraints involved in using simulation with the ME procedure, the researcher proposed estimating the reliability of a comprehensive set of conditions and then fitting a reliability regression function based only on predicted damage from the MnPave transfer functions (reliability as a function of damage) to allow for a quick estimation of reliability in the design process.

6. Crude Monte Carlo in Minitab

The Crude Monte Carlo solution for determining the probability of pavement failure in Minitab can be summarized in the following procedures:

<u>Step one: generate the random sample</u>

- Open new Minitab Project, then in the worksheet window define the name of 11 columns by the name of each design parameters (h_1, h_2, h_3, E_1, E_2, E_3, E_4, w_s, W , T_p, N).
- Calculate a random sample for each design parameter from Calc menu in the upper-left corner, then random data→Normal→ then insert the number of the iteration (sample size) and select the parameter Column then insert the mean values and standard deviations (S.D).
- Repeat the last step for all design parameter.

<u>Step two: calculate the design life (N-crit)</u>

- Save the Minitab worksheet as an Excel worksheet.
- For each iteration calculate ε_t, ε_v using Equation 3 & 4 then use Equation 1 & 2 to determine the fatigue life N_f and rutting life N_r, so that the design life N-cal is the Minimum of (N_f, N_r). Then add a column named "case" to decide the succeeded iteration (N-crit>N-design) and failed one.
- Remove all columns from worksheet except N-crit & case.

<u>Step three: determine the reliability</u>

- Open the previous worksheet in Minitab from file→ open→ then select the excel file.
- Identify the type of distribution that the N-cal follows as following: - Stat → Reliability/Survival → Distribution analysis (Right Censoring) → Distribution ID plot as shown in Figure A-1.
- Describe statically the N-crit distribution as following: - Stat → Reliability/Survival → Distribution analysis (Right Censoring) → Distribution Overview plot.
- Determine the reliability as following: - Stat → Reliability/Survival → Distribution analysis (Right Censoring) → Parametric Distribution analysis → Estimate survival probability (R_{act}) at the value of N-design.

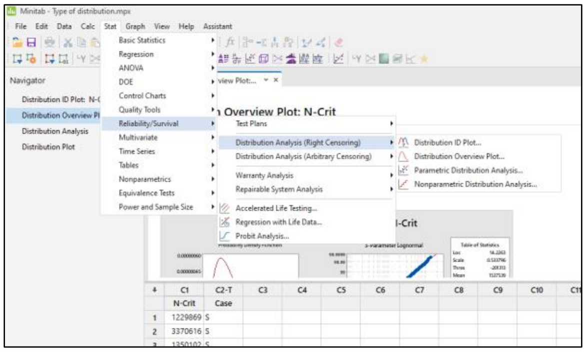


Figure 4. Identify the type of N-Crit distribution.

7. Design Example

According to the field observations conducted by Egyptian roads and bridges authority for traffic volumes and pavement characteristics, a design example simulating the Egyptian pavement design parameters was chosen from the Egyptian Code to be used in this study. Its required to design a flexible pavement for a main rural highway consists of 4 lanes, design period of 15 years, average annual daily traffic of 5000 Vech./day, annual growth rate of 2%, equivalent single axle loads W_18 of 455.2, aggregate sub-base with CBR=30%, crushed stone base with CBR≥ 60%, modulus of asphalt layer E=200,000 psi at 20℃, embankment soil with CBR≥ 15, existing sub-grade of CBR ≥ 5% and the precipitation of the road area is 10% per year.

Using the design procedures in Egyptian code (ECP, 2008) and (AASHTO, 1993) with initial reliability (R) of 90% and standard error (S) of 0.45, the pavement design is as shown in Figure 5. After approximating the layers thickness, the actual reliability become ($R_{ECP} = 91\%$) by inversing the design process using Equation 5.

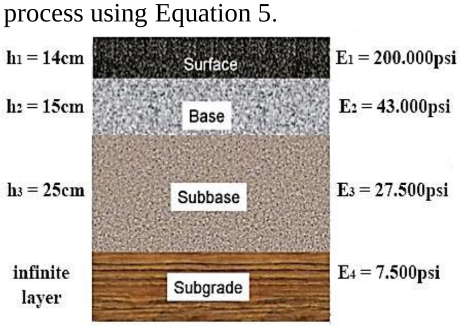


Figure 5. Designed cross section using (ECP, 2008) methodology.

8. Results and Discussion

A series of reliability-based analysis of pavement design was carried out using the previous methodology to assess the effect of input parameters divergence and temperature variation on reliability predicting using Crude Monte Carlo simulation (CMCs) implemented in Minitab application.

8.1 Effect of Design Parameters Variations on the Predicted Reliability

Attainment of the reliability concept in flexible pavement design is very essential to overcome the related problems with increasing traffic volumes and preserving the raw materials used in road construction and maintenance process. Thus, with increasing the reliability of pavement, economic and environmental benefits obtained. The effect of design parameters variations such as (traffic characterization and materials characteristics and pavement depths) have been studied considering five different regression models calculating pavement rutting and fatigue lives to identify the nearest one to Egyptian design methodology in the ECP.

As shown in Figure 6, the reliability based on ECP (91%) is different than reliability values based on regression models calculating rutting and fatigue life for the same study case using CMC simulation. Using asphalt institute method for calculating pavement life reduces the predicted reliability value by about 31% compared with ECP methodology. Shell Research and US Army Crops agencies achieve reliability values approaching the ECP methodology especially Shell Research method (86.57%). On the other hand during the application of CMC simulation for the regression model of Transport and Road Research Laboratory and Belgian Road Research center, the number of survival iteration in case column not exceed 12113 & 5 respectively from a sample size of 100000 iteration. Thus CMC simulation predict the reliability as 12% & 0% as shown in Figure 6.

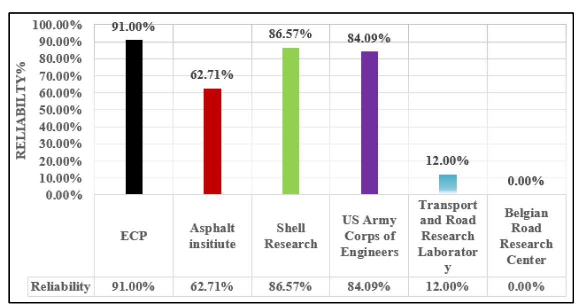


Figure 6. Effect of design parameters divergence on predicated reliability

8.2 Effect of Adding Temperature variation on the Predicted Reliability

To study the effect of temperature variation on the reliability prediction, Egypt was divided into five climate zones according to its location (North – East – middle – West – South).

Table 4. Egyptian climate zones [14].

Zone	Weather Stations (Cities)	Av. Temp. (°c)
East Egypt	Sharm El-Sheikh – Safaga	24.75
South Egypt	Qena – Luxor – Aswan	23.64
Middle Egypt	Ismailia – Mansura – Tanta – Banha – Cairo – Beni Suef	22.73
West Egypt	Siwa	22.16
North Egypt	Damietta – Alexandria – Port Said – Marsa Matruh	21.64

The average air temperature of each zone, arranged from the hottest zone to the coldest one, is as shown in Table 4, where the highest temperature is shown in east zone followed by south, middle, west to the north zone which is considered as the coldest Egyptian part.

To predict the reliability values, the approach (CMCs) was applied based on different regression models from different pavement agencies for each Egyptian climate zone as shown in Figure 7.

It can be illustrated that the pavement reliability is significantly affected due to temperature variation from zone to another all over Egypt. Moreover, depending on different pavement agencies, different predicted reliability values are provided. Table 5 presents the influence of the Egyptian temperatures (arranged from hottest to coldest) on the reliability prediction. From Table 5, it can be concluded that the predicted reliability based on two agencies (Asphalt Institute and Transport and Road Research) is inversely proportional with the temperature variance "from the higher temperature zone (East Egypt) to the lowest temperature zone (north Egypt)". While US Army Corps of Engineers agency provides a directly proportional relation between the reliability and temperature. Shell Research agency provide a semi fixed relation between reliability and temperature.

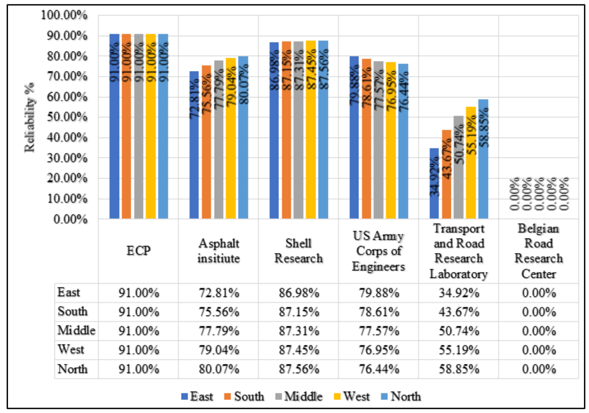


Figure 7. Reliability prediction for each Egyptian climatic zone using five agency

To determine the most appropriate regression model to Egyptian temperature variation, the error for each pavement agency is calculated compared with ECP using Equation 9 with a mean and standard deviation calculated from Equations 10 and 11 respectively.

$$error = R_{Ecp} - R_i \tag{9}$$

Where:

R_{Ecp} is the reliability estimated by Egyptian code;

R_i: is the reliability estimated by agency (i).

$$Error\ mean = \frac{\sum_{i=1}^{n} error_{(i)}}{n} \tag{10}$$

$$Error\ S.D. = \sqrt{\frac{\sum_{i=1}^{n} (error_{(i)} - error\ mean)^2}{n-1}} \tag{11}$$

From Table 5, it found that the regression model that provided the lowest error mean (0.04) and the lowest error standard deviation (0.002) is "Shell Research" followed by "US Army Corps". Thus, it can be concluded that the regression model of Shell Research agency for calculating the pavement life is the most appropriate to the Egyptian design methodology as it does effect by temperature variation. While the regression model of "Transport and Road Research" agency is not recommended for use in Egypt because it provides the highest error mean and the highest error and standard deviation.

Table 5. Reliability prediction based on different pavement agencies.

Location	Average (Temp.(℃)	ECP	Asphalt institute	Shell Research	US Army Corps of Engineers	Transport and road Research
East	24.75	91	72.81	86.98	79.88	34.92
South	23.64	91	75.56	87.15	78.61	43.67
Middle	22.73	91	77.79	87.31	77.57	50.74
West	22.16	91	79.04	87.45	76.95	55.19
North	21.64	91	80.07	87.56	76.44	58.85
Error mean (all over Egypt)			0.14	0.04	0.13	0.42
Error Standard Deviation			0.029	0.002	0.014	0.095

From presented results in sections 8.1 and 8.2, it is concluded that the addition of temperature variation has an obvious effect on the pavement reliability prediction. The regression model of "Shell Research" agency is recommended to be used in current Egypt methodology as it neglect the effect of temperature in the design process. But, it is very important to consider the effect of temperature variations in flexible pavement design methodology presented in Egyptian code for urban and rural pavements works for producing longer pavement life.

8.3 Relation between Temperature and Reliability

In this section the effect of Egyptian temperature variation on reliability prediction studied from the coldest average temperature (12℃) during the January as shown in Figure 1 to the highest average temperature (34℃) during August as shown in Figure 2 using Shell Research regression equations that achieved the closest reliability to current Egyptian pavement design. Considering the same methodology in Figure 3-(b).

Figure 8 shows the impact of temperature variation on predicted reliability. During low temperatures (lower than 32℃), the increase in temperature leads to decease of reliability due to decreasing the modules of elasticity of asphalt layer. The point of the curve inflection is occurred at 32℃. After 32℃, increasing of temperature does not affect the reliability because the modules of asphalt layer is nearest to base modules, the failure may occur due to exceed in axle load. From this relation, an Equation of correlation coefficient (R^2 = 0.99) can be conducted correlating between the predicted pavement reliability and temperature as follows:

$$R_{ECP} = 5 \times 10^{-07} * {T_{air}}^{3} + 6 \times 10^{-05} * {T_{air}}^{2} - 0.0057 * T_{air} + 0.9638 \quad (12)$$

(R^2 = 0.9997)

Where:

R_{ECP} (%): is pavement reliability based on pavement life regression model of Shell Research agency;

T_{air} : is the Egyptian air temperature (Cº).

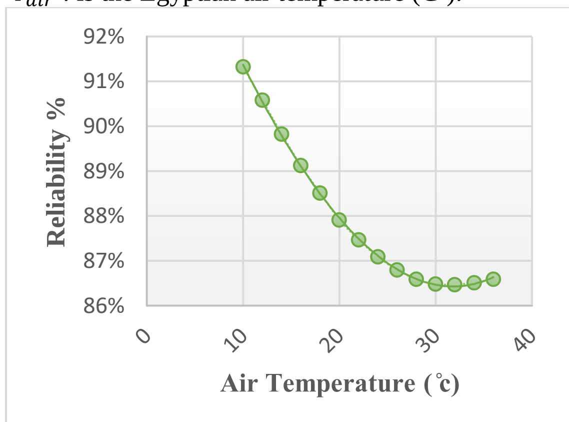


Figure 8. Effect of temperature variation on the predicted reliability

8. SUMMARY AND CONCLUSIONS

With the help of Minitab Software application the Crude Monte Carlo simulation (CMCs) considering fatigue and rutting failures models for five different agencies was implemented to study the effect of design parameters variations on the pavement reliability. Moreover, the temperature variation effect which is ignored in Egyptian design method was studied. Then an equation between predicted reliability and Egyptian temperature was performed to conclude that:

1. Considering variation in pavement design parameters such as traffic elements, material characteristics and pavement depths is very important to let the road survive as the predicted reliability was significantly affected by the variation of regression models of different agencies that calculating the pavement life. Using Shell Research method provided the nearest reliability (86.57%) to the reliability of Egyptian design methodology (91%). Asphalt Institute method didn’t match the Egyptian design because it gave a reliability value which was 31% lower than the value given by AASHTO methodology.

2. Adding of temperature variation in calculating the pavement life provides a significant effect on the predicted reliability where the most appropriate

regression model to Egyptian temperature was presented from Shell Research agency because it achieved the lowest error mean (0.04) and error standard deviation (0.002) for all Egyptian temperature zones. Thus, it was recommended to be used in Egypt for flexible pavement design.

3. The reliability predicted based on two agencies (Asphalt Institute & Transport and Road research laboratory) was inversely proportional with the temperature variation "from highest temperature in east Egypt to lowest temperature in north Egypt. While using US Army Corps agency provided a directly proportional relation between the reliability and temperature. Using Shell Research agency is recommended to be used with ECP methodology as it does effect by the temperature and provide a semi-fixed reliability all over Egypt and nearest to R_{ECP}.

4. A relation between the predicted reliability based on pavement life regression model of Shell Research agency and the Egyptian air temperature illustrated in Equation 12. Temperature of 32ºC was considered as inflection point for reliability in Egypt where at lower temperatures, the reliability values decreased significantly with increasing temperature, while at higher temperature, the reliability slightly increased.

5. It is very important and inevitable to consider the effect of temperature variations in flexible pavement design methodology presented in Egyptian Code for urban and rural pavements works for achieving longer life pavement.

9. References

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