Evaluation of Airport Flexible Pavement HMA Fatigue Using FAARFIELD

Mohamed Ibrahim El-Sharkawi Attia

ABSTRACT- "Federal Aviation Administration Rigid & Flexible Iterative Layered Elastic Design (FAARFIELD)" software is considered one of the most effective software for airport pavement design. FAARFIELD considers the cumulative damage factor (CDF) in the subgrade for the design of airport pavement layers. Though the software can calculate the damage within hot mix asphalt (HMA) layer, limited work was conducted to evaluate impact of aircraft types and pavement design on the fatigue within HMA layer. This paper investigates the impact of different aircraft models on pavement thickness design, subgrade CDF and HMA CDF for different classes of subgrade. The paper identifies the cases where the design will be controlled by the subgrade damage and the cases where the design will be controlled by HMA damage.
It was found that the A350-900 had the most severe impact on HMA CDF, followed by B777-300, A380, B747-400 then A350-1000. The HMA CDF for the air craft mix is much lower than the HMA CDF of the individual heavy aircrafts. For weak subgrade, the design was controlled by the subgrade damage while for strong subgrade the design was controlled by HMA damage. For CBR of 3 and 6, the total pavement thickness will be generally high to protect the subgrade and prevent HMA CDF for mixed air traffic. For stronger subgrade (CBR of 10 and 15), the HMA CDF was more than one for all cases of loading when the design was based only on subgrade CDF. Increasing base layer thickness, resulted in reducing HMA CDF for all aircraft models. The traffic mix needed the lowest increase in base thickness to assure safe design against HMA fatigue. A350-900 needed the highest increase in base layer thickness for subgrade with CBR of 10 while A350-1000 needed the highest increase in base layer thickness for subgrade CBR of 15.

Keywords: Airport Pavement, Pavement Fatigue, FAARFIELD, Cumulative Damage Factor, HMA CDF, Sensitivity Analysis

1 INTRODUCTION

"Federal Aviation Administration Rigid & Flexible Iterative Elastic Layer Design (FAARFIELD)" software was developed by Federal Aviation Administration (FAA) and it is considered one of the most effective software for airport pavement design [1].

In FAARFIELD, the design process for flexible pavement considers two modes of failure: vertical strain in the subgrade and horizontal strain in the asphalt layer made of hot mix asphalt (HMA).

Limiting subgrade vertical strain is intended to prevent subgrade rutting. Limiting the horizontal strain at the bottom of the asphalt layer guards against pavement failure initiated by cracking of the asphalt surface layer [1]. By default, FAARFIELD computes only the vertical subgrade strain for flexible pavement thickness design. However, the user has the option of enabling the asphalt strain. Advisory Circular (AC) 5320 6F states that "In most cases the thickness design is governed by the subgrade strain criterion however it is good engineering practice to perform the asphalt strain check for the final design."[1]

One of the outputs from FAARFIELD is the damage factor for each aircraft in the traffic mix along with the Cumulative Damage Factor (CDF) for the overall pavement structure. However, this CDF is based only on subgrade CDF. CDF is the amount of the structural life of a pavement that has been used up. CDF is the ratio of applied load repetitions to allowable load repetitions to failure [1-3]. When CDF = 1, Pavement used up all of its life. When CDF < 1,Pavement have some life remaining, and the value of CDF will give the fraction of the life used. When CDF > 1, all of the life has been used up and the pavement will fail before its target design life. Recent research evaluated the impact of different aircraft models on Subgrade CDF, for subgrade of CBR of 10 only [2].

Some researchers reported that fatigue life is not a major concern for airports compared to roads, because of the limited number of load repetition [4]. However, it was reported that fatigue cracking was one of the problems encountered and caused the need to rehabilitate Beijing Capital Airport (BCA) in China [5].

Limited work was conducted to evaluate the impact of different aircraft models on subgrade CDF and HMA CDF for different classes of subgrade. Limited work was conducted to understand the impact of aircraft model on the final design based on HMA CDF compared to the design based on subgrade CDF.

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2 RESEARCH OBJECTIVES

The aim of this paper is to develop in depth understanding of airport flexible pavement design using FAARFIELD, with emphasis on the fatigue life of the hot mix asphalt. The paper investigates the impact of aircraft models on subgrade CDF and HMA CDF for different classes of subgrade. The paper evaluates the sensitivity of HMA CDF to pavement thickness. The paper identifies the cases where the design will be controlled by the subgrade damage and the cases where the design will be controlled by HMA damage and the options for enhancing the design.

3 METHODOLOGY

The study focused on evaluating the subgrade CDF and HMA CDF under different cases of subgrade quality, aircraft models and aircraft traffic mix. For each case of subgrade and traffic loading, the pavement was designed based on subgrade CDF, the base layer thickness was compared for different cases of loading and subgrade and then HMA CDF was checked. In case of HMA CDF failures (HMA CDF >1), the design was altered by varying the thickness of the base layer tell reaching safe thickness for fatigue in HMA.

3.1 Subgrade classes

The research evaluated 4 levels of subgrade quality; mainly CBR of 3, 6, 10 and 15. This correspond to the four subgrade strength categories of A, B, C and D used in ICAO and AC No: 150/5335-5C to classify the strength of the subgrade [6]. In this classification CBR of 15 presents high strength subgrade, CBR of 10 presents medium strength subgrade, CBR of 6 presents low strength subgrade and CBR of 3 presents ultra-low strength subgrade [6].

3.2 Air traffic mix:

The study evaluated the impact of different aircrafts on pavement design using both single aircraft and aircraft mix. The benefit of studying single aircraft is that it gives opportunity to understand the pavement behavior under different aircraft loading conditions. The benefit of studying the aircraft mix is that it simulates the actual situation in most airports, where several models of aircrafts are using the airport. The FAARFIELD produces the HMA CDF for the overall mix, while it produces the relative subgrade damage for each aircraft in the traffic mix and the overall subgrade CDF. Evaluating each aircraft model individually enabled understanding the relative effect of each aircraft model on HMA Fatigue.

Table 1 presents the characteristics and weights of the evaluated air crafts. Figure 1 present the wheel configuration of the main aircrafts evaluated in the study. 10 different cases of loading were evaluated. The evaluated loading cases used during the study are presented in Table 2. All cases were evaluated for 100,000 annual departures and design life of 20 years.

Table 1 Characteristics of the evaluated aircrafts

Aircraft	Gross Taxi weight, 1000 lb	Tire pressure, psi	Percent weight on main gear (number of wheels)	Wheel load, 1000 lb
A380-800	1,238	218	38% (8 wheels)	58.8
A380-800-belly		218	57% (12 wheels)	58.8
A320-bogie	162.9	177	85% (4 wheels)	38.7
A321-200	197.1	212	95% (4 wheels)	46.8
A330-200 Std	509.1	206	95% (8 wheels)	60.4
A350-900	601.1	241	95% (8 wheels)	71.4
A350-1000	681.0	220	95% (12 wheels)	53.9
B737-800	174.4	204	95% (4 wheels)	41.4
B777-300-ER	777.0	221	95% (12 wheels)	61.5
B747-400-ER	913.0	230	95% (16 wheels)	54.2

A350-900 was compared with B777 as both are market competitors [7]. The A350-1000 is Airbus largest Wide Body aircraft in the twin-aisle category. The A350-900 is smaller than the A350-1000 in dimension. A350-1000 has 12 wheels on the main gear compared to 8 wheels on the A350-900 model [8].

A380 was selected for the study because it is the world's largest passenger aircraft [9]. B737 and A320, B747, B777 and A330 were chosen as they present the top five seller aircrafts in the world [10].

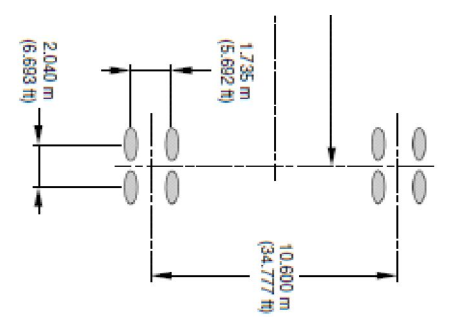
A340-500/600 was reported to cause the most damaging impact on the subgrade. However, it was not considered in the study because Airbus announced terminating the production of the A340 in 2011 [11]. A320 had the lowest wheel load, and A350 900 had the highest wheel load, as presented in Table 1.

3.3 Pavement thickness

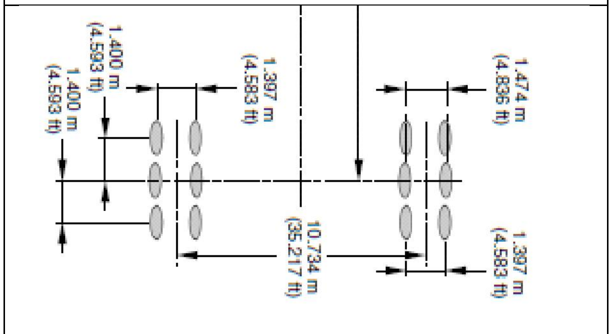
The starting level for the thickness is the minimum structure standard thickness assuming 4 in HMA as wearing course + 5 in HMA (P-401) as stabilized base course + 6 in high quality granular base (P-209) as shown in Figure 2. The final thickness for the base layer was defined for each case of analysis (Aircraft mix, number of load repetition and subgrade CBR).

Table 2 List of Evaluated Cases

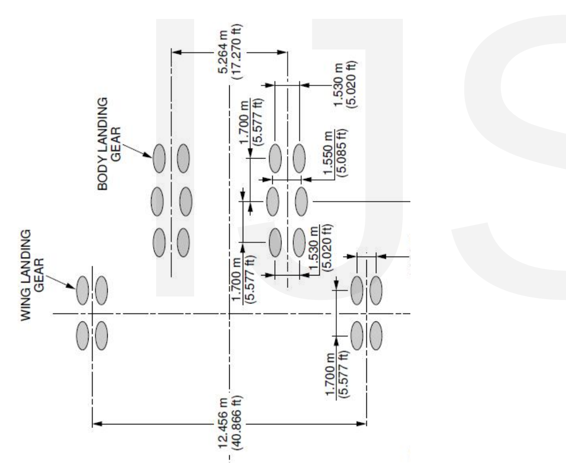
Case	Aircraft Model/s	Notes
1	A380	One single aircraft, presents 100% of the stream
2	A320	
3	A321-200	
4	100% A330-200	
5	A 350-900	
6	A 350-100	
7	B 737-800	
8	B 777-300	
9	B 747-400	
10	Aircraft mix, each of the evaluated models present 11.1%	Traffic mix



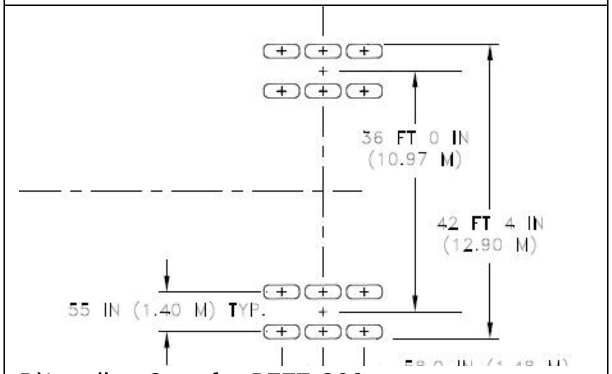
A)landing gear of A350-900



b)Landing Gear of A350-1000



C)Landing gear for A380



D)Landing Gear for B777-300

Fig. 1: Landing gear configuration for main evaluated aircrafts

3.4 Design Software

FAARFIELD 1.42.003 was used in the analysis. FAARFIELD was released September 30, 2009. Current version is FAARFIELD 1.42 as of September 2018. Advisory Circular (AC) 5320 6F states that "A fixed modulus value for hot mix surfacing is set in the program at 200,000 psi" which is the value used in the analysis. The modulus of the binder asphalt course (stabilized base course) is fixed by the software to 400,000 psi [1]. Starting thickness is the minimum thickness of the layers as defined in AC 5320 6F (4 in for HMA surface layer and 5 in for HMA stabilized base course) [1]. Fig. 2 shows the pavement structure that was used initially for the Design.

FAARFIELD software alters only the thickness of one layer during flexible pavement design, and use the same thickness for the top layer (wearing and binder asphalt layers).

P 401/403 HMA Asphalt Surface (Modulus 200,000 Psi, Fixed value defined by FAARFIELD)
P 401/403 Str. Flex (Modulus 400,000 Psi, Fixed value defined by FAARFIELD)
Base course (P-209 crushed aggregate base), Modulus calculated by FAAFIELD for each run
Subgrade CBR (Variable : 3, 6 10 and 15)

Fig 2: Pavement Structure used during the Design

3.5 Steps of the Analysis

The steps of the analysis are:

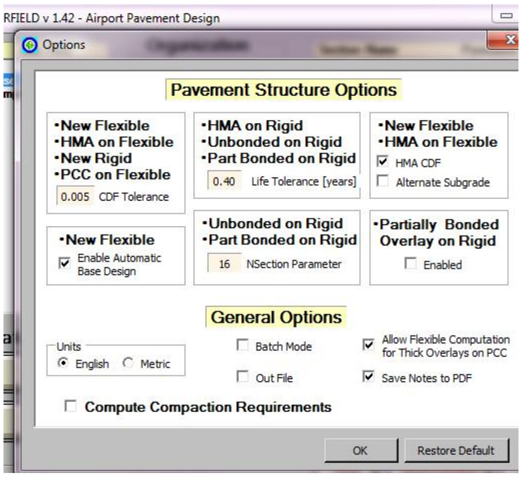
A. Initial pavement structure is defined for software, along with the loading aircrafts.

B. For all runs, HMA CDF was calculated and automatic base design option is enabled, as shown in Fig. 3. The arrow beside the base layer, reflect that this is the layer that will be altered during the design, and the other layers will stay as initially included in the design.

C. If the HMA CDF is less than 1, this reflects safe design, then the design is completed.

D. If the HMA CDF is more than one, this means that the design is safe for subgrade, however it is unsafe for HMA fatigue. Fig. 4 shows one run, where the design thickness is safe to protect the subgrade, however the HMA CDF is 3.39, reflecting failure in HMA fatigue.
In such case,
- The software is used in design life mode
- At each subgrade strength level, thickness of base layer was altered and HMA CDF was calculated, and compared for different air craft models, tell HMA CDF is less than 1.
- Impact of base layer thickness on HMA CDF was calculated for several options:

E. Comparison between different loading conditions for their impact on base layer thickness, HMA CDF, and final design thickness was conducted.



RFIELD v 1.42 - Airport Pavement Design

Options

Pavement Structure Options

- New Flexible
- HMA on Flexible
- New Rigid
- PCC on Flexible

0.005 CDF Tolerance

- HMA on Rigid
- Unbonded on Rigid
- Part Bonded on Rigid

0.40 Life Tolerance [years]

- New Flexible
- HMA on Flexible

☑ HMA CDF
☐ Alternate Subgrade

- New Flexible

☑ Enable Automatic Base Design

- Unbonded on Rigid
- Part Bonded on Rigid

16 NSection Parameter

- Partially Bonded Overlay on Rigid

☐ Enabled

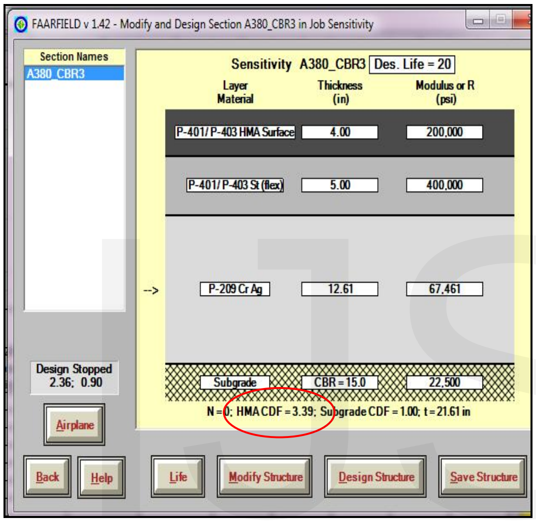
General Options

Units
● English ○ Metric

☐ Batch Mode
☐ Out File
☑ Allow Flexible Computation for Thick Overlays on PCC
☑ Save Notes to PDF

☐ Compute Compaction Requirements

Fig. 3 Pavement Structure options used during the analysis



FAARFIELD v 1.42 - Modify and Design Section A380_CBR3 in Job Sensitivity

Section Names
A380_CBR3

Sensitivity A380_CBR3 Des. Life = 20

Layer Material	Thickness (in)	Modulus or R (psi)
P-401/ P-403 HMA Surface	4.00	200,000
P-401/ P-403 St (flex)	5.00	400,000
P-209 Cr Ag	12.61	67,461
Subgrade	CBR = 15.0	22,500

N = 0; HMA CDF = 3.39; Subgrade CDF = 1.00; t = 21.61 in

Design Stopped
2.36; 0.90

Fig. 4 Sample of designed section, showing the design layer and HMA CDF more than 1

4 RESULTS and ANALYSIS

4.1 Sensitivity of Base Layer Thickness to Aircraft Mix based on Subgrade CDF

Fig. 5 shows the base layer thickness, based on the design from FAARFIELD. This design takes into consideration only the subgrade CDF. Increasing the CBR from 3 to 15 resulted in reducing the base layer thickness by about 75% for different loading conditions. A380 and B747-800 needed exactly same thickness for subgrade CBR of 6, 10 and 15. At ultra-low strength subgrade (CBR =3), A380 needed slightly more thickness (10 % increase) in base layer compared to the B747-800.

B777-300 resulted in the highest thickness of the base layer for case of CBR of 3, 6 and 10. A350-900 resulted in the highest pavement thickness in case of CBR of 15. A320 required the smallest pavement thickness for all CBR values. Using a traffic mix consisting of 11% of each aircraft did not result in significant reduction in the thickness for case of strong subgrade. For subgrade of 3, the base layer thickness was 46.8 inch for the traffic mix compared to 54 in in case of using 100% of the traffic of B777-300, about 15% reduction in base layer thickness.

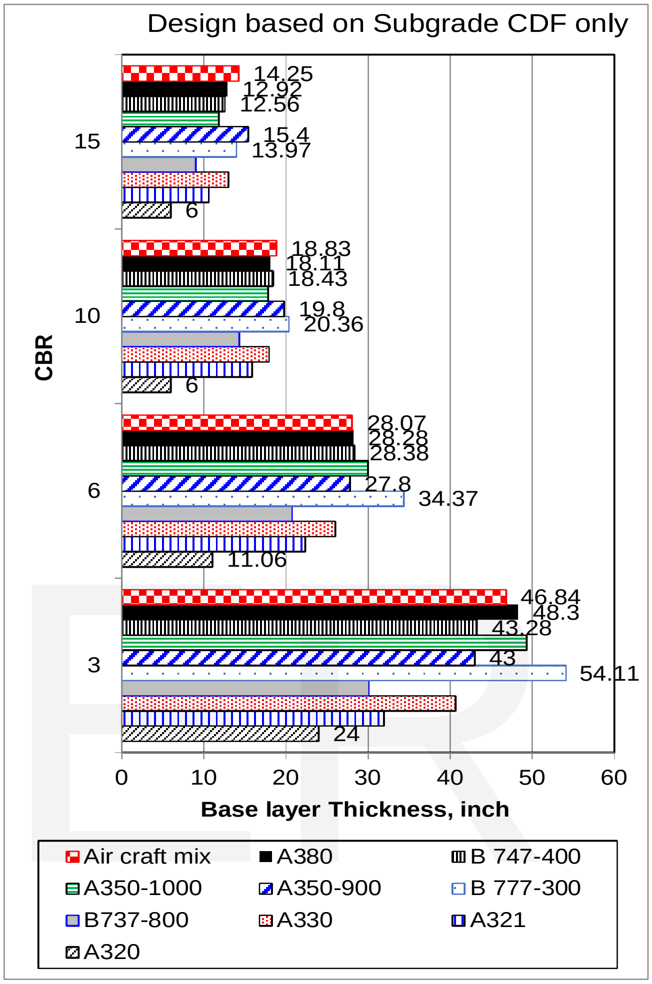
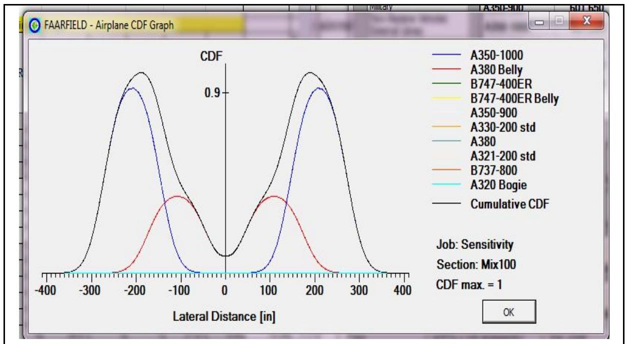


Fig. 5 Effect of aircraft type on base layer thickness

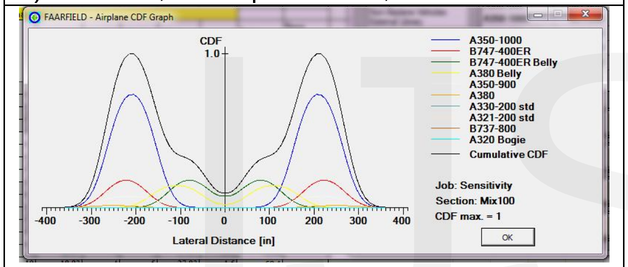
The evaluated aircrafts had different landing gear configuration, as presented in Fig. 1, and wander should distribute the load over wider area. For strong subgrade, the base layer thickness was small and the interaction between the wheels at the subgrade levels resulted in that the air traffic mix needed similar thickness as that used for 100% of the heaviest aircraft.

The relative effect between different aircrafts on subgrade CDF can be examined by investigating the CDF, as presented in Fig. 6 and 7, for the mixed air craft mix. Figure 6-A shows that for weak subgrade (CBR = 3), only 2 aircrafts controlled the CDF and showed impact on the subgrade, namely A350-1000 which contributed 92% of the damage and the A380-belly gear (body landing gear, 12 wheels) which contributed 34% of the damage, without any significant damage contributed from the other aircrafts. It must be noted that the A380 body gear is narrower than the A350-1000 gear. It is also noted that the aircraft that needed the biggest pavement thickness (B777-300) did not show impact on CDF once it is part of aircraft fleet for weak subgrade.

Figure 6-B (for CBR = 6) shows that the major impact on the CDF was contributed by A350-1000, which contributed 73% of the damage factor. The other aircrafts that affected the damage were (B747-400), which contributed 18% of the damage followed by the A380 that contributed 14% followed by A350-900 that contributed 7% of the damage. The different locations of the damage are resulting from the different wheel configurations of aircraft wheels in the different models.



A)Traffic Mix, Load repetition 100,00 and CBR = 3



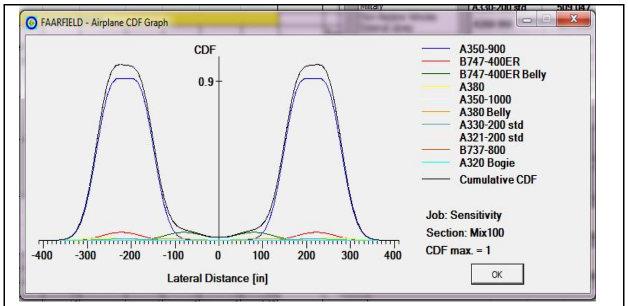
B)Traffic Mix, Load repetition 100,00 and CBR = 6

Fig. 6: Subgrade CDF under traffic mix case of loading for weak subgrade

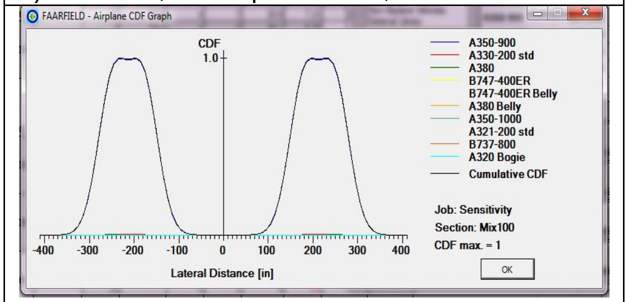
Figure 7-A shows that the major impact on the subgrade CDF was contributed by A350-900, 92% of the damage, followed by B747-400 which contributed 5% in the CDF.

Figure 7-B shows that the major aircraft that contributed to the damage for strong subgrade with CBR of 15 was A350-900, which contributed to almost all the damage (100%) and controlled the design. A350-900 had the highest wheel load, and with thin pavement resulting from the strong subgrade, it had the most damaging impact on the subgrade

In literature, B777 and B747 traffic loading did not differ significantly for their effect on subgrade [12]. However here in this analysis, B747 had more damaging effect on the subgrade compared to B777 and the relative impact between the different aircraft model is dependent on the subgrade strength.



A)Traffic Mix, Load repetition 100,00 and CBR = 10



B)Traffic Mix, Load repetition 100,00 and CBR = 15

Fig. 7: Subgrade CDF under traffic mix case of loading for strong subgrade

4.2 Impact of aircraft type on HMA CDF for sections designed based on subgrade CDF

The HMA CDF for all evaluated aircrafts is presented in Fig.7. These values are based on the design that resulted from FAARFIELD with Subgrade CDF = 1.

For weak subgrade (CBR of 3), HMA CDF was lower than one (1) for all aircraft models and for the mixed air traffic mix. The pavement thickness was enough to protect the subgrade and assure also protection for the HMA layer for all aircraft types.

For subgrade with CBR of 6, the A320 caused the highest HMA damage, with HMA CDF of 2.5. This reflects that based on subgrade CDF, the needed pavement thickness for the A320 was the smallest, but it was not enough to protect against pavement fatigue. It was found also that the design thickness for A321, A330, A350-900 and B737-800 was not enough to protect against fatigue. These air crafts has low weight per wheel compared to the other aircrafts, however, the resulted design thickness based on subgrade CDF was not enough to protect the HMA from fatigue. HMA CDF for heavy aircraft likes A380-800 and B747-400 was lower than 1, which means pavement structure is safe against HMA fatigue. For both CBR of 3 and 6, the mixed air traffic resulted in a thickness which was safe for HMA fatigue.

For stronger subgrade (CBR of 10 and 15), the HMA CDF was more than one for all cases of loading when the design was based only on subgrade. For CBR of 10, the B737 had the highest damaging impact on HMA layer followed by A350-1000. Both aircraft had similar landing gear configuration

The HMA CDF for the air craft mix is much lower than the HMA CDF of the individual heavy aircrafts, which reflect the wide variation of the stresses over wider area due to different aircrafts landing gear configurations.

It was found that the impact of the different aircraft varied based on the subgrade strength. For example, A350-900 had more severe impact on HMA CDF for subgrade of CBR of 6, however A350-1000 had more severe impact on HMA CDF for cases of CBR of 10 and 15.

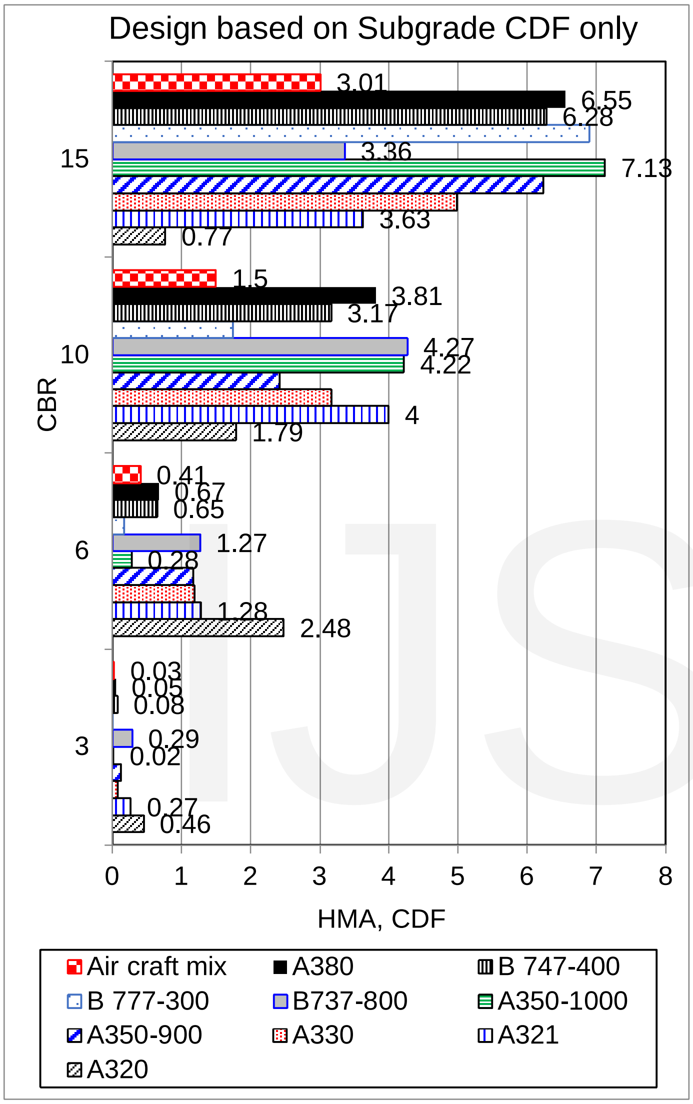


Fig. 8: Impact of different aircraft on HMA CDF, for designed sections

4.3 Impact of aircraft type on HMA CDF for sections of similar thickness

All the HMA CDF results presented so far are for cases where the thickness was designed by the software based on subgrade CDF. This means that the base layer thickness is different for different cases. To improve the understanding about the impact of the different aircraft model on pavement sections with the same thickness, the thickest design for all aircrafts was used and HMA CDF was evaluated. The base layer thickness used was 34.5, 20.5 and 15.5 inches for Subgrade CBR of 6, 10 and 15 respectively. Because HMA CDF was safe for all cases of Subgrade CBR of 3, it was not included in this analysis, as the HMA CDF results for this subgrade were far below one.

The HMA CDF for the cases of similar base layer thickness is presented in Fig. 9. It was found that the A350-900 had the most severe impact on HMA CDF, followed by B777-300, A380, B747-400 then A350-1000. Once the comparison is for the same section, the rank of the aircraft is almost the same for all subgrade strength levels. Also for the same thickness, using a mix of the aircrafts resulted in reducing HMA CDF from 2.04 and 5.95 to 0.82 and 2.4 for subgrade of CBR of 10 and 15 respectively.

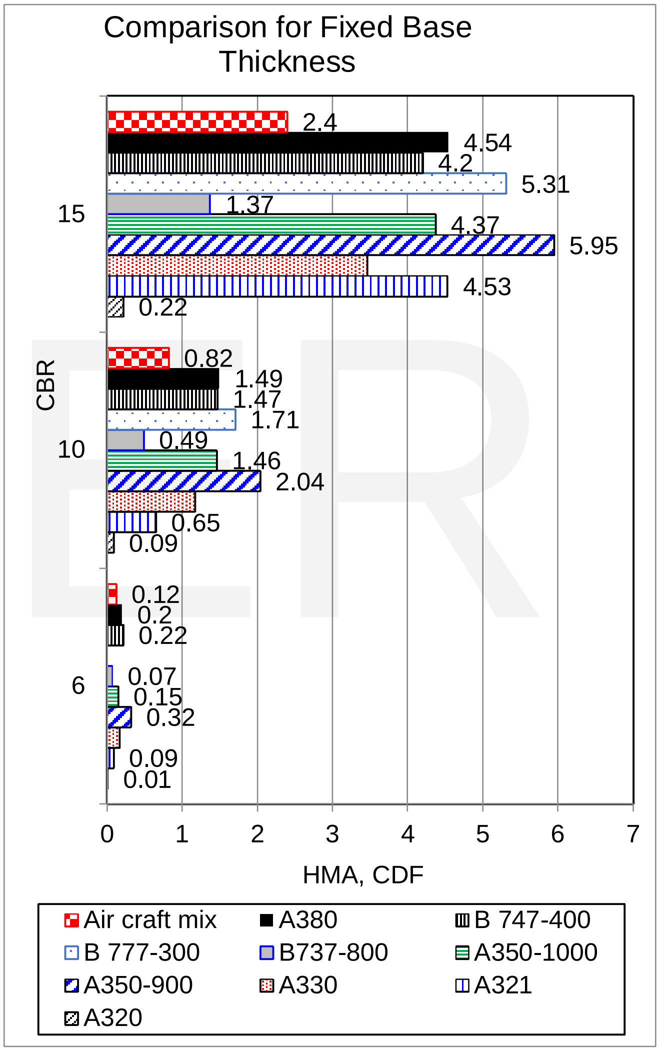


Fig. 9: Impact of different aircraft on HMA CDF, for same base thickness for each subgrade

4.4 Sensitivity of HMA CDF to base layer thickness

Fig. 10, 11 and 12 show the impact of increasing base layer thickness on HMA CDF. The starting point for the analysis (upper most left point in each line) is the design case for each traffic loading, where the design life is 20 years and subgrade CDF is one. The HMA CDF varied from 2.5 to 7.0 initially.

Increasing base layer thickness resulted in reducing the HMA CDF.

For subgrade with CBR of 6, Fig. 10 shows that the design thickness based on subgrade CDF resulted in safe thickness for HMA for A380, A350-100, B747 and the traffic mix. A320 needed a major increase in base thickness from 11 inches to 16 inches. For other aircraft models, the increase in base thickness to assure safe design in both HMA and subgrade was less than 2 inches.

Fig. 11 shows the impact of increasing base layer thickness on HMA CDF for subgrade of CBR of 10. Increasing base layer thickness resulted in reducing HMA CDF for all models. The traffic mix needed the lowest increase in base thickness (only one inch) to assure safe design against HMA fatigue, as the HMA CDF was close to unity. A321 and B737-800 and needed small increase in base layer thickness (3.4 and 4.3 inches) which represent about 25% increase in base layer thickness. A350-900 needed the highest increase in base layer thickness of 6.2 inches (31% increase in base thickness).

Fig. 12 shows the impact of increasing base layer thickness on HMA CDF For subgrade of CBR 15. The traffic mix needed the lowest increase in base thickness (4.2 inches) to assure safe design against HMA fatigue, this present 26% increase in base thickness. A350-1000 needed the highest increase in base layer thickness of 7.6 inches (65% increase in base thickness). A320 resulted in safe thickness. However this was due to the fact that the minimum base layer thickness (6 inches) was more than the needed thickness to assure protecting the subgrade.

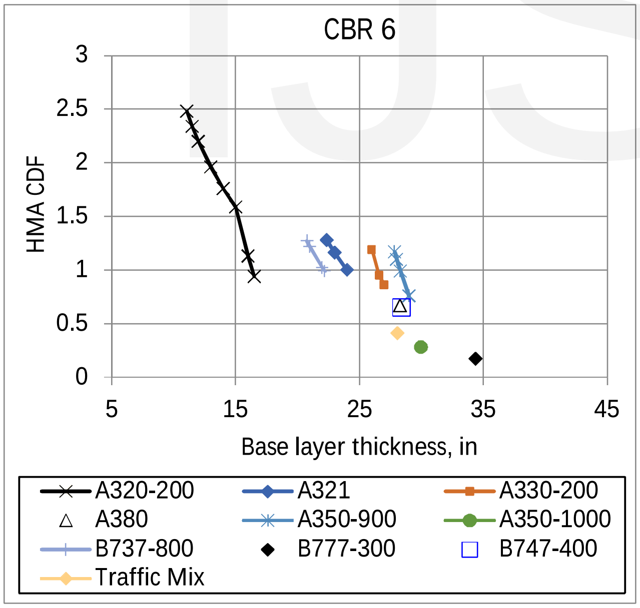


Fig. 10 Impact of changing base layer thickness on HMA CDF, CBR = 6

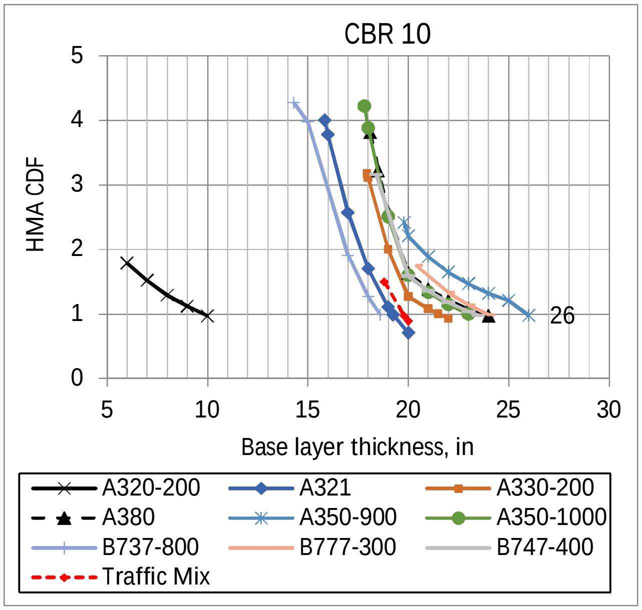


Fig. 11 Impact of changing base layer thickness on HMA CDF, CBR = 10

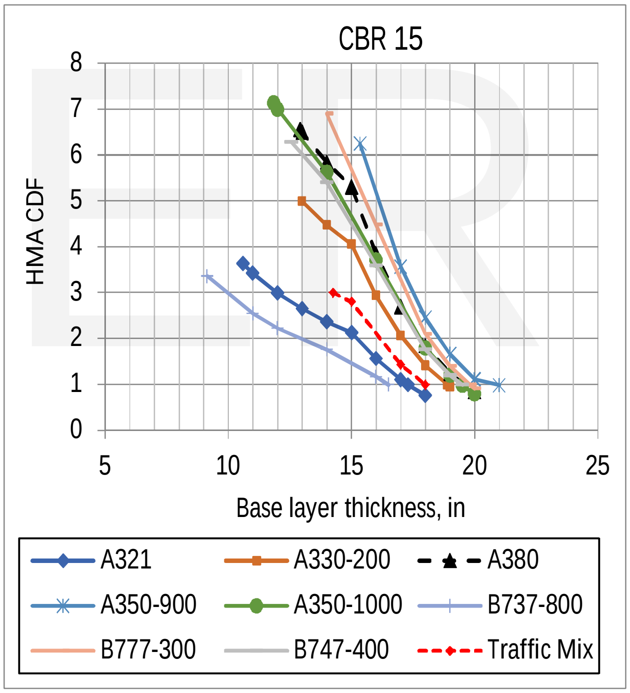


Fig. 12 Impact of changing base layer thickness on HMA CDF, CBR =15

5 CONCLUSIONS

The following points represent the main conclusions of this research:

1. The paper investigated the impact of different aircraft models and one air craft mix on the Subgrade CDF and HMA CDF using FAARFIELD software. The paper further evaluated the impact of base layer thickness on HMA CDF.

2. Studying individual aircraft models, enabled understanding the relative effect of each aircraft model on HMA damage.
3. The FAARFIELD software produces the relative damage for each aircraft in the traffic mix for the subgrade CDF. However, it does not produce such relative damage for the HMA CDF. It is recommended that that FAARFIELD be enhanced to produce relative damage HMA CDF for the overall mix.
4. During the design, the controlling air craft that contributed to most of the subgrade damage was dependent on the subgrade CBR. For weak subgrade, CBR of 3, A350-1000 and the A380 body gear were the most damaging aircrafts. For CBR of 6 the major impact on the subgrade CDF was contributed by A350-1000, which contributed 73% of the damage factor. The other Aircrafts that affected the damage were (B747-400), which contributed 18% of the damage followed by the A380 that contributed 14% followed by A350-900 that contributed 7% of the damage. For subgrade with CBR of 10, the major impact on the subgrade CDF was contributed by A350-900, exactly 92% of the damage, followed by B747-400 which contributed by 5% in the CDF. For strong subgrade with CBR of 15, A350-900 contributed to almost all the damage (100%) and controlled the design. A350-900 had the highest wheel load, and with thin pavement resulting from the strong subgrade, it had the most damaging impact on the subgrade.
5. For weak subgrade (CBR of 3 or 6), the design will be controlled by the subgrade damage while for strong subgrade (CBR of 10 and 15) the design will be controlled by HMA damage.
6. For CBR of 3 and 6, the total pavement thickness will be generally high to protect the subgrade and prevent HMA CDF for a mixed air traffic.
7. The A350-900 had the most severe impact on HMA CDF, followed by B777-300, A380, B747-400 then A350-1000.
8. When using the design feature in FAARFILED software, the design is controlled only by the damage in the subgrade and does not assure safe thickness for hot mix asphalt layers, i.e many cases showed HMA CDF more than 1.0, reflecting possible fatigue during the proposed design life. It is critical to use the design life feature in the FAARFIELD software and check for the HMA CDF to assure that the designed asphalt layer can resist fatigue cracking.
9. The HMA CDF for the air craft mix is much lower than the HMA CDF of the individual heavy aircrafts.
10. To assure safe design against HMA Fatigue, the need to increase pavement thickness beyond the results based on subgrade CDF was dependent of subgrade strength.
11. For stronger subgrade (CBR of 10 and 15), the HMA CDF was more than one for all cases of loading when the design was based only on subgrade CDF.
12. Increasing base layer thickness resulted in reducing HMA CDF for all aircraft models.
13. The traffic mix needed the lowest increase in base thickness (only one and 4.3 inches) to assure safe design against HMA fatigue for case of subgrade CBR of 10 and 15 respectively. A350-900 needed the highest increase in base layer thickness of 6.2 inches (31% increase in base thickness) for case of subgrade of CBR of 10. A350-1000 needed the highest increase in base layer thickness of 7.6 inches (65% increase in base thickness) in case of CBR of 15.
14. Pavement structure with minimum wearing course and stabilized asphalt course thickness (4 inches and 5 inches respectively) was enough for all cases of loading with the heaviest aircrafts, as long as the base layer thickness was increased to protect against HMA and subgrade failures.
15. There is a need for a hot mix asphalt rutting module in the software that evaluates the rutting within HMA layers as it is proven to be a critical problem in airports serving large aircrafts in areas with high summer temperatures.

6 REFERENCES

[1] Advisory Circular (AC) No: 150/5320-6F (2016). Airport Pavement Design and Evaluation. U.S. Department of Transportation, Federal Aviation Administration

[2] G. A. Shafabakhsh, E. Kashi (2015). "Effect of Aircraft Wheel Load and Configuration on Runway Damages". Periodica Polytechnica Civil Engineering, Vol. 59, No.1, pp. 84-95.

[3] R. A. C. Vieira, "Airport Pavement Designs Consideration of New Guidelines. https://fenix.tecnico.ulisboa.pt/downloadFile/1126295043834869/Extended%20Abstract%20-%2062975.pdf. Accessed online November 2018.

[4] S. Emery, "Pavements and Surfacing On WA Airports. Australian Geomechanics Journal, March 2015.

[5] World Highways (2017). Beijing airport runway. July, August2017. http://www.worldhighways.com/categories/asphalt-paving-compaction-testing/features/beijing-airport-runway-features-novel-asphalt-solution/. Accessed online November 2018.

[6] Advisory Circular AC No: 150/5335-5C, Standardized Method of Reporting Airport Pavement Strength – PCN. U.S. Department of Transportation, Federal Aviation Administration.

[7] https://www.businessinsider.com/airbus-a350-vs-boeing-777x-2013-10. Accessed online Nov. 2018.

[8] A350, Aircraft Characteristics. Airport and Maintenance Planning. AIRBUS S.A.S. Issue: Nov 01/16, Rev: Jun 01/18.

[9] https://www.aviationcv.com/aviation-blog/2015/top-largest-passenger-aircraft. Accessed online Nov. 2018/

[10] https://www.safran-group.com/media/top-5-best-sellers-commercial-aviation-history-20180330

[11] https://www.aviationwa.org.au/2011/11/10/airbus-end-production-of-the-a340

[12] Kasthurirangan Gopalakrishnan and Marshall Thompson (2006). Evaluation of Traffic Induced Subgrade Stresses in Flexible Airfield Pavements. Road Materials and Pavement Design. Volume 7, 2006 - Issue 4., Pages 457-476.