The Influence of the AASHTO Rigid Pavement Design Equation Variables on the Load-Carrying Capacity of the Pavement Structure: A Parametric Study

Mohammad A. Khasawneh
Department of Civil Engineering, Prince Mohammad Bin Fahd University, Al Azeziya, Eastern Province, Kingdom of Saudi Arabia
Email: mkhasawneh@pmu.edu.sa

Tamara H. Bani Ata
Department of Civil Engineering, Jordan University of Science and Technology, Irbid, Jordan
Email: thbaniata@just.edu.jo

Abstract—**The effect of design variables on the modification of traffic capacity utilized for rigid highway pavement designed by AASHTO procedure was investigated and studied. The variation in the total equivalent single axel load (ESAL) that a pavement can carry due to a change in the overall standard deviation, reliability level, serviceability index, slab thickness variation, rupture modulus, drainage coefficient, load transfer and elastic concrete and the subgrade reaction modulus ratio (Ec/K) has been inspected and examined. AASHTO rigid pavement design equation was divided into different simple models that introduce and explain the relation between the change in each design variable and their effect on the total ESAL to be held by roadway pavement. The sensitivity analysis was conducted for rigid pavement to understand pavement performance with the effect of design parameters as design inputs using Microsoft Excel. Based on the sensitivity analysis, rigid pavement input parameters were ranked from most sensitive to insensitive to help pavement design engineers to identify the level of importance for each input parameter. The results of the analysis showed that pavement thickness and reliability have the highest effect on pavement capacity while load transfer coefficient, overall standard deviation, coefficient of drainage, (Ec/K), present serviceability index and modulus of rupture have less effect.**

Index Terms—**rigid pavement, sensitivity analysis, pavement performance, Equivalent Single Axel Load (ESAL), Portland Cement Concrete (PCC)**

I. Introduction

Two different types of pavement can be used; the Flexible and Rigid pavements. Rigid pavement is the technical expression for any road made of concrete material. The main advantage of using the rigid (concrete) pavement is its rigidity and durability under traffic loading. Rigid pavement is defined simply as a surface layer made up of Portland Cement Concrete (PCC) slabs sits on the top of sub-layers. The durability and the hardness of rigid pavement surface are the two main reasons for its wide usage; this allows the road to function effectively over the pavement life in the presence of various repeated traffic loadings. There are many applicable procedures for rigid pavement design. The American Association of State Highway and Transportation Officials (AASHTO) is widely known and used method.

Rigid pavement materials, design, analysis, construction, rehabilitation and maintenance have been studied widely in the literature [1], [2], [3], [4], [5]. Reference [6] considered several models with many concepts that helped in pavement performance prediction, analysis and design. Reference [7] studied the stress-strain relationship for the longitudinal cracks in pavement using 3D-finite element model of the tire rubber-block. They found that there was a nonlinear relation between traffic loads and stress intensity of pavement.

Reference [8] investigated that the design of rigid pavement must consider pavement structure with all design features to determine the flexural fatigue of concrete. Safe and economical design was achieved near 100% with the use of genetic algorithm to find the optimum design needed. Reference [9] presented rigid pavements structural performance in California. They included seven different types of PCC pavement sections and layers in their experiments. Pavement distress conditions with its deflection were evaluated and tested for the concrete slabs. They showed that thick concrete slabs lower the deflection response and decrease the propagation of voids under the corners of concrete slabs.

Reference [10] introduced numerical steps based on iterative procedure by finite element method for rigid pavements response analysis study. They presented the pavement as a beam element in their study. Their results

Manuscript received December 2, 2020; revised December 30, 2020; accepted January 7, 2021.

doi: 10.18178/ijscer.10.1.35-42

were focused on a parametric analysis study to understand the responses of rigid pavements. Reference [11] implemented axisymmetric finite element analysis study using various design parameters mainly; the elastic modulus of subgrade, pavement thickness and pressure. They found that rigid pavement has been exemplified as elastic material with linear behavior, while soil has been presented as nonlinear material by Drucker Prager criterion.

Reference [12] characterized a design procedure of concrete highway pavement by Portland Cement Association (PCA). They found that both wheel load magnitude and the modulus of subgrade reaction are affected on pavement thickness determination process and value. Reference [13] studied the effect of temperature on plain jointed concrete pavements using finite element analysis method. They developed 3D-model for concrete slabs with the presence of longitudinal and transverse joints. Their studies were performed parametric analysis on thermal-expansion stresses to address temperature effects and changes on joints.

Reference [14] presented 3D finite elements study for concrete pavements on load transfer at doweled joints. The results of the study discussed the effect of slab curling and foundation type on joint and the potential for distress. Reference [15] reported a design of rigid pavements using Westergaard's analysis that considered the pavement as a thin elastic plate on the soil. The study showed that the slab deflection depends in the stiffness of soil and the flexural strength of concrete slab.

Reference [16] focused on the determination of critical pavement technology element based on ranking of priority to achieve the objective of the green highway design. Based on the weighted analysis adopted in this study, it has been shown that the soil erosion control element has achieved first ranking followed by permeable and cool pavement.

Reference [17] carried out a parametric sensitivity study to evaluate the influence of design variables on the change in traffic capacity used for flexible pavements designed by the AASHTO design method. It was found that the structural number of the construction materials and the subgrade modulus of resilience have the greatest effect on the load carrying capacity; whereas the change in serviceability index, reliability and overall standard deviation levels have relatively less effect.

The objectives of this study are focused on addressing the impact of each design variable change on the total ESAL (load capacity) of the pavement and to build several models with various relationships between load carrying capacity (total ESAL) and each design variables help in pavement performance prediction. In this research study, a modern parametric sensitivity analysis of AASHTO rigid pavement design equation will be studied and discussed. Therefore, the authorities can make action faster in order to prevent more danger to road users.

II. Methodology

The main criteria of this study gained from AASHTO rigid pavement equation that is used for highway rigid pavement design. The design equation (see Equation 1) is arranged in the following form:

$$\log_{10}(W_{18}) = Z_R \times S_o + 7.35 \times \log_{10}(D+1) - 0.06 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.5-1.5}\right)}{1+\frac{1.624\times 10^7}{(D+1)^{8.46}}} + (4.22 - 0.32 p_t) \times \log_{10}\left[\frac{(S_c')(C_d)(D^{0.75}-1.132)}{215.63(J)\left(D^{0.75} - \frac{18.42}{\left(E_c/k\right)^{0.25}}\right)}\right] \tag{1}$$

where W18, is the predicted number of 18 kip equivalent single axle loads (ESALs); ZR, standard normal deviation (function of the design reliability level); S0,overall standard deviation; ΔPSI, allowable serviceability loss at end of design life; pt, terminal serviceability; k, modulus of subgrade reaction (pci); Sc, PCC modulus of rupture (psi); Ec, PCC modulus of elasticity (psi); J, an empirical joint load transfer coefficient; Cd, an empirical drainage coefficient; D, required PCC slab thickness (inches).

Performing the sensitivity analysis procedure for equation variables is satisfied in the studying of its impact on ESAL. The analysis is investigated based on main criteria depending on varying one of the variables value while the others have a fixed value based on the standards with a manipulating equation variables description. AASHTO Rigid pavement design equation was written as: $\log_{10}(W18) = X + C$, where X is the design variable under studying and C is a constant for the other equation variables.

III. Results and Discussion

The effect of variation of traffic loadings which are performed by ESAL or (W18), reliability, overall standard deviation So, ΔPSI which describe pavement performance represented by the allowable serviceability loss at end of design life, modulus of subgrade reaction, PCC modulus of elasticity, joint load transfer, drainage and PCC slab thickness on ESAL carried by rigid pavement were analyzed and discussed in this study.

Reliability variable is an indicator for pavement design degree of certainty. The main AASHTO equation re-arranged as shown in Equation 2:

$$\log(W_{18}) = Z_R S_0 + C \tag{2}$$

From the equation, the reliability is performed by its standard normal deviation. The relation between the reliability and ESAL represented from the derivation of the above equation and the re-arranged step as shown in Equation 3:

$$W_{18} = 10^{S_0(Z_R)} \tag{3}$$

Reliability was represented in (ZR) variable with the range between 75% and 99%. The overall standard deviation (So) ranging from 0.25 and 0.35 based on AASHTO recommendation for rigid pavement. The average, min and max values of (So) respectively, were chosen and substituted in Equation 3 with different values of reliability within the ranges mentioned above. Figs. 1, 2 and 3 were developed to represent the relationship described in Equation 3.

Figs. 1, 2 and 3 describe the logarithmic relationship between the change of reliability and the change in ESAL.

From the analysis; the change in ESAL due to the minimum value of (So) (0.25) has the highest effect rather than the other values with coefficient of determination; R^2 equal to 99.78%.

The overall standard deviation identifies the performance prediction of pavement materials and the amount of traffic will occupy the facility. Equation 4 was arranged to show the relationship between (So) and ESAL in the presence of the average, min and max values of reliability based on the range between 75% and 99%.

$$W_{18} = 10^{Z_R(S_0)} \tag{4}$$

Different values of (So) were taken based on the range 0.25 and 0.35 with considering the reliability values. Figs. 4, 5 and 6 show the effect of overall standard deviation on ESAL based on equation 3 with the ranges respectively.

Figs. 4, 5 and 6 describe the logarithmic relationship between the change of overall standard deviation and the change in ESAL. From the analysis; the change in ESAL with the change of (So) due to the minimum value of reliability (75%) has the highest effect rather than the other values with coefficient of determination; R^2 equal to 99.5%.

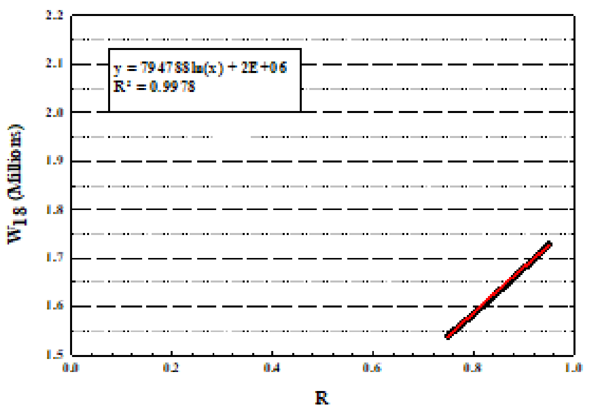

Figure 1. Effect of reliability on ESAL with the average So-value.

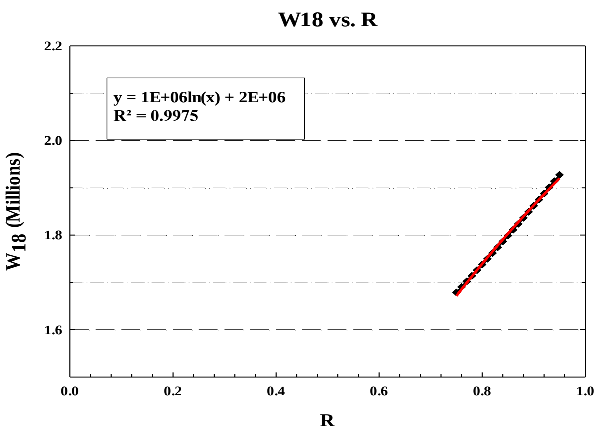

Figure 2. Effect of reliability on ESAL with the min. So-value

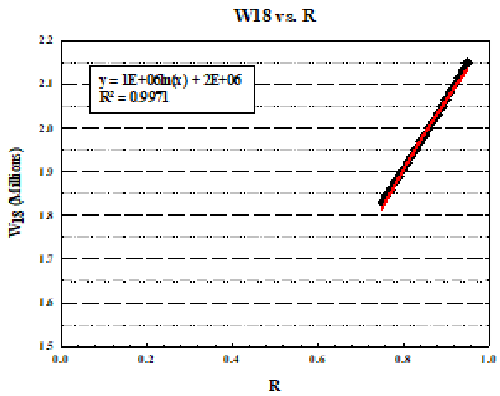

Figure 3. Effect of reliability on ESAL with the max. So-value

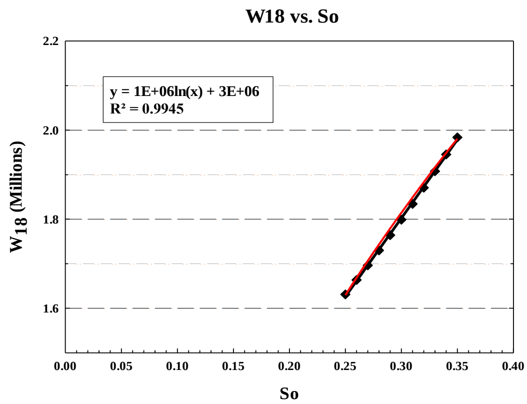

Figure 4. Effect of standard deviation on ESAL with the average reliability value

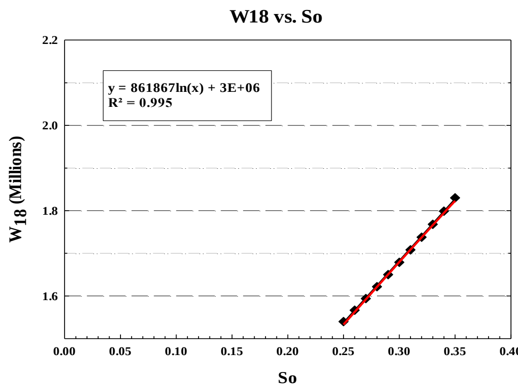

Figure 5. Effect of standard deviation on ESAL with the with the min reliability value

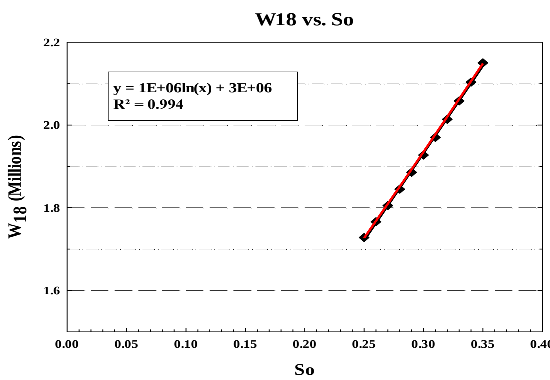

Figure 6. Effect of standard deviation on ESAL with the max. reliability value

The difference between terminal (Pt) and initial serviceability (Pi) is defined as; loss in serviceability index (ΔPSI). The value of initial established for rigid pavement depends on AASHTO standards was 4.4, while the terminal was 2.5 used. Based on the above values of serviceability; ΔPSI range from 0.5 to 2.5. Equation 5 was arranged to show the relationship between (ΔPSI) and ESAL in the presence of the average, min and max values of pavement thickness (D) based on the range between 6 and 14 inches.

$$W_{18} = 10^{\boldsymbol{log((\Delta PSI)/3)/1+\{1.624*10^7/(D+1)^{8.46}\}}} \quad (5)$$

Different values of ΔPSI were taken based on the range 0.5 and 2.5 with considering the average, min and max values of thickness (D). Figs. 7, 8 and 9 show the effect of present serviceability index on ESAL based on Equation 5 with the ranges respectively.

The above figures (Figs. 7, 8 and 9) describe the logarithmic relationship between the change of present serviceability index and the change in ESAL. From the analysis; the change in ESAL with the change of (ΔPSI) due to the minimum value of pavement thickness (6) has the highest effect rather than the other values with coefficient of determination; R^2 equal to 98.9%.

Pavement thickness (D) is an important variable in rigid pavement design. Equation 6 was arranged to show the relationship between the change in thickness (D) and ESAL in the presence of the average, min and max values of present serviceability index based on the range between 0.5 and 2.5.

$$W_{18} = 10^{7.35\log(D+1)-0.06+\frac{log\left(\frac{\Delta PSI}{3}\right)}{X}} \quad (6)$$

Where;

$$X = 1 + \left[\frac{1.624 * 10^7}{(D+1)^{8.46}}\right]$$

Different values of D were taken based on the range between 6 and 14 inches, with considering the ΔPSI values. Figs. 10, 11 and 12 show the effect of thickness on ESAL based on Equation 6with varying in ranges respectively.

Figs. 10, 11 and 12 describe the power and exponential relationships between the change of pavement thickness and the change in ESAL. From the analysis; the change in ESAL with the change of (D) due to the maximum value of present serviceability index (2.5) has the highest effect rather than the other values with coefficient of determination; R^2 equal to 99.99% with power relationship.

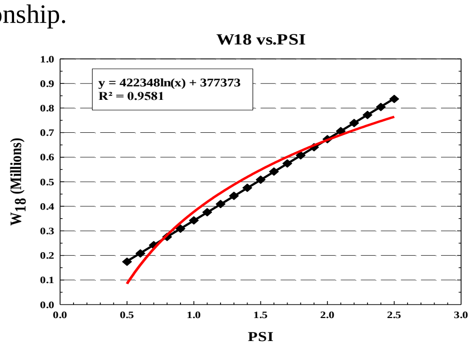

Figure 7. Effect of present serviceability index on ESAL with the average D value

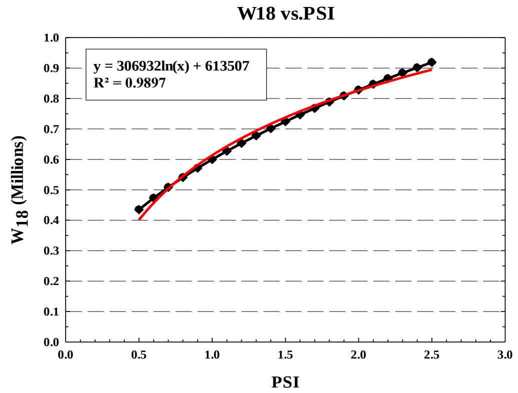

Figure 8. Effect of present serviceability index on ESAL with the min. D value

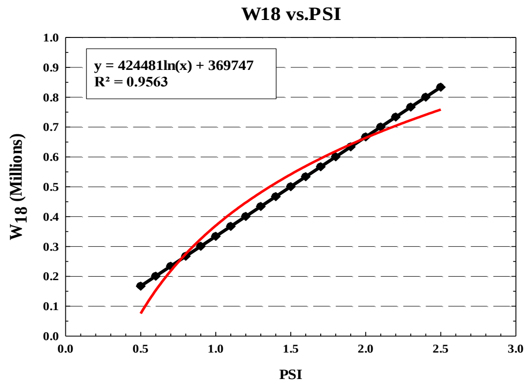

Figure 9. Effect of present serviceability index on ESAL with the max. D value

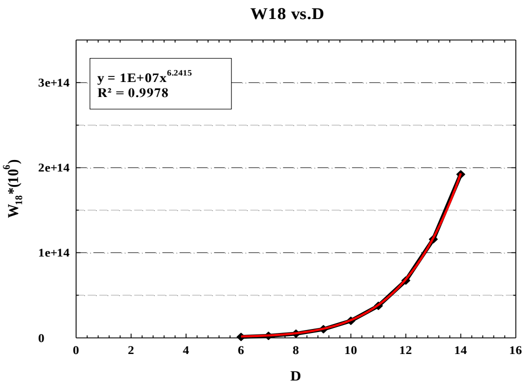

Figure 10. Effect of pavement thickness (D) on ESAL with the average PSI value

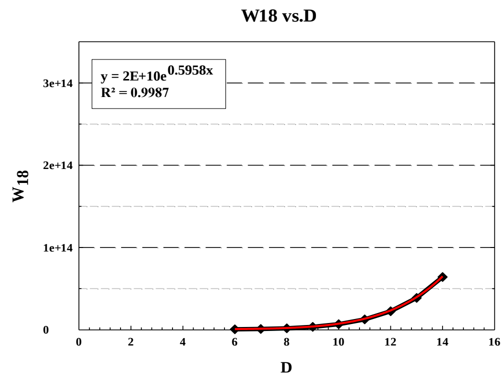

Figure 11. Effect of pavement thickness (D) on ESAL with the min. PSI value

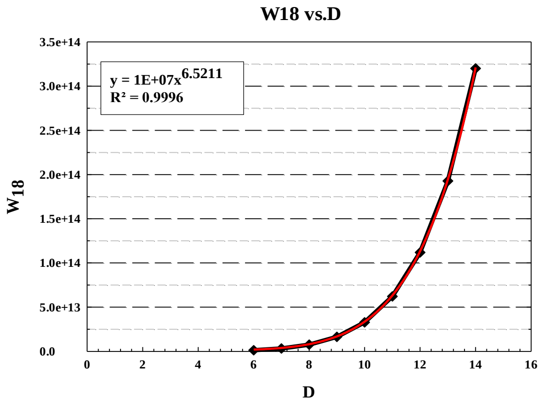

Figure 12. Effect of pavement thickness (D) on ESAL with the max. PSI value

Modulus of Rupture (Sc') is an important design variable of rigid pavement. Equation 7 was derived to show the relationship between the change in rupture (Sc') with the range between (500 to 1200 psi) and ESAL in the presence of the average, min and max values of (D), load transfer coefficient; (J) with the values between (2.3 to 3.8) and (Ec/K) ratio.

$$W_{18} = 10^{3.42 \log\left(Sc'/X\right)} \tag{7}$$

where;

$$X = 215.63\, J * \left[D^{0.75} - \left(\frac{18.42}{\left(E_C/K\right)^{0.25}} \right) \right]$$

Different values of Sc' were taken based on the range between 500 and 1200 psi with considering the D, J and (Ec/K) values. Figs. 13, 14 and 15 show the effect of modulus of rupture on ESAL based on Equation 7 respectively.

The exponential relationships between the change of modulus of rupture and the change in ESAL were shown in Figs. 13, 14 and 15. From the analysis; the change in ESAL with the change of (Sc') due to the average, minimum and the maximum values of D, J and (Ec/K) have the same effect with coefficient of determination; R^2 equal to 98.59% with exponential relationship.

The coefficient of drainage (Cd) is an essential design variable in rigid pavement for drainage purposes. It depends on the percent of time pavement structure is exposed to moisture levels. Equation 8 below was derived to show the relationship between the change in drainage coefficient (Cd) with the range between (0.7 to 1.25) based on AASHTO standards with the changing in ESAL with the presence of the average, min and max values of (D), load transfer coefficient; (J) with the values between (2.3 to 3.8), (Ec/K) ratio and (Sc') with their standard ranges.

$$W_{18} = 10^{3.42 \log\left(\frac{Sc' * Cd}{X}\right)} \tag{8}$$

where;

$$X = 215.63\, J * \left[D^{0.75} - \left(\frac{18.42}{\left(E_C/K\right)^{0.25}} \right) \right]$$

Various values of (Cd) were taken based on (0.7 and 1.25) range considered D, J, (Ec/K) and Sc' values. Figs. 16, 17 and 18 show the effect of coefficient of drainage (Cd) on ESAL based on Equation 8 above.

The exponential relationships between the change of coefficient of drainage and the change in ESAL were shown in Figs. 16, 17 and 18. From the analysis; the change in ESAL with the change of (Cd) using the average, minimum and the maximum values of D, J, Sc' and (Ec/K); have the same effect with coefficient of determination; R^2 equal to 99.36% with exponential relationship.

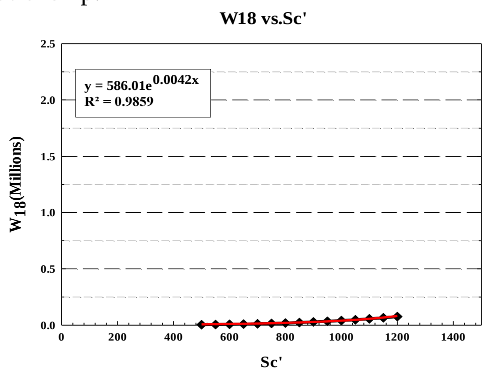

Figure 13. Effect of modulus of rupture on ESAL with the average D, J and (Ec/K) values

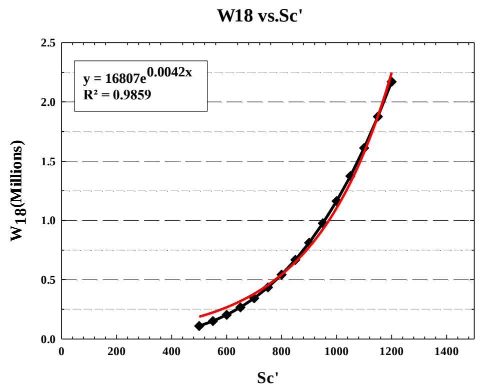

Figure 14. Effect of modulus of rupture on ESAL with the min. D, J and (Ec/K) values

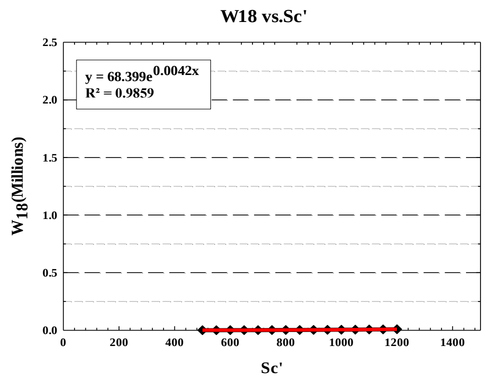

Figure 15. Effect of modulus of rupture on ESAL with the max. D, J and (Ec/K) values

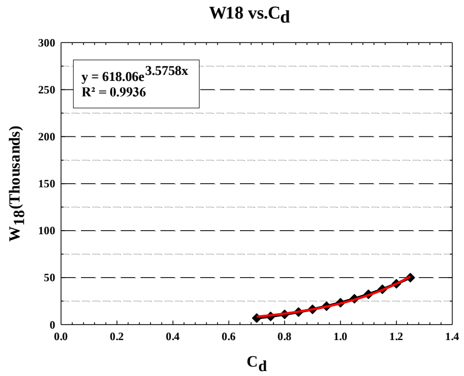

Figure 16. Effect of drainage coefficient on ESAL with the average D, J, Sc' and (Ec/K) values

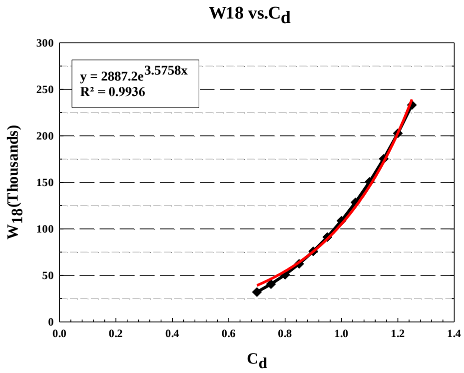

Figure 17. Effect of coefficient of drainage on ESAL with the min. D, J, Sc' and (Ec/K) values

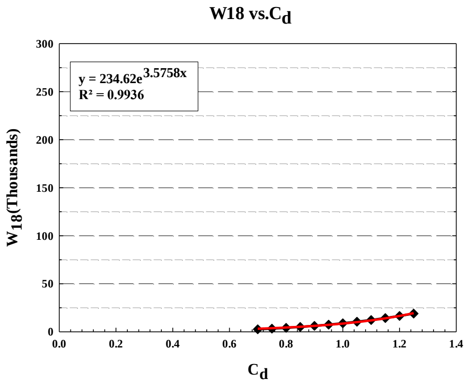

Figure 18. Effect of coefficient of drainage on ESAL with the max. D, J, Sc' and (Ec/K) values

The effect of load transfer coefficient (J) on the change of ESAL could be shown using Equation 9that was derived from rigid pavement AASHTO equation. The range of load transfer (J) from 2.3 to 3.8 was used for relation study. The relationship between the change of load transfer (J) coefficient and ESAL in the presence of the average, min and max values of D, J Cd and Sc' was described in equation 8 below.

$$W_{18} = 10^{3.42\log\left(Sc'*Cd*\left(D^{0.75}-1.132\right)/X\right)} \quad (9)$$

Where;

$$X = 215.63 * J * (D^{0.75} - 1.5489)$$

Various values of (J) were chosen based on (2.3 and 3.8) range; with considering on D, J, Cd and Sc' values. Figs. 19, 20 and 21 show the effect of load transfer coefficient (J) on ESAL based on Equation 9 above.

The exponential relationships between the change of load transfer coefficient and the change in ESAL were as shown above. From the analysis; the change in ESAL with the change of (J) using the average, minimum and the maximum values of D, J, Sc' and Cd; have the same effect with coefficient of determination; R^2 equal to 99.56% with exponential relationship.

The variation of (Ec/K) is dealing with the compressive strength of material with the modulus of subgrade reaction. Equation 10 below was derived to show the relationship between the change in (Ec/K) based on AASHTO standards and the change in ESAL value with the presence of the average, min and max values of D, J, Cd and Sc'.

$$W_{18} = 10^{3.42\log\left(Sc'*Cd*\left(D^{0.75}-1.132\right)/X\right)} \quad (10)$$

where;

$$X = 215.63\,J * \left[D^{0.75} - \left(\frac{18.42}{\left(E_c/K\right)^{0.25}}\right)\right]$$

All possible values of (Ec/K) were chosen with the considered of D, J, Cd and Sc' values. Figs. 22, 23 and 24 show the effect of (Ec/K) on ESAL based on Equation 10 above.

The logarithmic relationships between the change of (Ec/K) and the change in ESAL were shown in Figs. 22, 23 and 24. From the analysis; the change in ESAL with the change of (Ec/K) using the maximum value of D, J, Sc' and Cd; has the highest effect with coefficient of determination; R^2 equal to 99.18%.

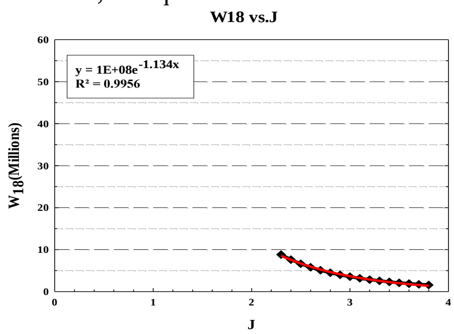

Figure 19. Effect of load transfer on ESAL with the average D, J, Sc' and Cd values

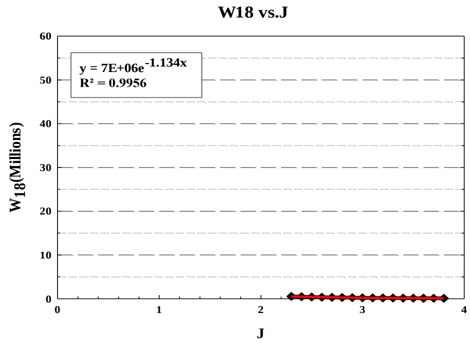

Figure 20. Effect of load transfer on ESAL with the min. D, J, Sc' and Cd values

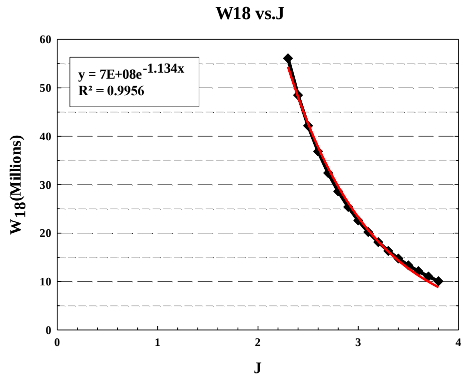

Figure 21. Effect of load transfer on ESAL with the max. D, J, Sc' and Cd values

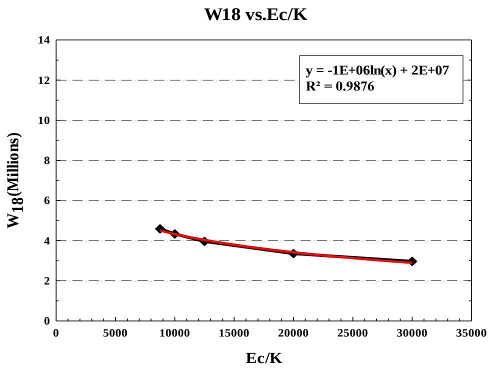

Figure 22. Effect of (Ec/K) on ESAL using the average value of D, J, Sc' and Cd

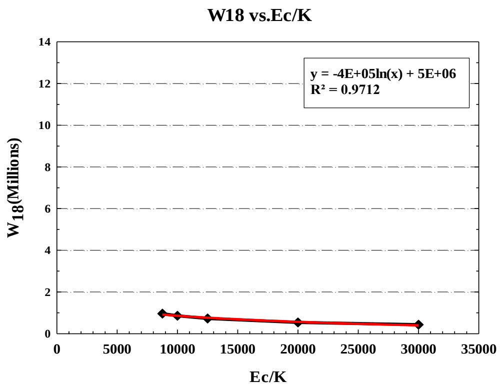

Figure 23. Effect of (Ec/K) on ESAL using the min. value of D, J, Sc' and Cd

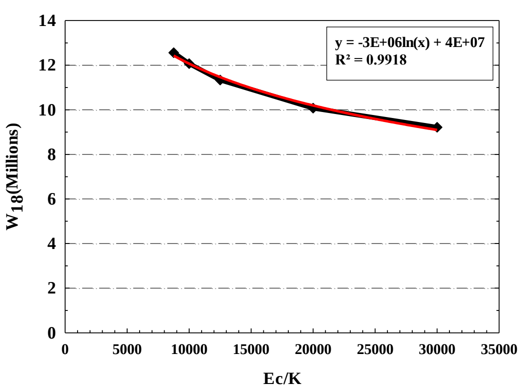

Figure 24. Effect of (Ec/K) on ESAL using the max. value of D, J, Sc' and Cd

IV. Conclusions

The results of this study implied that the variation of rigid pavement thickness has the highest effect on the load carrying capacity of the pavement structure. This effect was confirmed by the high value of the coefficient of determination (99.99%). Variation in the reliability of rigid pavements has the second highest effect on pavements'' load carrying capacity. The variation in load transfer coefficient, overall standard deviation, coefficient of drainage, (Ec/K), present serviceability index and modulus of rupture have respectively lower effect on the rigid pavements' load carrying capacity than thickness and reliability.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

MAK: Conceptualized the research, tailored methodology, secured resources, reviewed and edited the paper and supervised and administrated the project; THB: conducted literature review and formal analysis, cured data, wrote original draft of the paper.

References

[1] E. J. Yoder and M. W. Witczak, *Principles of Pavement Design*, John Wiley & Sons, 1991.

[2] Y. H. Huang, *Pavement Analysis and Design,* 1993.

[3] R. G. Packard, *Thickness Design for Concrete Highway and Street Pavements*, 1984.

[4] R. G. Packard and S. D. Tayabji, "New PCA thickness design procedure for concrete highway and street pavements," in *Proc. Third International Conference on Concrete Pavement Design and Rehabilitation*, Purdue University, School of Civil Engineering; Federal Highway Administration; Portland Cement Association; Transportation Research Board; Federal Aviation Administration; and Indiana Department of Highways. (No. 1 Volume), 1985.

[5] Austroads, "Pavement design: A guide to the structural design of road pavements," *Austroads*, 2004.

[6] K. R. Arora, *Soil Mechanics and Foundation Engineering*, Standard Publishers and Distributors, Delhi, 2003.

[7] E. Masad, R. Taha, and B. Muhunthan, "Finite-element analysis of temperature effects on plain-jointed concrete pavements," *Journal of Transportation Engineering*, vol. 122, no. 5, pp. 388-398, 1996.

[8] M. N. S. Hadi and Y. Arfiadi, "Optimum rigid pavement design by genetic algorithms," *Computers & Structures*, vol. 79, no. 17, pp. 1617-1624, 2001.

[9] B. Long and S. Shatnawi, "Structural evaluation of rigid pavement sections," *Road Materials and Pavement Design*, vol. 1, no. (1-2), pp. 97-117, 2000.

[10] L. Yongjie, Y. Shaopu, and W. Jianxi, "Research on pavement longitudinal crack propagation under non-uniform vehicle loading," *Engineering Failure Analysis*, vol. 42, pp. 22-31, 2014.

[11] D. K. Maharaj and S. Gill, "Development of design chart for flexible pavement by finite element method," *International Journal of Latest Research in Engineering and Computing*, vol. 2, no. 2, pp. 8-23, 2014.

[12] National Cooperative Highway Research Program (NCHRP). (2004). Guide for mechanistic-empirical design of new and rehabilitated pavement structures. *National Cooperative Highway Research Program 1-37 A.*

[13] V. Patil, V. Sawant, and K. Deb, "Finite element analysis of rigid pavement on a nonlinear two parameter foundation model," *International Journal of Geotechnical Engineering*, vol. 6, no. 3, pp. 275-286, 2012.

[14] B. Punmia and A. K. Jain, *Soil Mechanics and Foundations*, Firewall Media, 2005.
[15] W. G. Davids, "3D finite element study on load transfer at doweled joints in flat and curled rigid pavements," *International Journal of Geomechanics*, vol. 1, no. 3, pp. 309-323, 2001.
[16] W. N. Aifa, M. R. Hainin, M. A. Majid, R. MohamadZin, H. Yaacob, R. Zakaria, and M. Bujang, "Pavement technology elements in green highway," *Jurnal Teknologi*, vol. 73, no. 4, pp. 45-49, 2015.
[17] F. A. Gharaybeh, H. R. AL-MASSACID, and M. T. Obaidat, "Parametric sensitivity study of the AASHTO flexible pavement design equation," *Journal of the Institution of Engineers. India. Civil Engineering Division*, *78*(FEV), 175-179, 1998.

Mohammad A. Khasawneh was born in Irbid, Jordan on August 17th, 1980. Dr. Khasawneh has M.Sc. and Ph.D. degrees in civil engineering from the University of Akron, Ohio, USA in the years 2005 and 2008, respectively. He earned his B.Sc. degree in civil engineering from Jordan University of Science and Technology (JUST) in 2003.
He is an Associate Professor of civil engineering at Prince Mohammad Bin Fahd University (PMU), Kingdom of Saudi Arabia. His research interests include highway materials, pavement engineering and surface characterization using experimental, numerical and statistical analysis approaches. Besides, he is interested in educational technology research and development.
Dr. Khasawneh is a registered professional engineer (registration #: 76806) in the state of Ohio since 2012 and a graduate of the Excellence in Civil Engineering Education (ExCEEd) program. He is a member of the American Society of Civil Engineers (ASCE), Institute of Transportation Engineers (ITE), American Society of Engineering Education (ASEE) and Jordan Engineers Association (JEA). Dr. Khasawneh has been the recipient of the Best Thesis Award 2018 at Jordan University of Science and Technology and was selected as the OUTSTANDING SCIENTIST IN CIVIL ENGINEERING under the Engineering Discipline by the 4th Venus International Research Awards (VIRA 2018), Venus International Foundation (VIF). He has also been the recipient of the Best Paper Presentation Award at the 10th International Conference on Key Engineering Materials 2020.

Tamara H. Bani Ata was born in Irbid, Jordan on April 29th, 1991. Eng. Bani Ata has B.Sc. and M.Sc. degrees in civil engineering from Jordan University of Science and Technology (JUST) in the years 2014 and 2016, respectively.
She is interested in studying pavement materials and design.
Eng. Tamara is a member of the Jordan Engineers Association (JEA).