SEMARAK ILMU
PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

A Comprehensive Review of Rigid Pavement Design Methods

Hadier Galal Aboelhassan[1,*], Ayman Mahmoud Othman[2], Hassan Yuones Ahmed[2]

[1] Department of Construction and Building Engineering, College of Engineering, South Valley Campus, Arab Academy for Science, Technology & Maritime Transport, Giza Governorate 3650111, Egypt
[2] Department of civil Engineering, Faculty of Engineering, Aswan University, Aswan, Egypt

ABSTRACT

Several methods are available for designing rigid pavements, each with its own set of advantages and limitations. These methods include the American Association of State Highway and Transportation Officials (AASHTO) model (ESAL method), which calculates the total number of equivalent 18-kip single axle loads expected to pass over the pavement during its design life, the classical Portland Cement Association (PCA) procedure (PCA methods), which use empirical relationships between traffic loading, subgrade strength, and concrete slab thickness to determine the required thickness of the pavement. a method published by the Egyptian code, and a modified PCA approach that has been verified in the TKUPAV program. However, it is important to note that the PCA procedure, AASHTO model, and Egyptian code only consider fatigue analysis in their determination of slab thickness based on stresses acting on the slab. They do not consider the impact of thermal variation on the thickness of the slab. Only the modified PCA and PCA verified in the TKUPAV program approach accounts for climatic changes, specifically thermal curling, when designing the slab thickness.

Keywords:

Rigid pavement; Thermal curling; Fatigue analysis; Erosion analysis

1. Introduction

Rigid pavement has been identified as a major system of transportation system because it has more advantages than flexible pavement [1]. Now world prefers rigid pavement to flexible because it is more economical, environmentally friendly, and longer life cycle conducted by [2]. Rigid pavement is a cement concrete slab resting on the base layer [3,4]. This type of pavement has high tensile strength, due to its rigidity it can transfer the load over a wide range of subgrade area under it [5,6]. Rigid pavement is used to provide a surface with adequate skid resistance [3], and decreased stresses effects on sub-grade soil [7], this type of pavement resists high stresses due to wheel's load so it is needed to construct above low bearing sub-grade layer to cover these loads [8].The primary drawback of this pavement type is that its permeability decreases over time as the pores become blocked, resulting in reduced compressive strength [9]. The life cycle of concrete slab increased with the high efficiency of the base of the sub-base layer which is more economical in construction [3]. In

* *Corresponding author.*
E-mail address: had_6111@aast.edu

https://doi.org/10.37934/araset.56.2.219228

case of poor sub-grade strength, and heavier loads, rigid pavement can be used to carry these heavy loads [8]. Waste materials can be used in rigid pavement, these materials include coconut shells, reclaimed aggregate, crushed brick, etc. [10]. In the last years using of reclaimed materials increased widely due to the increase of highway construction in the opposite [3]. The use of wastes from construction and destruction materials improves the soil [11-18]. These materials include reclaimed asphalt concrete, cement concrete and crushed bricks also [13,19]. The Winkler approach is often used to analyse rigid pavements and involves representing the subgrade as a series of independent springs with a constant stiffness value, known as the modulus of subgrade reaction. This simplifies the analysis process for engineers but may not always produce accurate results if the actual behaviour of the subgrade differs significantly from the assumed behaviour [20]. This paper will carry out comparison between each technique used to design slab thickness according to considering the effect of thermal condition.

2. Design Techniques of Rigid Pavement

2.1 Classical Portland Cement Association Method (PCA)

PCA technique is the most widely and most known method for designing the thickness of rigid pavement [4]. This technique is based on the analysis of finite elements and results of J-SLAB [21] The PCA method begins by assuming the slab thickness according to the cumulative assumption of fatigue damage, then calculating the stress ratio (ratio between the stress of concrete and modulus of rupture for concrete) ($\frac{\sigma_{eq}}{S_C}$) for each axle load and axle type. The maximum allowable load repetitions (N_f) needed to be calculated to complete the route of this techniques, by using the following relationships (N_f) can be determined Eq. (1), Eq. (2), Eq. (3) and Eq. (4) [22].

$$log\, N_f = 11.737 - 12.077x\left(\frac{\sigma_{eq}}{S_C}\right) \qquad for \frac{\sigma_{eq}}{S_C} \geq 0.55 \tag{1}$$

$$N_f = \left(\frac{4.2577}{\frac{\sigma_{eq}}{S_C} - 0.4325}\right)^{3.268} \qquad for\ 0.45 < \frac{\sigma_{eq}}{S_C} < 0.55 \tag{2}$$

$$N_f = unlimited \qquad for\ \frac{\sigma_{eq}}{S_C} \leq 0.45 \tag{3}$$

$$N_f = unlimited \qquad for\ \frac{\sigma_{eq}}{S_C} \leq 0.45 \tag{4}$$

To complete the route, percentage of damage due to fatigue for each axle load and axle type should be calculated. This percentage is calculated by dividing the expected number of load repetitions by (N_f), this value should be within the limits of design criteria. To achieve the final thickness several trials must be calculated. Finally, the PCA technique can be noticed as a relationship between stress repetitions and fatigue that happened on concrete slabs due to this stress [22].

2.2 Modified PCA Route

The route to design rigid pavement slab thickness using this method is based on stress calculation as same as the traditional (classical) PCA route plus the effect of environmental conditions (thermal curling). According to load repetitions, fatigue stress occurred on the concrete slab. The same stress equations were used to determine the thickness, this thickness developed according to thermal curling effects Eq. (5) [23].

$$h_{modified}=h_{stress}+h_{thermal\ bend.} \tag{5}$$

ILLI-SLAB finite element program was design to measure the developed thickness. All variables are dimensionless, and the main ones are detected by [F] for force and [L] for length. Lec and Darter explained the relationship between thickness and the effects of loading and thermal curling [24].

The developed thickness can be determined using the following route [24]:

i. Assume a trail thickness for the slab.
ii. Record material properties, distribution of loading, and variables degrees of temperature.
iii. Measure the repetitions (ni) for all loading cases (loading without thermal curling and loading with thermal curling during the daytime in the period of design).
iv. Determine modified corresponding stress (σeq) using the following equations Eq.(6), Eq. (7) and Eq. (8).

$$\sigma_{eq}=(\sigma_W\times R_1\times R_2\times R_3\times R_4\times R_5+R_T\times\sigma_C)\times f_3\times f_4 \tag{6}$$

$$\sigma_w=\left(\frac{3(1+\mu)P}{\pi(3+\mu)h^2}\right)[\log\left(\frac{Eh^3}{100ka^4}\right)+1.84-\frac{4}{3}\mu+\frac{1-\mu}{2}+1.18(1+2\mu)\frac{a}{l} \tag{7}$$

$$\sigma_c=\frac{CE\alpha\Delta T}{2}=\frac{E\alpha\Delta T}{2} \tag{8}$$

Where:
σ eq = adapted equivalent stress,
σ w = Westergaard’s edge stress,
σ c = Westergaard/Bradbury’s curling stress,
E = elastic modulus of the slab,
h = slab thickness,
λ= W/(($8^{0.5}$)* l),
C = the curling stress coefficient.
R_1= alteration factor for different gear configurations including dual-wheel, tandem axle, and tridem axle.
R_2 = alteration coefficient for finite slab length and width.
R_3 = alteration coefficient for a tied concrete shoulder.
R_4 = alteration coefficient for a widened outer lane.
R_5 = alteration coefficient for a bonded/unbounded second layer.
R_T = alteration coefficient for the combined effect of loading plus daytime curling.

i. Determine stress ratio ($\frac{\sigma_{eq}}{S_C}$)for all cases of loading.
ii. Calculate maximum allowable load repetitions for all stress ratios (Ni) using Eq. (1), Eq. (2) and Eq. (3).
iii. Determine the percentage fatigue for each case ($\frac{\text{ni}}{\text{Ni}}$).

iv. Be sure that the summation for all percentages of fatigue damage does not exceed 100% if not, return of assuming slab thickness and report the same route from 1 to 8 to find the minimum required slab thickness.

2.3 PCA Procedure Verified in the TKUPAV Program

TKUPAV is a software program that was developed by the Texas Department of Transportation (TX DOT) to facilitate the determination of rigid pavement thickness for highways and other transportation infrastructure in Texas [23,24]. The program uses a mechanistic-empirical approach to calculate the required slab thickness based on a range of design parameters, including traffic loading, subgrade conditions, and material properties. This technique stands on the last modification of the Westergard stress analysis and fatigue modal. The TKUPAV program incorporates a few analytical models and algorithms to simulate the behaviour of the pavement structure under different loading and environmental conditions. The program uses finite element analysis techniques to calculate stresses and strains within the pavement layers, and it considers factors such as fatigue cracking, rutting, and joint faulting in its design recommendations. The program also allows users to input data on project-specific conditions, such as climate and soil characteristics, to generate more accurate thickness recommendations. The output from the program includes recommended thicknesses for the concrete slab and any asphalt or granular layers, as well as estimates of the expected performance and service life of the pavement. Overall, the TKUPAV program provides a powerful tool for engineers and designers to optimize the design of rigid pavements for specific conditions and requirements.

2.4 AASHTO Model to Estimate the Concrete Slab Thickness.

The AASHTO (American Association of State Highway and Transportation Officials) model is commonly used to estimate the required thickness of concrete slabs for highway and bridge structures. This model considers the loads that the slab must support, as well as other factors such as subgrade strength, and material properties. The design route of this model depends on a certain decrease in serviceability, PCC slab thickness was determined by the level of pavement strength reduction. The following equation is used to find the slab thickness Eq. (9) [22].

$$\log_{10}(W18) = ZR\,S0 + 7.35\log_{10}(h+1) - 0.06 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.5-1.5}\right)}{1+\frac{1.624*10^{7}}{(h+1)^{8.46}}} \quad (9)$$

$$+(4.22-0.32TSI)\log_{10}\frac{ScCd\left(h^{0.75}-1.132\right)}{215.63J\left(h^{0.75}-\left(\frac{18.42}{\left(\frac{Ec}{K}\right)^{0.25}}\right)\right)}$$

Figure 1 and Figure 2, were used to find the parameters of this equation [25]. On the other hand, this study doesn't take the effect of temperature on slab thickness.

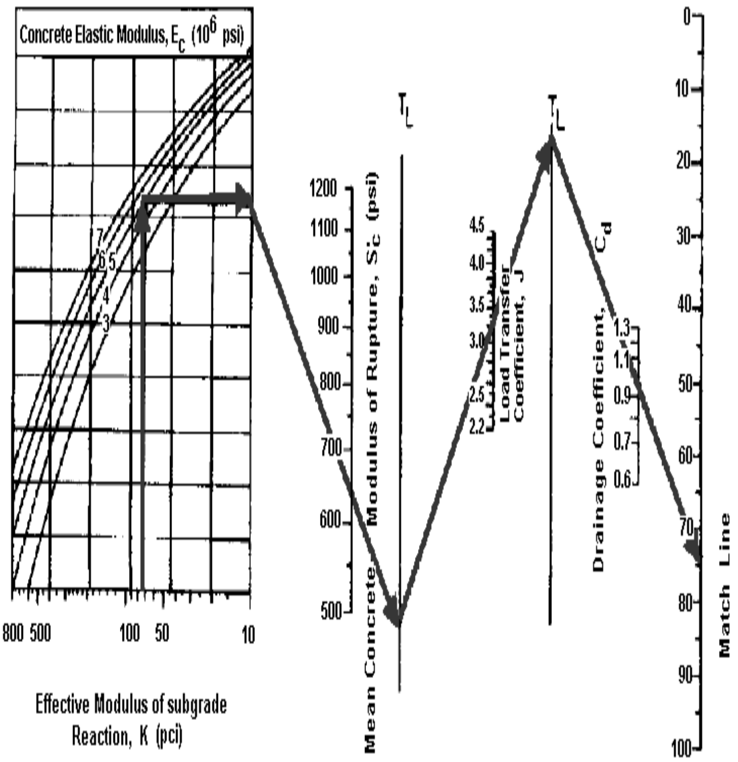

Fig. 1. Section 1 of the design of rigid pavement based on choosing expected values for each input of variables [27]

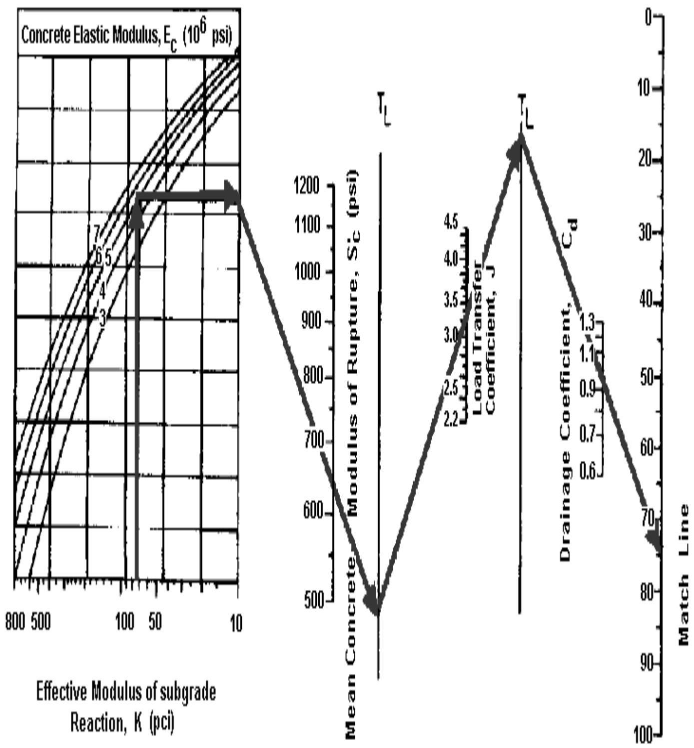

Fig. 2. section 2 of the design of rigid pavement based on choosing expected values for each input of variables [27]

i. W18: (correspondence factor refers to the number of passages of each axle load needed to cause the same stress as one passage of a (standard axle) of 8160 Kg = 18 Kip.

ii. ZR: It is referring to the probability that serviceability will be kept at sufficient levels from a user's point of view throughout the design life of the facility.
iii. S0: factor of safety to fade away the error in the equation that occurred resulting from a change in material types and construction way and to cover the estimation future value, it values between 0.3 to 0.4
iv. TSI: It is the value at which the pavement can't achieve the service level that is needed.
v. Δ PSI: it is the algebraic different between the initial PSI and the TSI during the design period of the pavement.
vi. Sc: It is the value of the tensile strength of concrete, and it is the result of the bending test (third points of loading test) for a beam. This value is between 500 to 1200 psi (3.45 to 8.27 MPa).
vii. Cd: coefficient refers to the water flow in the subgrade, 1.0 refer to material with high drainage features like sand and other material that are less drainage this value can take less than 1.
viii. J: it is referred to the facility of the pavement to transfer load between slabs during slab joints.
ix. Pavements with dowel bars take a J value equal to 3.2.
x. Ec: Young's modulus, usually the range of values of Ec for Portland cement concrete is 3-7 million-psi (20.7 and 48.3 GPa).
xi. K: It depends on many different factors, these factors contain density of soil and moisture content, usually the values for K are between 100 to 800 Psi (27.1 and 216.5) N/cm3. Table 1 provides the relationship between CBR and K values.

Table 1
K, the relationship between modulus of subgrade reaction and California bearing ratio (CBR) [27]

CBR Value	K value, psi
2	100
10	200
20	250
25	290
40	420
50	500
75	680
100	800

2.5 The Route used in Egyptian Code

The procedure of designing PCA rigid pavement used in Egyptian code considers all typing of failure modes erosion failure and fatigue failure [27,28]. Subgrade and subbase modulus of reaction and base types are the parameters used to determine slab thickness. Due to the repetition of stresses the first type of cracking appeared this crack caused fatigue of concrete which is related to pavement failures. The concept of this method considers that 6% of wheel loads passed near the edge of the slab, according to this certain loading tensile stress happened in this part of the slab [26]. The fatigue procedure calculated the load repetitions from stress ratio and axle types using Figure 3. Tensile stress that occurred in the slab was determined according to (K) of subgrade, subbase, and trials of slab thickness.

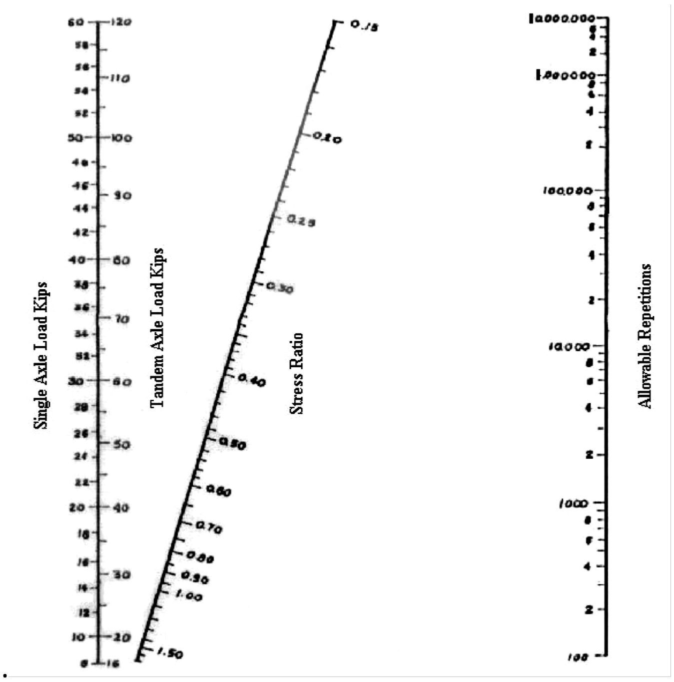

Fig. 3. Fatigue Analysis [21,27]

Table 2 represent the value of (k) according to the type of axle and trials of slab thickness.

Table 2
Corresponding Stress according to the type of axle (Single Axle Load / Tandem Axle Load) [22,28]

Slab thickness	K of subgrade- subbase, pci						
in.	50	100	150	200	300	500	700
4	825/679	726/585	671/542	634/516	584/486	523/457	484/443
4.5	699/585	616/500	571/450	540/435	498/405	448/378	417/363
5	602/516	531/436	493/399	467/376	432/349	390/321	363/307
5.5	526/451	464/387	431/353	409/331	379/305	343/278	320/284
	465/416	411/348	382/316	362/296	336/271	304/246	285/232
6.5	417/380	367/317	341/286	300/244	300/244	270/220	256/207
7	375/349	331/290	307/262	292/244	271/222	246/199	231/188
7.5	340/323	300/268	279/211	265/224	248/203	224/181	210/169
8	311/300	274/249	255/223	242/208	225/188	205/167	192/155
8.5	285/281	252/232	234/208	222/193	206/174	188/154	177/143
9	264/261	232/218	216/195	205/181	190/163	174/144	163/133
9.5	245/218	215/205	200/183	190/170	175/153	161/134	151/124
10	228/235	200/193	186/113	177/160	164/144	150/126	141/117
10.5	213/222	187/183	174/164	165/151	153/136	140/119	132/110
11	200/211	175/174	165/155	154/143	144/129	131/113	123/104
11.5	188/201	165/165	153/148	145/136	135/122	123/107	116/98
12	177/192	155/158	144/141	137/130	127/116	116/102	109/93
12.5	168/183	147/151	136/135	129/124	120/111	109/97	103/89
13	159/116	139/144	129/129	122/119	113/106	103/90	97/85
13.5	152/168	132/136	122/123	116/114	107/102	98/89	92/81
14	144/162	125/133	116/118	110/109	102/98	98/85	88/78

Erosion failure procedure avoids erosion of subgrade soil and base layer. This procedure computes the erosion constant for all types of axles (single and tandem) related to K of subgrade and sub-base layer and assuming thickness Table 3.

Table 3
Erosion constant according to the type of axle and K of subgrade and sub-base [21,27]

Slab thickness in.	K of subgrade- subbase, pci					
	50	100	200	300	500	700
4	3.94/4.03	3.91/3.95	3.88/3.89	3.86/3.86	3.82/3.83	3.77/3.8
4.5	3.79/3.91	3.76/3.82	3.73/3.75	3.71/3.72	3.68/3.68	3.64/3.65
5	3.66/3.81	3.63/3.72	3.60/3.64	3.58/3.6	3.55/3.55	3.52/3.52
5.5	3.54/3.72	3.51/3.62	3.48/3.53	3.46/3.49	3.43/3.44	3.41/3.4
6	3.44/3.64	3.4/3.53	3.37/3.44	3.35/3.40	3.32/3.34	3.30/3.30
6.5	3.34/3.56	3.30/3.46	3.26/3.336	3.25/3.31	3.22/3.25	3.20/3.21
7	3.25/3.49	3.21/3.39	3.17/3.29	3.15/3.24	3.13/3.17	3.11/3.13
7.5	3.18/3.43	3.13/3.32	3.09/3.22	3.07/3.17	3.04/3.10	3.02/3.06
8	3.11/3.37	3.05/3.26	3.01/3.16	2.99/3.10	2.95/3.03	2.94/2.99
8.5	3.04/3.32	2.98/3.21	2.93/3.10	2.91/3.04	2.88/2.97	2.87/2.93
9	2.98/3.27	2.91/3.16	2.85/3.05	2.84/2.99	2.81/2.92	2.79/2.87
9.5	2.92/3.22	2.95/3.11	2.80/3.00	2.77/2.94	2.75/2.86	2.73/2.81
10	2.86/3.18	2.79/3.05	2.74/2.95	2.71/2.89	2.68/2.81	2.66/2.76
10.5	2.81/3.14	2.14/3.02	2.68/2.91	2.65/2.84	2.62/2.78	2.60/2.72
11	2.77/3.10	2.69/2.98	2.63/2.86	2.60/2.80	2.57/2.72	2.54/2.67
11.5	2.72/3.05	2.64/2.94	2.58/2.82	2.55/2.75	2.51/2.68	2.49/2.63
12	2.68/3.03	2.60/2.90	2.53/2.78	2.50/2.72	2.46/2.54	2.34/2.51
12.5	2.64/2.99	2.55/2.87	2.48/2.75	2.45/2.68	2.41/2.60	2.30/2.48
13	2.60/2.96	2.51/2.83	2.44/2.71	2.40/2.65	2.36/2.56	2.34/2.51
13.5	2.56/2.93	2.47/2.80	2.40/2.68	2.36/2.61	2.32/2.53	2.30/2.48
14	2.53/2.90	2.44/2.77	2.36/2.65	2.32/2.58	2.28/2.50	2.25/2.44

According to this value of erosion constant, the allowable load repetitions are defined using Figure 4.

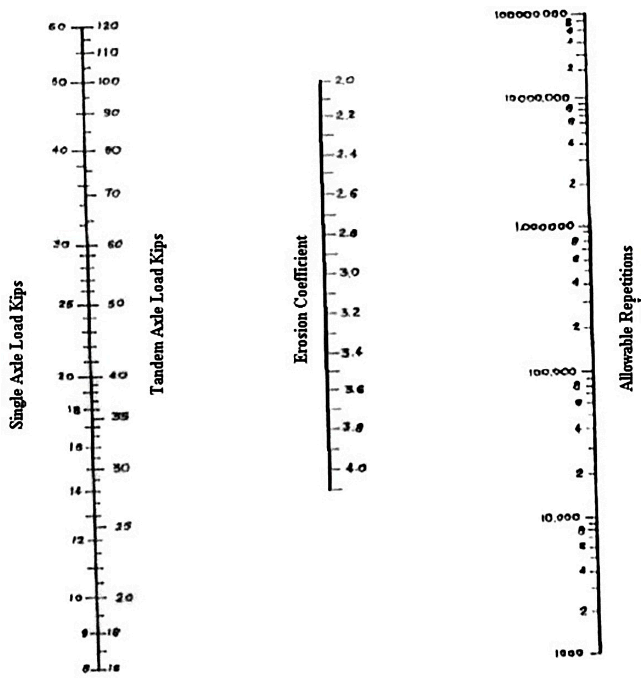

Fig. 4. Erosion Analysis [21,27]

3. Conclusion

i. TKUPAV program reduces the time taken to achieve optimum thickness because it is dependent on a software program which makes it faster to get the thickness. But this procedure is not satisfactory for heavy traffic (average daily traffic larger than 1000 v/day) because it doesn't consider erosion failure. but a variation in temperature during the day was taken into consideration during the design of the slab thickness.
ii. Egyptian code and modified (PCA) routes are satisfied enough to be used this procedure considers erosion failure after fatigue failure which makes them more accurate than other methods.
iii. Despite Modified PCA and Egyptian code criteria take a variation in temperature during the day into consideration during the design of the slab thickness but Modified PCA preferred over Egyptian code criteria, because it is depended on computer software which save time and make it easier to use, in the other hand Egyptian code depended on curves and table (manual solution) which need several trials to run it will be related to spending a lot of time.
iv. Also, PCA method is the most widely known method, this method is the most safety and most accurate procedure to design slab thickness due to maximum allowable load repetitions being determined according to the level of loads which gave an accurate result for each level. The defects of this method are it takes a lot of time to achieve final thickness due to several trials that should be checked to achieve optimum thickness (manual solution). Also, a variation in temperature during the day doesn't take into consideration during the design of the thickness of the slab.
v. AASHTO procedure is based on past performance and several engineering studies, so this technique has less accuracy than other techniques also it doesn't study the effect of variation on temperature during the day. The most advantage of this design criteria that the thickness of the slab is dependent on the level of serviceability was recommended.

Acknowledgement
This research was not funded by any grant.

References

[1] Eipe, Priya Grace Itti, M. Nazeer, and Reebu Zachariah Koshy. "Experimental and Numerical Studies on the Effect of Built-In Gradient on Rigid Pavements." In *Recent Advances in Materials, Mechanics and Structures: Select Proceedings of ICMMS 2022*, pp. 529-542. Singapore: Springer Nature Singapore, 2022. https://doi.org/10.1007/978-981-19-3371-4_45
[2] Chau, Anh D., Hiep T. Hoang, Long D. Nguyen, and Long Le-Hoai. "Construction of Rigid Pavement in Emerging Economies: Challenges and Opportunities." In *Canadian Society of Civil Engineering Annual Conference*, pp. 461-473. Singapore: Springer Nature Singapore, 2021. https://doi.org/10.1007/978-981-19-0968-9_37
[3] Deshmukh, Ashlesha, Ahsan Rabbani, and N. K. Dhapekar. "Study of rigid pavements—review." *International Journal of Civil Engineering and Technology* 8, no. 6 (2017): 147-152.
[4] Portland Cement Association. "The design for concrete highway and street pavements." *PCA, Skokie, Illinois* (1984).
[5] TRANSPORTATION, OF. "Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects."
[6] Ioannides, Anastasios M., and Ricardo A. Salsilli-Murua. "Temperature curling in rigid pavements: an application of dimensional analysis." *Transportation Research Record* 1227 (1989): 1-11.
[7] Krishna, K. Vamshi, and J. Venkateswara Rao. "Experimental study on behavior of fiber reinforced concrete for rigid pavements." *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE)* 11, no. 4 (2014): 49-53. https://doi.org/10.9790/1684-11474953
[8] Gill, Sanjeev, and D. K. Maharaj. "COMPARATIVE STUDY OF DESIGN CHARTS FOR RIGID PAVEMENT."

[9] Ab Latif, Amminudin, Ramadhansyah Putrajaya, and Doh Shu Ing. "A Review of Porous Concrete Pavement: Compressive Strength and Clogging Investigation." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 29, no. 3 (2023): 128-138. https://doi.org/10.37934/araset.29.3.128138
[10] Khope, Rishikesh A., and Milind V. Mohod. "A review paper on recycled materials in concrete pavement." *Int J Res Eng Sci Technol* 1, no. 8 (2015): 186-94.
[11] Moreno-Juez, Jaime, Iñigo J. Vegas, M. Frías Rojas, R. Vigil de la Villa, and E. Guede-Vázquez. "Laboratory-scale study and semi-industrial validation of viability of inorganic CDW fine fractions as SCMs in blended cements." *Construction and Building Materials* 271 (2021): 121823. https://doi.org/10.1016/j.conbuildmat.2020.121823
[12] Mohammadinia, Alireza, Arul Arulrajah, Suksun Horpibulsuk, and Piltan Tabatabaie Shourijeh. "Impact of potassium cations on the light chemical stabilization of construction and demolition wastes." *Construction and Building Materials* 203 (2019): 69-74. https://doi.org/10.1016/j.conbuildmat.2019.01.083
[13] Arulrajah, Arul, Mahdi M. Disfani, Suksun Horpibulsuk, Cherdsak Suksiripattanapong, and Nutthachai Prongmanee. "Physical properties and shear strength responses of recycled construction and demolition materials in unbound pavement base/subbase applications." *Construction and Building Materials* 58 (2014): 245-257. https://doi.org/10.1016/j.conbuildmat.2014.02.025
[14] Mohammadinia, Alireza, Arul Arulrajah, Mahdi M. Disfani, and Stephen Darmawan. "Small-strain behavior of cement-stabilized recycled concrete aggregate in pavement base layers." *Journal of Materials in Civil Engineering* 31, no. 5 (2019): 04019044. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002671
[15] Saberian, Mohammad, Jie Li, Salpadoru Tholkamudalige Anupiya M. Perera, Gang Ren, Rajeev Roychand, and Hamayon Tokhi. "An experimental study on the shear behaviour of recycled concrete aggregate incorporating recycled tyre waste." *Construction and Building Materials* 264 (2020): 120266. https://doi.org/10.1016/j.conbuildmat.2020.120266
[16] Deng, Yongfeng, Chenchen Xu, Fisonga Marsheal, Xueyu Geng, Yonggui Chen, and Honglei Sun. "Constituent effect on mechanical performance of crushed demolished construction waste/silt mixture." *Construction and Building Materials* 294 (2021): 123567. https://doi.org/10.1016/j.conbuildmat.2021.123567
[17] Bessa Ferreira, Fernanda, Paulo Pereira, Castorina Silva Vieira, and Maria Lurdes Lopes. "Long-term tensile behavior of a high-strength geotextile after exposure to recycled construction and demolition materials." *Journal of Materials in Civil Engineering* 34, no. 5 (2022): 04022046. https://doi.org/10.1061/(ASCE)MT.1943-5533.0004166
[18] Al-Obaydi, Moataz A., Mohammed D. Abdulnafaa, Orhan A. Atasoy, and Ali Firat Cabalar. "Improvement in field CBR values of subgrade soil using construction-demolition materials." *Transportation Infrastructure Geotechnology* 9, no. 2 (2022): 185-205. https://doi.org/10.1007/s40515-021-00170-x
[19] Cardoso, Rafaela, Rui Vasco Silva, Jorge de Brito, and Ravindra Dhir. "Use of recycled aggregates from construction and demolition waste in geotechnical applications: A literature review." *Waste management* 49 (2016): 131-145. https://doi.org/10.1016/j.wasman.2015.12.021
[20] El-Garhy, Basuony, Saad El-Hamrawy, and Talaat Abdel-Wahed. "3D Finite Element Analysis Of Rigid Airport Pavement-Parametric Study."
[21] Tayabji, Shiraz D., and Bert E. Colley. "Analysis of jointed concrete pavements." (1986).
[22] Lee, Ying-Haur, Jean-Hwa Bair, Chao-Tsung Lee, Shao-Tang Yen, and Ying-Ming Lee. "Modified Portland cement association stress analysis and thickness design procedures." *Transportation research record* 1568, no. 1 (1997): 77-88. https://doi.org/10.3141/1568-10
[23] Lee, Ying-Haur, and Michael I. Darter. "Loading and curling stress models for concrete pavement design." *Transportation Research Record* (1994): 101-101.
[24] Lee, Ying-Haur, and Michael I. Darter. "Loading and curling stress models for concrete pavement design." *Transportation Research Record* (1994): 101-101.
[25] Lee, Ying-Haur, Shao-Tang Yen, Chao-Tsung Lee, Jean-Hwa Bair, and Ying-Ming Lee. "Development of new stress analysis and thickness design procedures for jointed concrete pavements." In *Proceedings of the 6th International Conference of Concrete Pavements, Purdue University, West Lafayette, IN, USA*, pp. 18-21. 1997.
[26] Lee, Ying-Haur. "TKUPAV: stress analysis and thickness design program for rigid pavements." *Journal of Transportation Engineering* 125, no. 4 (1999): 338-346. https://doi.org/10.1061/(ASCE)0733-947X(1999)125:4(338)
[27] Mannering, Fred L., and Scott S. Washburn. *Principles of highway engineering and traffic analysis*. John Wiley & Sons, 2020.
[28] Attia, Shady, and Omar Wanas. "The Database of Egyptian Building Envelopes (DEBE): A database for building energy simulations." In *SimBuild 2012*. 2012.