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Reliability Analysis of Flexible Pavement Using First Order Method

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Authors' contributions

This work was carried out in collaboration among all authors. Author SSAEF conducted the research stages, performed the statistical analysis, managed the literature searches and wrote the first draft of the manuscript. Author AEAEM designed the study, managed the analyses, revised the results and participated in writing the manuscript. Author IHH supervised the study. All authors read and approved the final manuscript.

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Abstract

Flexible pavement design is influenced by many design parameters such as (traffic characterization, pavement depths, structure materials and environmental conditions). To study the impact of variations in design parameters on pavement performance, several attempts have been achieved to add reliability concept to the mechanistic-empirical (M-E) design of pavements. In (M-E) design of pavements, the pavement life depends on subgrade rutting and fatigue cracking, considering them as independent failure patterns. The current design methodology used in many countries such as Egypt is ignoring the impact of temperature variation (despite its importance) on the pavement design. This research aimed to predict the pavement reliability due to variation in pavement design parameters especially temperature using the first-order reliability method (FORM) 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 US Army Corps method (91.64%) was the nearest one to the current design methodology in Egypt (91.0%). After adding temperature variations, the reliability was clearly affected where the regression model of Shell Research agency was the most appropriate one for all Egyptian temperature zones as it achieved the lowest error mean (-0.03) and the lowest error standard deviation (0.0011). Moreover, the air temperature of 28ºC was considered as the inflection point for pavement reliability-temperature curve in Egypt.

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Keywords: Reliability; first-order method; subgrade rutting; fatigue cracking; pavement life; Egyptian climatic.

1 Introduction

Structural design of asphaltic pavement demands assessment of each layer thickness, this is considered as an uphill mission. Intricacy in asphalt pavement design is increased by blended traffic flows, material conduct and pavement attitude under various climatic cases. Recently, many studies have concentrated on converting the design steps of flexible pavement from empirical to mechanistic process. New probabilistic concepts such as reliability analysis are extremely utilized in pavement design [1].

Reliability steps depending on sampling methods, deterioration patterns, and transfer tasks were suggested by many recent studies [2,3]. The previous researches well discussed the quality of flexible pavements versus the failure ways such as rutting and fatigue separately. But, the quality and safety of the entire flexible pavement with reference to all deterioration patterns is substantial. Calculating pavement layers thickness is depending on rutting and fatigue, where the appearance of each one of them 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 [4].

In pavement structural design methodology according to Egyptian Code for urban and rural pavements works (ECP) [5] which is adopted from American Association of State Highway and Transportation Officials (AASHTO) [6], it is common to consider the input variables as predefined. There are exceptions of some variables, such as modulus of the supporting layers. However, they are still considered to be deterministic or fixed [7]. A field monitoring evaluation for conditions of pavement surface of Egyptian road’s network showed that rutting and fatigue cracking are considered the most important distresses surveyed that determining the pavement life [8].

Despite the importance and impact of the temperature variation on the flexible pavement performance and life, it hasn’t been considered yet in the Egyptian code for urban and rural pavements (ECP) that based on (AASHTO) design guide. Thus, this study aims to study the reliability prediction for a four-layer flexible pavement system depending on two ingredients failure patterns (rutting and fatigue). The main objectives of this study are:

- Studying the impact of design parameters variation such as (traffic characterization, pavement depths and structure materials) on the reliability considering different regression models that calculating pavement rutting and fatigue life to determine the nearest one to Egyptian design methodology.
- Investigating the effect of adding temperature variation on the pavement reliability change and determining the most appropriate regression model to Egyptian temperature.

1.1 Fatigue and rutting failures

Each pavement is designed to last 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. Several fatigue and rutting models have been developed to relate the asphalt modulus and/or the measured strains to the number of load recurrence to pavement failure [9].

Pavement is designed to serve a certain number of years (design life) in 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]. The most fatigue and rutting models have been developed take the following form [9]:

$$N_f = f_1 \times \varepsilon_t^{-f_2} \times E_1^{-f_3} \tag{1}$$

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

where:

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

N_r : is the allowable number of load recurrence to prohibit rutting from attaining a certain limit (0.5 in.);

ε_t : is the maximum tensile horizontal strain on the bottom of the asphalt layer which computed from equation 3;

ε_v : is the maximum compressive vertical strain on the surface of subgrade which computed from equation 4;

E_1 : is the elastic modulus of the asphalt layer;

f_1, f_2, f_3, f_4,and f_5 are the regression coefficients of different agencies as shown in Tables 1 and 2 to be used in equations 1 and 2.

Table 1. Coefficients of fatigue model according to 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	4.92E-14	4.76	0
5	Transport and Road Research Laboratory	1.66E-10	4.32	0

Table 2. Coefficients of rutting model according to different organizations [9]

No.	Organization	f_4	f_5
1	Asphalt Institute	1.365E-09	4.477
2	Shell Research	6.15E-07	4
3	US Army Corps of Engineers	1.81E-15	6.527
4	Belgian Road Research Center	3.05E-09	4.35
5	Transport and Road Research Laboratory	1.13E-06	3.75

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 can be calculated as following:

$$\varepsilon_t = 0.259421 \times 0.93637^{T_{asph}\,logE_{asph}} \times 0.999999^{E_{asph}\backslash logE_{asph}} \times 1.346352^{T_{asph}} \times 1.004334^{\mathrm{Tp}} \times 1.059582^{W_{load}} \times 0.22101^{logE_{Base}} \times 0.996338^{T_{Base}} \quad (3)$$

$$\varepsilon_v = 0.005897 \times 0.997936^{E_{subgrade}\backslash logE_{subgrade}} \times 0.992823^{T_{Base}} \times 0.999987^{E_{subbase}} \times 0.969754^{logE_{asph} \times T_{asph}} \times 1.0004^{E_{subgrade}} \times 0.990023^{T_{subBase}} \times 1.09869^{W_{load}} \quad (4)$$

Where, T_{asph} : is asphalt thickness (cm); E_{asph}: asphalt elastic module (psi); T_{base}: base thickness (cm); E_{base}: base elastic module (psi); $T_{subbase}$: subbase thickness (cm); $E_{subbase}$: subbase elastic module (psi); $E_{subgrade}$: subgrade elastic module (psi); Tp tire pressure (psi); and, W_{load}: is axle load (ton).

1.2 Reliability

Other than design parameters such as traffic characterization, environmental conditions and structure materials, there are many factors have a significant effect on pavement performance that cannot be directly accounted in design process, such as construction quality and preventive and routine maintenance activities, thus using reliability is necessary in pavement design requirements [7]. Reliability was considered into (ECP) [5] and (AASHTO) [6] in the empirical design equation 5, by including a term that accounts for uncertainty in the design process known as a safety factor " $Z_r \times S_0$" [12].

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

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.

After the designer specifies the level of reliability, the Z_r can directly calculated (AASHTO [6]). The ECP [5] which based on AASHTO guide [6] defines reliability as “The reliability of a pavement design-performance procedure is the probability that a section of designed pavement using this operation will perform satisfactorily over the climatic conditions and traffic volumes during the design period”. From the above definition, reliability can be drawn mathematically by equation 6.

$$R = P[g(x) \geq 0] = 1 - P_f \quad (6)$$

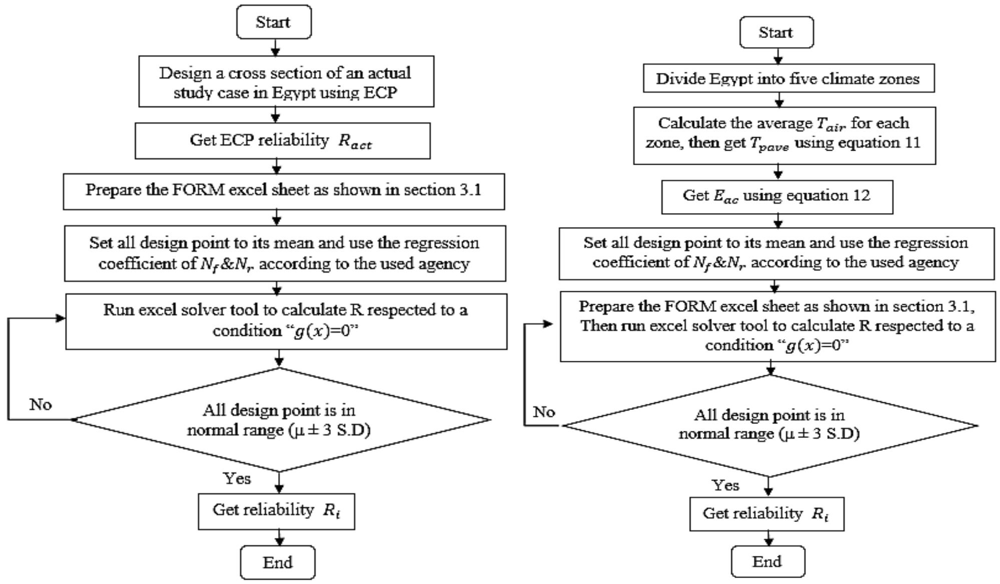
Where, $g(x)$ is the limit state function (function that separates the failure and non-failure domains) and P_f is the probability of failure “$P[g(x) \leq 0]$”.

2 Methodology

Analysis of reliability was achieved in this research utilizing the first-order reliability method (FORM) to estimate the probabilities of pavement failure considering the rutting and fatigue standard. Nonlinear regression relations for fatigue and rutting strains (equations 3 and 4 in this study) were used for evaluating the reliability indicator versus failure patterns of rutting and fatigue. The range of interconnectedness in failure patterns was determined by estimating the coefficients of linkage “F.s” for the rutting and fatigue failures. Thereafter, the reliability steps were calculated to provide a comparison between different agencies estimating pavement rutting and fatigue life and determine the most efficient one for Egyptian temperature. Thus this study can be divided into two sections, the first one investigates the impact of variation in pavement design parameters that used in ECP [5] method on the reliability value using different agencies methods. The second section investigates the effect of adding temperatures variations on the reliability to estimate the importance of considering temperature in pavement design as it has been ignored in ECP [5] which is adapted from AASHTO design method [6]. Fig. 1 illustrates the procedure of the reliability analysis due to (a) design input variance and (b) after adding temperature variance using FORM.

3 First Order Reliability Method (FORM)

In most reliability-based approaches, the reliability index (β) is generally estimated as shown in equation 7 where X_i is one of the uncertain variables in the vector x* of input parameters in the reliability analysis; μ_i and σ_i are the corresponding mean value and standard deviation of variableX_i; $[\rho]$ is the correlation matrix for all the input variables. The equivalent probability of failure can be computed as illustrated in equation 8 [13].



(a) Variations in design parameters **(b) adding temperature variation**

Fig. 1. Flowchart for reliability analysis steps using FORM

$$\beta = \min_{X\in F}\sqrt{\left[\frac{X_i-\mu_i}{\sigma_i}\right]^T [\rho]^{-1}\left[\frac{X_i-\mu_i}{\sigma_i}\right]} \tag{7}$$

$$P_f = 1-\phi(\beta) \tag{8}$$

which, ϕ declares the standard normal cumulative distribution function. The reliability index (β) can be computed according to FORM as the shortest distance between the limit state surface and the origin in normalized variable space as shown in Fig. 2 [7].

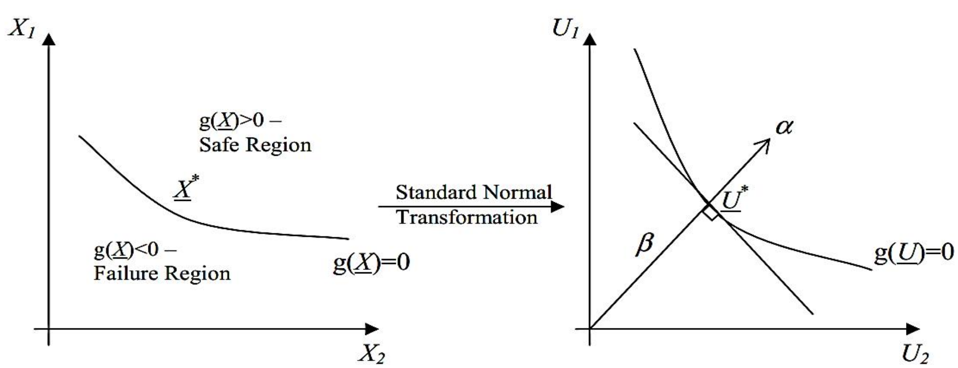


Fig. 2. Concepts of reliability index [7]

3.1 First-order reliability method (FORM) spread sheet

In this study, an efficient approach for reliability considering fatigue and rutting failures relies on the first-order reliability method (FORM) was implemented in a spreadsheet to assess the impact of variation in design parameters such as (traffic characterization, environmental conditions and structure materials) on the pavement reliability. FORM is an efficient approach as it needs much less computational effort comparing with other reliability analysis methods such as Monte Carlo simulation (MCS). Some previous studies concluded that the FORM can produce failure probability almost similar to that provided utilizing Monte Carlo simulation method [13]. The FORM procedure implemented in spread sheet as shown in Figure 3 was used in this study to compute the reliability index. The spreadsheet solution for setting the probability of pavement failure can be summarized in the following procedures:

1. The input design parameters ($h_1, h_2, h_3, E_1, E_2, E_3, E_4, w_s, W, T_p, N$) are shown in the upper-left corner, the mean values, coefficient of variance (COV) and standard deviations (S.D) are shown for each design parameter. José Pablo et al. [7] reported that h_1 and h_2 have a negative correlation and the correlation coefficient is -0.21; also E_2, E_3 and E_4 have a positive correlation and the correlation coefficient is 0.32 as shown in the correlation matrix in the lower-left corner.
2. The coefficients in upper-right corner are the regression coefficients for each studied pavement agency. The coefficients in middle-right corner is the estimated strain levels ε_t and ε_v from equations 3 and 4, the pavement fatigue life (N_f) and rutting life (N_r) that calculated using equations 1 and 2. Then the factor of safety (F.s) is calculated as:

$$F.s = \frac{\text{Min}\,(N_f, N_r)}{N} \tag{9}$$

Knowing, N is the number of load recurrence at the design point. In each simulation the design parameters are used to compute F.s. If F.s is less than 1.0, the failure occurs.

3. The cells in the upper-middle corner show the design points that estimated in the reliability analysis. The optimization process will later on yield a set of design points that have the lowest distance between the limit state surface and the origin in normalized variable area.
4. The results of reliability analysis are shown in the lower-right corner in the spreadsheet. The limit state function $g(x)$ based on the factor of safety (F.s) can be calculated from equation 10. Value of β is estimated using equation 7. The corresponding P_f and estimated reliability (R) are calculated using equation 8 and 6 respectively.

$$g(x) = F.s - 1 \tag{10}$$

The limit state function is entered into lower-right corner. The inverse of correlation matrix is realized using the function of ‘‘MINVERSE’’ in EXCEL. The product of matrixes in equation 7 is realized with the function of ‘‘MMULT’’. After equation 7 is entered into excel cell, press ‘‘enter’’, ‘‘ctrl’’ and ‘‘shift’’ simultaneously to activate this cell to generate a trial reliability index. The corresponding probability of failure is calculated with Equation 8.the lowest cell in the right corner shows the estimated reliability (R) that calculated with Equation 6.

5. β, P_f and R are computed using the solver’s function in the spreadsheet by setting initial design points to be the mean values. When solver is worked, the reliability index is calculated through minimizing β as mentioned in section 3.

4 Pavement Design Parameters

4.1 Traffic

According to AASHTO design methodology [6], all axles are converted to 18-kip equivalent single axle loads (ESALs) as a method of capturing cumulative loading. To obtain axle load in the case of the M-E pavement design guide, vision for the different vehicle classes “weight-in-motion (WIM) station” is required [14]. Unfortunately, WIM stations are not used in Egypt yet, a design example from ECP [5] was utilized in this study with an appropriate coefficient of variation (COV) collected from previous studies as shown in Table 3.

4.2 Environmental conditions

The environmental factors have a major influence in pavement performance. Figs. 4 and 5 show the minimum, average, and maximum air temperature as well as the monthly standard deviation (S.D) in many Egyptian cities during August and January, respectively [15]. The following equation 11 shows the relation between air temperature and pavement temperature [16].

$$T_{pave} = 1.118 \times T_{air} - 0.23 \times h + 4.1 \tag{11}$$

where, T_{pave} is the temperature of asphalt pavement (°C) at depth h (cm) from the surface,

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

The following equation 12 illustrates the dependency relations between pavement temperature and asphalt concrete modulus [17].

$$E_{ac} = 16693.4 \times \mathrm{e}\left[\frac{(T_p+26.2)^2}{-1459.7}\right] \tag{12}$$

where, E_{ac} is the modulus of hot mix asphalt concrete (MPa) and T_p is the average of the asphalt layer temperature (°C).

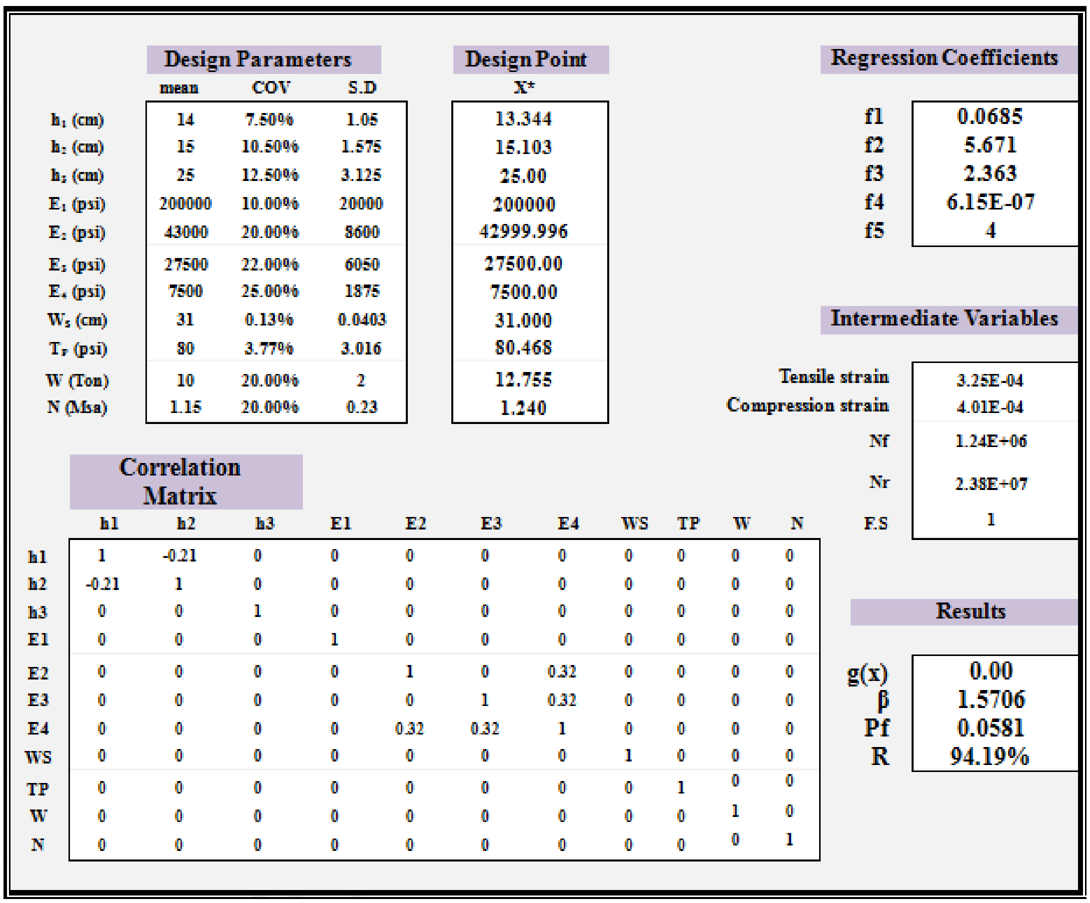
4.3 Pavement materials

The materials used in different layers have a significant impact on the predicted performance of the pavement. Therefore it is extremely important to identify material properties and its variation accurately to characterize the material. In this study, Microsoft excel solver changes the value of design inputs randomly to reach the critical point which is the most probable failure point without any limitation in range. Thus it is needed to have a factor to emphasize that all design inputs are all in normal distribution range (μ ± 3 S.D) according to bell curve. Unfortunately, there is not any previous Egyptian-studies investigated the variation of pavement materials. Thus the coefficients of variations (COV) in different design parameters were collected from previous studies and summarized in Table 3.

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

Design parameters	Variables	Symbol	COV%	Reference
Wheel loads	Wheel Space	W_s	0.13%	[13]
	Tire Pressure	T_p	3.77%	[13]
	Design Traffic	N	42%	[17]
			20%	[13]
Asphalt Layer	Thickness	h_1	5 – 12%	[18]
			5%	[19]
			3-15%	[20]
			10%	[17]
			10.5%	[7]
			7.5%	[13]
	Elastic Modulus	E_1	10 – 20%	[18]
			20%	[19]
			25%	[17]

Design parameters	**Variables**	**Symbol**	**COV%**	**Reference**
Granular Layer (base & subbase)	Thickness	h_2, h_3	10 – 15%	[18]
			8 – 15%	[19]
			10-20%	[20]
			10.3%	[7]
			10.5%	[13]
	Elastic Modulus	E_2, E_3	8 – 20%	[18]
			30%	[19]
			15%	[17]
			10.1%	[7]
			20%	[13]
Sub-grade	Elastic Modulus	E_4	10 – 30%	[18]
			40%	[19]
			35%	[17]
			9.3%	[7]
			22%	[13]



Design Parameters / **Design Point**

	mean	COV	S.D	X*
h_1 (cm)	14	7.50%	1.05	13.344
h_2 (cm)	15	10.50%	1.575	15.103
h_3 (cm)	25	12.50%	3.125	25.00
E_1 (psi)	200000	10.00%	20000	200000
E_2 (psi)	43000	20.00%	8600	42999.996
E_3 (psi)	27500	22.00%	6050	27500.00
E_4 (psi)	7500	25.00%	1875	7500.00
W_s (cm)	31	0.13%	0.0403	31.000
T_P (psi)	80	3.77%	3.016	80.468
W (Ton)	10	20.00%	2	12.755
N (Msa)	1.15	20.00%	0.23	1.240

Regression Coefficients

f1	0.0685
f2	5.671
f3	2.363
f4	6.15E-07
f5	4

Intermediate Variables

Tensile strain	3.25E-04
Compression strain	4.01E-04
Nf	1.24E+06
Nr	2.38E+07
F.S	1

Correlation Matrix

	h1	h2	h3	E1	E2	E3	E4	WS	TP	W	N
h1	1	-0.21	0	0	0	0	0	0	0	0	0
h2	-0.21	1	0	0	0	0	0	0	0	0	0
h3	0	0	1	0	0	0	0	0	0	0	0
E1	0	0	0	1	0	0	0	0	0	0	0
E2	0	0	0	0	1	0	0.32	0	0	0	0
E3	0	0	0	0	0	1	0.32	0	0	0	0
E4	0	0	0	0	0.32	0.32	1	0	0	0	0
WS	0	0	0	0	0	0	0	1	0	0	0
TP	0	0	0	0	0	0	0	0	1	0	0
W	0	0	0	0	0	0	0	0	0	1	0
N	0	0	0	0	0	0	0	0	0	0	1

Results

g(x)	0.00
β	1.5706
Pf	0.0581
R	94.19%

Fig. 3. The spread-sheet used in FORM

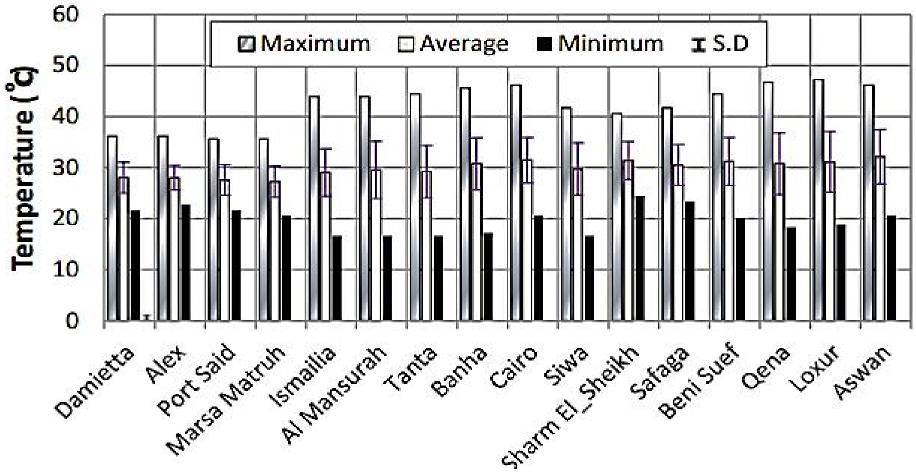


Fig. 4. Egyptian air temperatures during August [15]

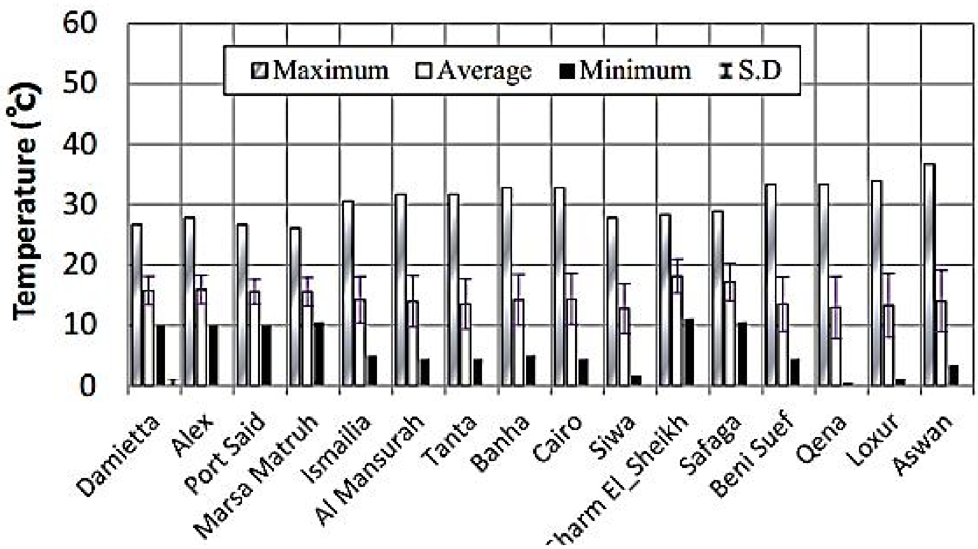


Fig. 5. Egyptian air temperatures during January [15]

5 Design Example

Based on 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. It is 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 E1=200,000 psi at 20°C, 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 [5] and AASHTO [6] with initial reliability (R) of 90% and standard error (S) of 0.45, the pavement design is as shown in Fig. 6. After approximating the layers thickness, the design process was inversed using equation 5 to calculate the actual reliability that found to be ($R_{act} = 91\%$).

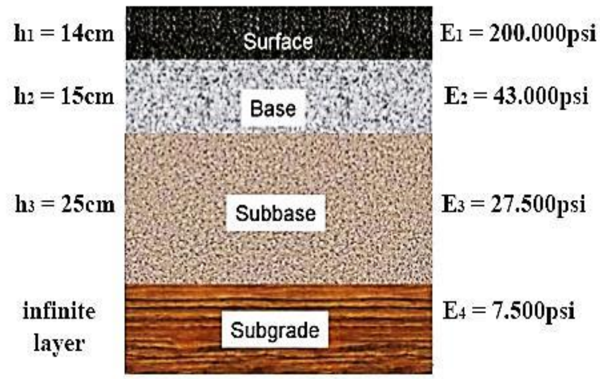


Fig. 6. Designed cross section using (ECP, 2019) methodology

6 Results and Discussion

A series of reliability-based analysis of pavement design was carried out to assess the effect of input parameters divergence and temperature variation on reliability predicting using FORM implemented in excel sheet.

6.1 Effect of design parameters variations on the predicted reliability

Realization of the reliability concept in flexible pavement design is very important to face concurrent problems with increasing traffic volumes and save the raw materials used in road construction and maintenance process. Thus, with increasing the reliability of pavement, economic and environmental benefits achieve. The effect of design parameters variations such as (traffic characterization and materials characteristics and pavement depths) have been studied considering different regression models calculating pavement rutting and fatigue lives to determine the nearest one to Egyptian design methodology.

By using the methodology shown in Fig. 1-(a), the reliability based on ECP (91%) is different than reliability values based on rutting and fatigue life of other agencies for the same study case using FORM, as shown in Fig. 7. Using asphalt institute method for calculating pavement life reduces the predicted reliability value by about 30% compared with ECP methodology. Other agencies achieve reliability values approaching the ECP methodology especially US army corps method (91.64%). During the application of FORM for the regression model of Belgian Road Research center, the excel solver couldn't find the design point of N and put it equal to zero. Thus FORM spreadsheet failed to predict the reliability.

FORM spreadsheet method is easy to use due to its good features, however because the limit state function is approximated by a linear function at the design point (x^*), there are some limitations in cases where the limit state function is highly nonlinear. Moreover, the accuracy of the FORM is dependent on the radius of curvature at the design point, the number of indiscriminate variables, and the first-order reliability index (β). This may be the reason for the failure of FORM in predicting the reliability with regression model of "Belgian road research center".

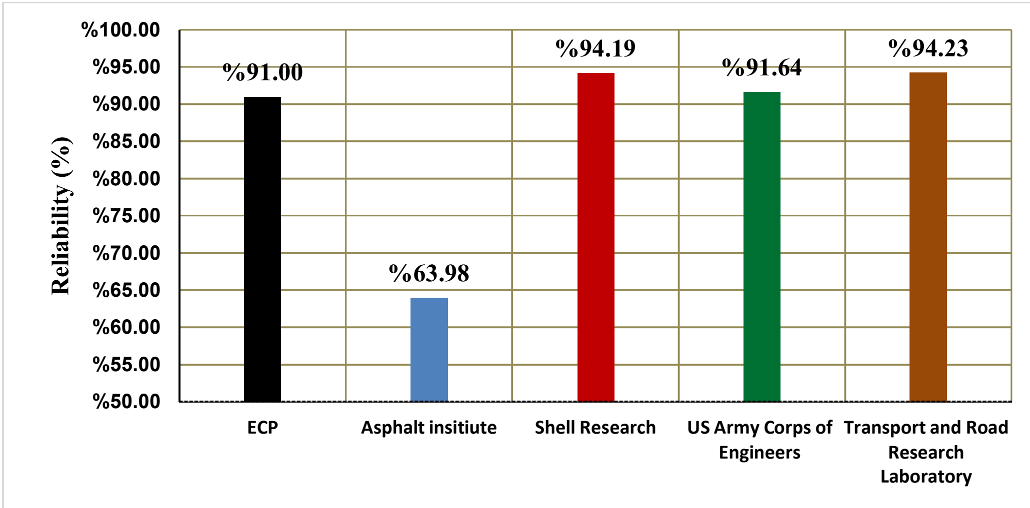


Fig. 7. Effect of design parameters divergence on predicated reliability

6.2 Effect of adding temperature variation on the predicted reliability

By using the methodology shown in Fig. 1-(b) for studying 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). The average air temperature of each zone (arranged from the hotter to the colder) is shown in Table 4, where the highest temperature is shown in east zone followed by south, middle, west then the north zone which is considered as the coldest Egyptian part.

Table 4. Egyptian climate zones [15]

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

To predict the reliability values, the approach (FORM) was applied based on different regression models from different pavement agencies for each climate zone as shown in Figs. 8 to 11. It can be illustrated that the pavement reliability is significantly affected due to temperature variation all over Egypt by using the same agency. Moreover, depending on different pavement agencies, different predicted reliability values are provided. Table 5 presents the influence of the Egyptian temperatures (arranged from hotter to colder) on the reliability prediction. From Table 5, it can be concluded that the predicted reliability based on two agencies (Asphalt Institute and Shell 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. Beside that Transport and Road Research agency doesn’t provide a clear relation between reliability and temperature.

Table 5. Reliability prediction based on different pavement agencies

Pavement Agencies		ECP	Asphalt institute	Shell Research	US Army Corps of Engineers	Transport and road Research
Location	Average Temp.(˚c)					
East	24.75	91.00%	77.21%	94.29%	87.06%	70.67%
South	23.64	91.00%	80.60%	94.37%	85.57%	59.38%
Middle	22.73	91.00%	83.07%	94.45%	84.38%	50.17%
West	22.16	91.00%	84.53%	94.51%	83.62%	56.21%
North	21.64	91.00%	85.75%	94.56%	82.96%	61.42%
Error mean (all over Egypt)			0.09	-0.03	0.06	0.31
Error Standard Deviation			0.034	0.0011	0.016	0.075

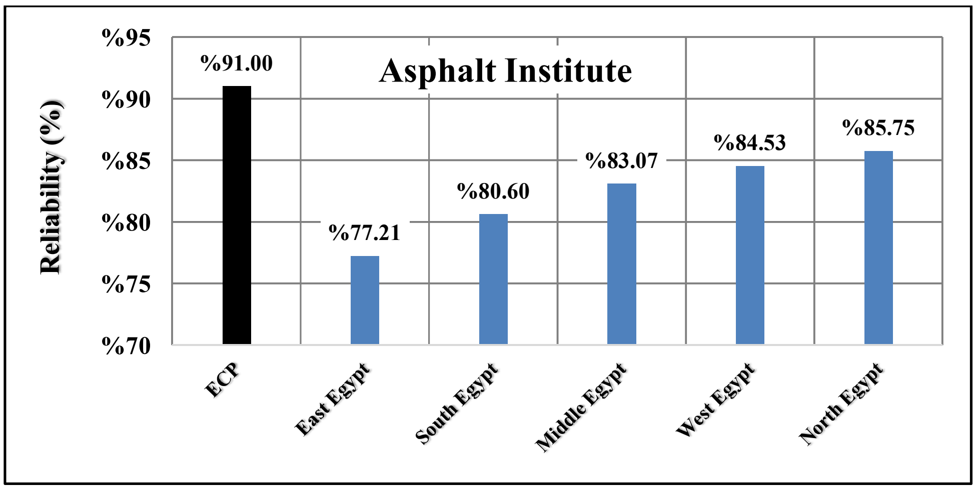


Fig. 8. Reliability prediction for each Egyptian climatic zone using Asphalt Institute method

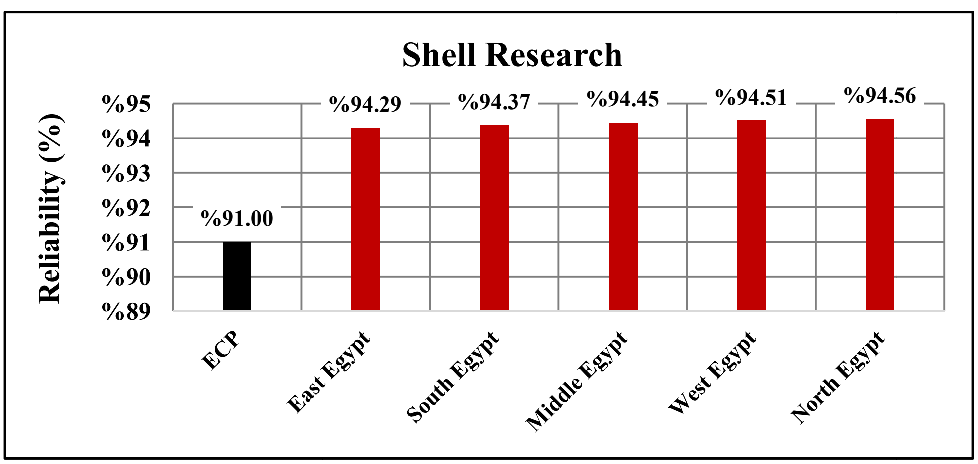


Fig. 9. Reliability prediction for each Egyptian climatic zone using Shell Research method

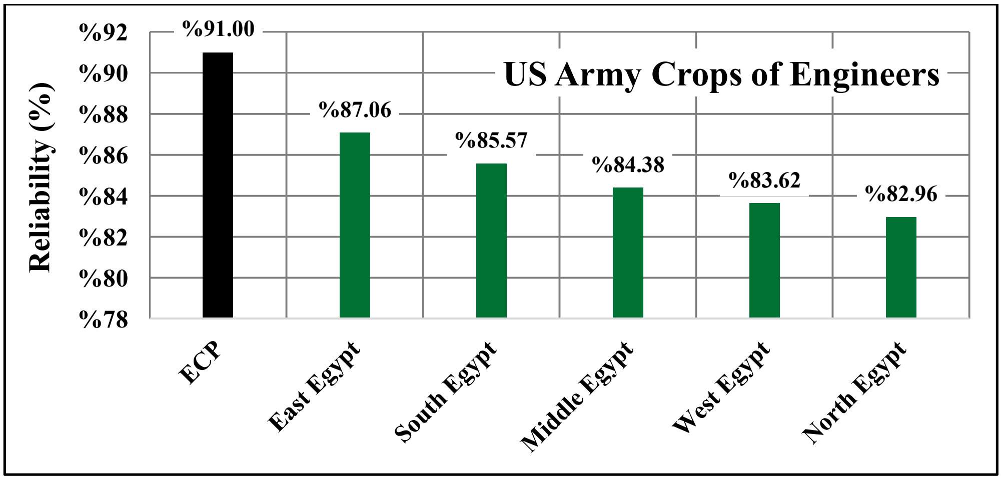


Fig. 10. Reliability prediction for each Egyptian climatic zone using US army corps method

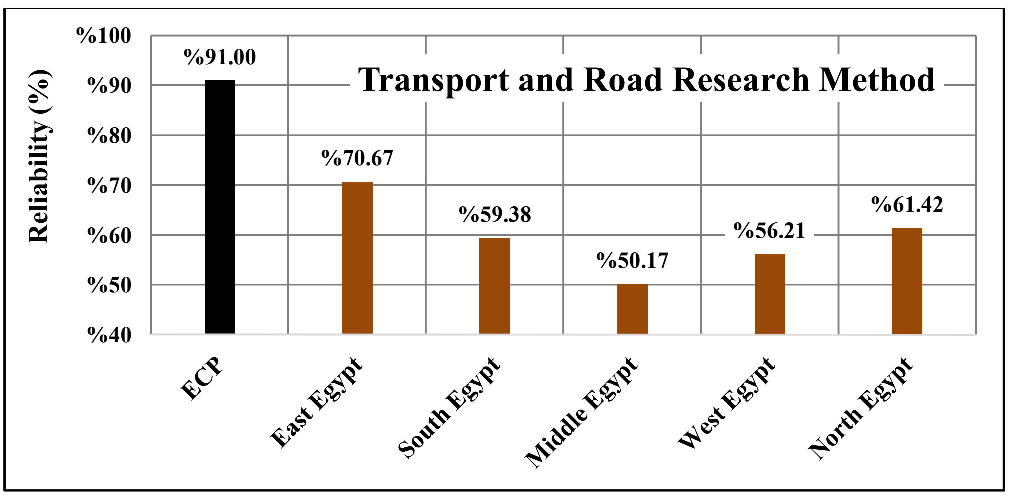


Fig. 11. Reliability prediction for each Egyptian climatic zone using Transport and Road Research method

To determine the most appropriate regression model to Egyptian temperature variation, the error for each pavement agency is calculated compared with ECP using equation 13. The error mean and standard deviation calculated from equations 14 and 15 respectively.

$$error = R_{Ecp} - R_i \tag{13}$$

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

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

$$Error\ mean = \frac{\sum_{i=1}^{n} error_{(i)}}{n} \tag{14}$$

$$Error\ standard\ deviation = \sqrt{\frac{\sum_{i=1}^{n}(error_{(i)} - error\ mean)^2}{n-1}} \qquad (15)$$

From Table 5, it found that the regression model that provided the lowest error mean (-0.03) and the lowest error standard deviation (0.0011) 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 considering 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 standard deviation.

From presented results in sections 6.1 and 6.2, 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 Egypt. Thus, 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 reliable pavement life**.**

6.3 Relation between temperature and reliability

The effect of Egyptian temperature variation on reliability prediction was studied from colder temperature (10°c) during the January as shown in Fig. 5 to higher temperature (36°c) during August as shown in Fig. 4 using Shell Research method that achieved the closest reliability to Egyptian pavement design. To achieve more accuracy in the results, the model error was added as a factor in the methodology and considering the model error mean (-.03) and error standard deviation (0.11%), therefore, the limit state function is modified from equation 10 into the following equation 16:

$$g(x) = F.s + \varepsilon - 1 \qquad (16)$$

knowing that, ε is the uncertainty factor.

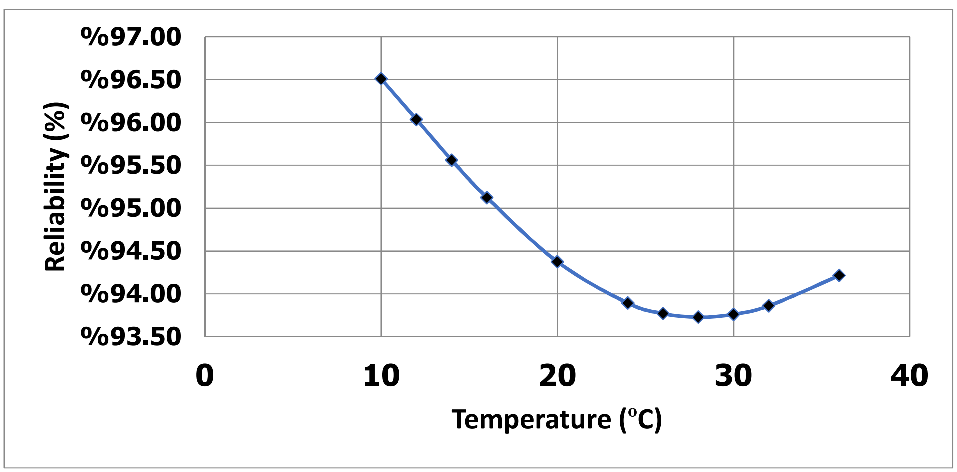


Fig. 12. Effect of temperature variation on reliability values

Fig. 12 shows the impact of temperature variation on reliability values. During low temperatures (lower than 28°C), the increase in temperature decease the reliability values due to decreasing the modules of elasticity of asphalt layer. The point of the curve inflection is occurred at 28°C. After 28°C, increasing of temperature does not affect the reliability because the nearest point to failure found 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:

$R = [8(10)^{-7} \times T^3] + [3(10)^{-5} \times T^2] - 0.0035T + 0.9972$ (17)

Where, R (%) is pavement reliability based on pavement life regression model of Shell Research agency and T is the Egyptian air temperature (°C).

7 Summary and Conclusions

The first order method (FORM) based on fatigue and rutting failures models from different agencies was implemented to study the effect of design parameters variations on the pavement reliability. Moreover, the temperature variation effect that is negligent in Egyptian design method was studied. An equation between predicted reliability and Egyptian temperature was performed. Thus, the following conclusions could be drawn:

1. Considering variation in pavement design parameters such as traffic elements, material characteristics and pavement depths, the pavement reliability prediction was significantly affected by the variation of regression models of different agencies that calculating the pavement life. In case of negligent the temperature effect, using US Army Corps method provided the nearest reliability (91.64%) 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 30% lower than the value given by AASHTO methodology.
2. Adding of temperature variation provided a significant effect on the reliability prediction where the most appropriate regression model to Egyptian temperature was presented from Shell Research agency as it achieved the lowest error mean (-0.03) and error standard deviation (0.0011) 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 and Shell Research) was inversely proportional with the temperature variation "from higher temperature in east Egypt to lower temperature in north Egypt. While using US Army Corps agency provided a directly proportional relation between the reliability and temperature. Using Transport and Road Research agency didn't provide a clear relation between reliability and temperature.
4. A relation between the predicted reliability based on pavement life regression model of Shell Research agency and the air Egyptian temperature was performed. Temperature of 28°C 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 didn't change or 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 reliable life pavement.

8 Recommendations for Future Studies

It is recommended for further studies to try more accurate reliability methods such as Markov Chain Monte Carlo simulation (MCMCs) for all considered pavement agencies in this research to confirm these results. Moreover, a comparison between the results of first order method (FORM) and Monte Carlo simulation method for all environmental zones in Egypt will be very important for this essential topic.

Competing Interests

Authors have declared that no competing interests exist.

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