**PROJECT ID:**

# "COMPARATIVE ANALYSIS OF EMPIRICAL AND MECHANISTIC -EMPIRICAL DESIGN METHODS FOR AIRPORTS FLEXIBLE PAVEMENT ""

**MASTER OF SCIENCE RESEARCH DISSERTATION**

*Submitted by*

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## DECLARATION

I, …Bonheur DUKUNDANE, with Reg. No 220017068., from University of Rwanda College of Science and Technology, School of Engineering; Department of Civil, Environmental and Geomatics Engineering, following studies of Master of Science in Highway Engineering and Management Program, hereby declare that this work is of my original and has never been submitted for any academic award in any other University or Institution or anyone else where he/she had the same purpose.

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# CERTIFICATION

This research proposal has been submitted with approval from the University supervisor (Main supervisor).

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**“Special Thanks to God”**

# ABSTRACT

Pavement design must ensure sufficient protection of the subgrade by keeping stress levels low enough to avoid excessive deformation. To address the varying demands of different climates and traffic loads, a range of pavement design methods have been developed.

The scientific basis for pavement design began in the 18th century with British engineer John Loudon McAdam, who introduced systematic methods primarily for road construction. However, the invention of the airplane by the Wright brothers in the early 20th century created the need for dedicated airfield pavement design to accommodate the rapidly growing aviation industry.

Empirical methods rely heavily on historical data and require minimal material testing, whereas the mechanistic-empirical approach evaluates the stresses and strains within each pavement layer, providing a more scientific basis for design. This research will focus on assessing both methods in terms of their performance reliability and cost-effectiveness.

In this research, six airfield pavement sections from three major airports in Rwanda—New Bugesera International Airport, the existing Kigali International Airport, and Kamembe Airport—will be evaluated. The analysis will be conducted using both the mechanistic-empirical design approach and the empirical CBR design method, utilizing the United States Army Corps of Engineers' software **PCASE** (Pavement-Transportation Computer Assisted Structural Engineering). For consistency, similar traffic loading conditions and subgrade strength will be applied to each airport. Merits and demerits of each method is highlighted.

Following the initial design computations, the resulting pavement thicknesses will be further assessed using the **FAARFIELD** software (FAA Rigid and Flexible Iterative Elastic Layered Design). This step will involve converting traffic data into equivalent load repetitions to estimate pavement life and compare the design outcomes for each airport.

At Kigali International Airport, the PCASE-CBR method produced a pavement design with a thicker base layer, resulting in a structurally robust pavement expected to last the 20-year design period without structural failure. However, it’s important to note that environmental factors cause deterioration in flexible pavements regardless of layer thickness. Even with a thicker pavement, environmental degradation will still occur.

Specifically, the PCASE-CBR design for Kigali resulted in a 257 mm base and a 102 mm subbase, whereas the PCASE-Layered Elastic Design (LED) yielded a 153 mm base and a 211 mm subbase. Since the upper pavement layers protect the lower ones, this difference leads to higher costs, especially because stabilized base materials are significantly more expensive than subbase materials. Despite the robust structure, environmental factors will still require maintenance, such as milling and overlay or simple overlays, during the pavement’s life cycle.

For New Bugesera International Airport, a similar trend was observed. The PCASE-CBR method produced a thicker base (267 mm) compared to the PCASE-LED (194 mm), resulting in a stronger but more expensive pavement structure. However, considering all other parameters such as testing materials, required personnel and equipment for ME designed pavement structures, the overall initial construction cost is higher than the Empirically

designed pavement, however reliability itself has its cost implication, see 71 the conclusion part for overall cost benefit analysis

Kamembe Airport presented a different scenario. Here, the PCASE-CBR design led to thinner pavement layers compared to the PCASE-LED method. Kamembe Airport serves smaller Code C aircraft, which have lower load demands. As a result, the software recommended minimum practical pavement thicknesses, focusing more on constructability and resistance to environmental degradation rather than structural strength. This indicates that for airports with lighter traffic loads, like Kamembe, pavement deterioration is more likely due to environmental conditions than traffic loading. Additionally, the PCASE-CBR and PCASE-LED methods have different minimum layer thickness standards, as reflected in the design outcomes.

In comparison, the CBR design method tends to underestimate the strength contribution of the aggregate subbase, often resulting in unnecessarily thick base layers. In this study, the pavement designs based on the CBR method produced significantly thicker base courses than those designed with LED method, however the other cost parameters related to this LED design method make the pavement initial cost goes higher, however the life cycle cost analysis proven that empirically designed pavement might be cheaper but not economical in the long run.

Based on these findings, the following recommendations are made:

- **Avoid constructing airfield flexible pavements on weak subgrades.** If subgrade strength is insufficient, ground improvement techniques should be applied to achieve more practical and cost-effective pavement thicknesses.
- **Consider using thinner surface courses with stabilized bases.** The Layered Elastic Design suggests a surface course of approximately 100 mm, compared to the 127 mm typically used in the CBR method. A stabilized base layer provides better structural value at a lower cost than excessively thick surface courses.
- **Limit design life to a maximum of 20 years.** Due to the inherent uncertainty in traffic forecasting, shorter design periods are recommended to reduce the risks associated with over- or under-design, as pavement thickness requirements may vary depending on future traffic conditions.

## Contents

List of Tables

List of Figures

## List of Abbreviations

AC:Asphalt Concrete
AIP:Aeronautical Information Publication
APSDS: Airport Pavement Structural Design System
CBR:Califonia Bearing Ratio
CDF:Cumulative Damage Factor
COE:Corps of Engineers
DOT:Department of Transportation
ESWL:Eqyuvalent Single wheel Load
FAA:Federal Aviation Administartion
FAARFIELD: FAA Rigid and Flexible Iterative Elastic Layered Design
FOD:Foreign Object Debris
HFWD:Heavy Falling Weight Deflectometer
HMA:Hot Mix Asphalt
KIA:Kigali International Airport
LCPC: Laboratoire Central des Ponts et Chaussées
LED:Layered Elastic Design
ME:Mechanistic Empirical
M&R:Maintenance and Rehabilitation
NBIA:New Bugesera International Airport
PCASE: Pavement-Transportation Computer Assisted Structural Engineering
PCC:Plain Cement Concrete
PGA:Peak Ground Acceleration
TxDOT:Texas Department of Transportation
US COE:United States Army Corps of Engineers

# 1. INTRODUCTION

## 1.1 General Introduction

Design should aim at providing adequate cover to the subgrade so that the stresses at the subgrade level are low enough to prevent excessive deformation. Many design methods have been developed to suit different climatic and traffic loading conditions.

The scientific approach to pavement design was first introduced in the 18th century by British engineer John Loudon McAdam, primarily for road construction. However, with the invention of aircraft by the Wright brothers in the early 20th century, the need for specialized airfield pavement design emerged to support the rapidly expanding aviation industry.

Over the years, numerous flexible pavement design methods have been developed and refined by various transportation agencies. These methods range from basic concepts to highly advanced techniques. While individual agencies adopt procedures tailored to their specific local conditions, pavement design methods generally fall into four main categories

In recent years the aviation market has changed, opening to private operators has reduced costs and popularized aircraft use. Consequently, this demand has put pressure on the creation of more infrastructure [1]. Likewise, in this period, Rwanda has had remarkable growth in tourism. Nevertheless, airport infrastructure is not keeping up with demand as the single main airport in Rwanda, Kigali International Airport serving as the main entry gateway to Rwanda operate almost to the full capacity limit [2].

Airfield pavement design reliability is of great concern, as any premature failure of pavement leads to disruption of airport operations leading to great economic loses. With most busy airports like

Hartsfield–Jackson Atlanta International Airport currently has rigid runways, due to little maintenance works required, flexible pavements can also be designed, maintained appropriately to serve with minimal to no interruptions to Airport operations.

Flexible pavement designs have different pavement design methodologies, nevertheless all methods are either classified as “purely Empirical”, Mechanistic Empirical” purely Mechanistic”, the latter being rarely applicable as the past performance experience is of great concern even though sufficient test are done. Empirical and mechanistic empirical methods will be discussed in this study to understand their reliability, cost effectiveness and recommendation on design methods.

The invention of computer in late 20th Century has led to the development of Finite Element Methods, the introduction of mechanistic analysis in pavement design was evolved. With mechanistic approaches being widely recognized, the empirical approaches are well liked due to their simplicity in design and requires less sophisticated testing.

In this study, the comparative analysis of the two design approaches will be discussed by adopting six pavement design sections for three major airports in Rwanda namely “Kigali

International Airport, New Bugesera International Airport and Kamembe Airport". By using the United States Army Corps of Engineers Methods "PCASE" which has both CBR and LED design methods and checking the design life of pavement sections in FAA software" FAARFIELD".

The pavement sections will be analyzed to understand the benefits, drawbacks of each methodology in terms of cost effectiveness, reliability and overall suitability to modern airport pavements design.

Mechanistic empirical methods being believed to be more reliable in terms of durability compared to empirical approaches, the former requires sophisticated testing to understand materials under loading, whilst the empirical method requires less testing, the cost of disruptions and maintenance due to unpredictable failure cannot be analyzed in this study, the focus will only be to initial construction cost.

## 1.2Problem Statement

The design of scientific pavement developed earlier by the British engineer John Loudon McAdam in 18th Century were primarily for Road's construction. With the invention of aircrafts by the two wright brothers in earlier 20th Century, the design of airfield pavements came in demand to accommodate the rapidly growing aviation industry. With methods of pavement designs developed initially like CBR methods which are currently in use, the empirical methods developed were based on the existing aircraft. With the evolution of large body aircrafts such as the Boeing 747, A380s and many others with higher single wheel load and tire pressure, the empirical methods are missing the capability to accommodate these changes hence leading to costlier pavement and some unpredicted pavement failures.

The empirical methods are based on past experience and in most cases fewer materials testing is done compared to Mechanistic-empirical approach which takes into account the stress and strain behaviors of individual pavement layer. This research will focus on analyzing the effectiveness of both methods to understand their performance reliability, cost effectiveness.

The pavement sections performance will be compared and the initial cost of design and construction will be analyzed to better understand which method of choice is suitable for current aircraft generation. With the output data from pavement sections, a comparative analysis of reliability will be analyzed based on lifetime analysis from FAAFIELD and initial cost of construction being compared based on pavement layers thicknesses.

## 1.3Research objectives

The core objective of this research is to compare the effectiveness of empirical and mechanistic -empirical pavement design methods for Airfield flexible pavement. the study aims to

- Identify the gap of empirical pavement design methods for current airfield design
- Elaborate the efficiency of mechanistic-empirical design methods
- Analyze different design parameters using both methods (tire pressure, axle configurations, aircraft types, etc.)

- Cost effective analysis using both design methods. The cost analysis will solely rely on initial cost of design and construction as the LCCA of the entire pavement lifetime is beyond this research

## 1.4. Research question

this comparative analysis will be guided by the following research questions:

1.what is the reliability of empirical methods for airfield flexible pavement for new generation aircrafts

2.what are the drawbacks of empirical methodologies as compared to mechanistic empirical types

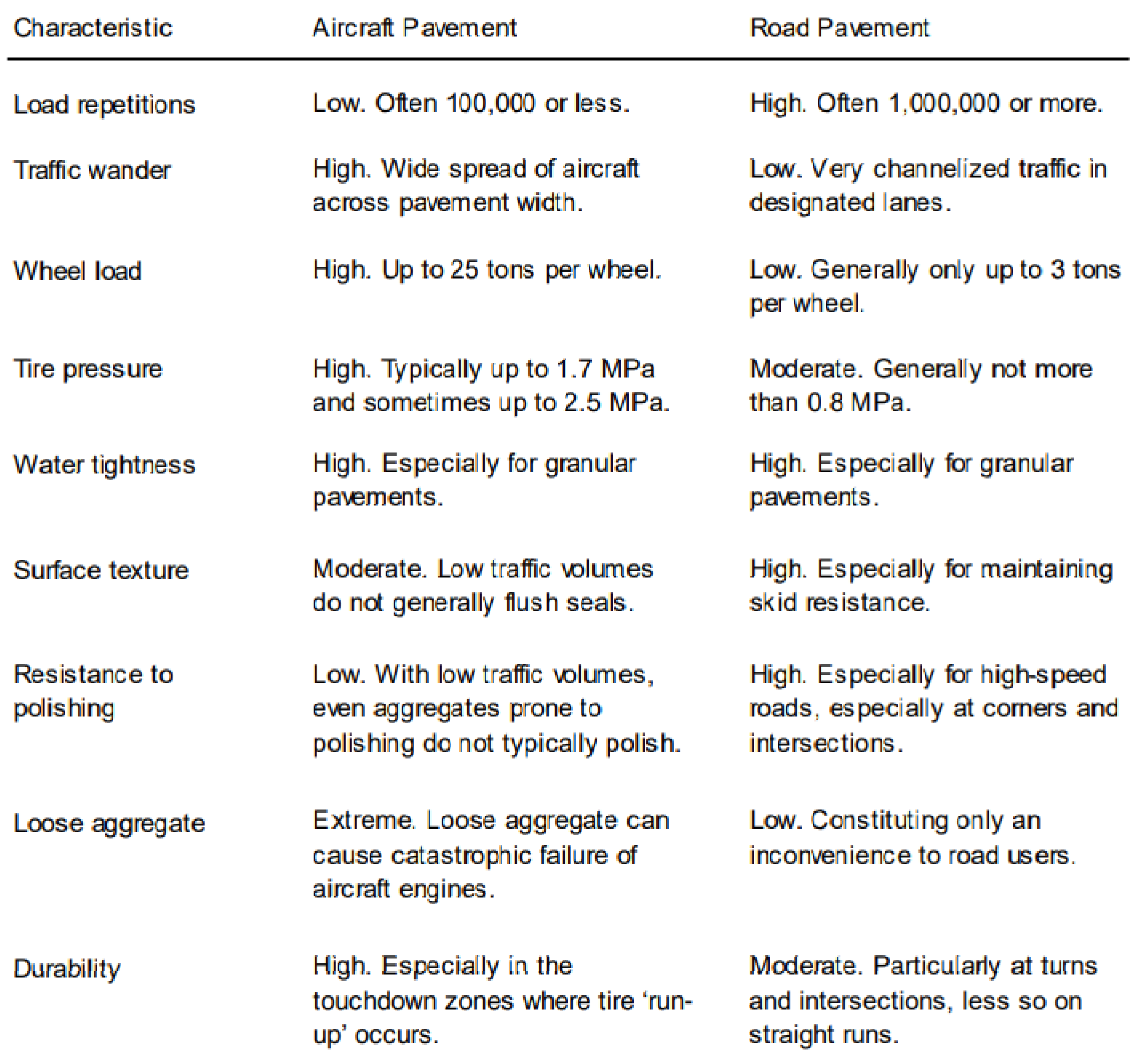
# 2. LITERATURE REVIEW

## 2.1Introduction

Two sources are considered the most important for the design of airport pavements: Federal Aviation Administration and International Civil Aviation Organization [3]. These two organizations present the state-of-the-art regarding airport pavement design, their recommendations and standards are widely adopted in the aircraft industry and are the main sources for the development of this chapter.

Airport pavements must be built following strict guidelines and specifications; the aim is to ensure maximum safety [3]. For example, loose particles can damage jet engines when sucked in, damage propellers, and become deadly projectiles. In this study it was found that most of the airport pavements design methods apply to the runway, which is the region with the highest pavement demand. the function of a pavement is to protect the lower layers of the load, as it should provide a good surface for its users. Consequently, the pavement has a structural and functional function, elements that must be considered during design [4]. Besides, when thinking about pavements, it is typically associated with roads. However, there are other types of pavements, such as sidewalks, parking lots, cycle paths, airports. Thus, airport and road pavements are not substantially different, and the basic principles for design, construction, and maintenance are almost the same [5]. Nevertheless, what is different is the magnitude of load applied, which in the case of airport infrastructures are higher, an item that can be explained by force applied by aircraft during landings and take-offs, the inflation pressure of tires and wheel loading. Also, it should be noted that aircraft are less tolerant of slippage or deflection than automobiles, so it can be said that the level of demand for an airport infrastructure is higher [6]

Table 2-1: Comparison of aircraft pavements and road pavements [5]



| Characteristic | Aircraft Pavement | Road Pavement |
|---|---|---|
| Load repetitions | Low. Often 100,000 or less. | High. Often 1,000,000 or more. |
| Traffic wander | High. Wide spread of aircraft across pavement width. | Low. Very channelized traffic in designated lanes. |
| Wheel load | High. Up to 25 tons per wheel. | Low. Generally only up to 3 tons per wheel. |
| Tire pressure | High. Typically up to 1.7 MPa and sometimes up to 2.5 MPa. | Moderate. Generally not more than 0.8 MPa. |
| Water tightness | High. Especially for granular pavements. | High. Especially for granular pavements. |
| Surface texture | Moderate. Low traffic volumes do not generally flush seals. | High. Especially for maintaining skid resistance. |
| Resistance to polishing | Low. With low traffic volumes, even aggregates prone to polishing do not typically polish. | High. Especially for high-speed roads, especially at corners and intersections. |
| Loose aggregate | Extreme. Loose aggregate can cause catastrophic failure of aircraft engines. | Low. Constituting only an inconvenience to road users. |
| Durability | High. Especially in the touchdown zones where tire 'run-up' occurs. | Moderate. Particularly at turns and intersections, less so on straight runs. |

Therefore, based on the data presented, among the main factors that influence the design of airport pavements, one of the most critical specifications is how the load is applied by the aircraft on the pavements. In this sense, it is essential to understand a little about the geometry of aircraft, so according to [5] "The wheelbase of an aircraft is defined as the distance between the center of the aircraft's main landing gear and the center of its nose gear, or tail-wheel, in the case of a tail-wheel aircraft. An aircraft's wheel track is defined as the distance between the outer wheels of an aircraft's main landing gear." In Figure 2-1, these distances are presented.

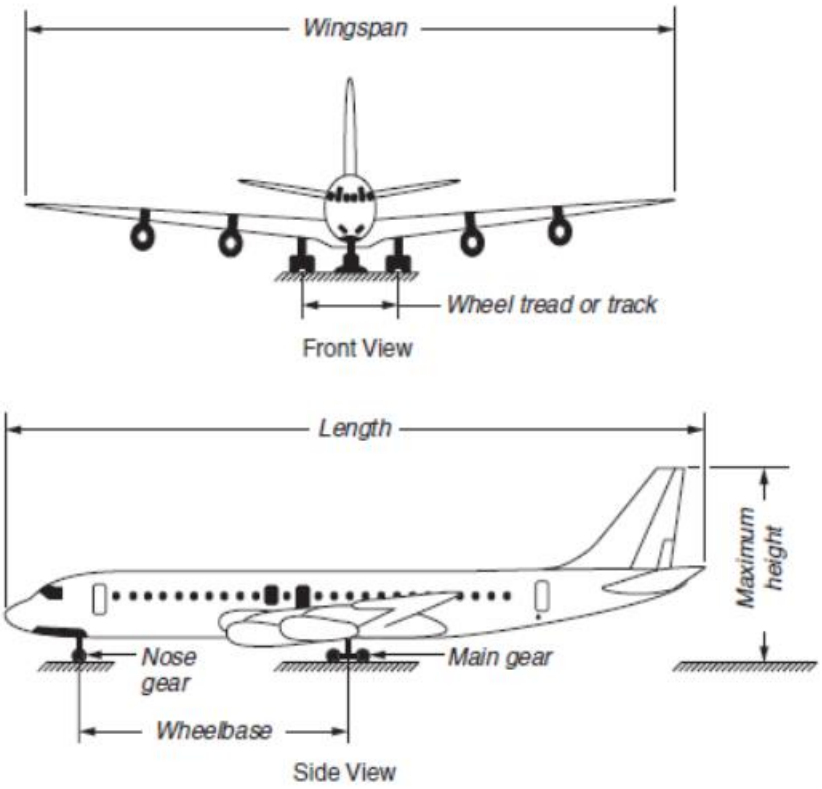


Figure 2-1: Aircraft dimensions [5]

Regarding the landing gear, aircraft used in civil aviation use several configurations, in this sense, there are three basic configurations of the landing gear, which are a single wheel, dual wheel, and dual-tandem as observed in Figure 2-2.

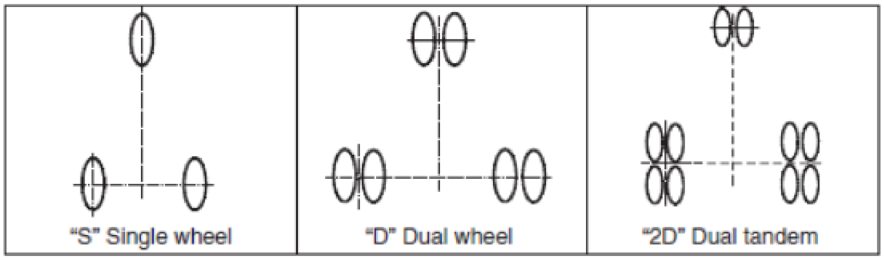


Figure 9 – Traditional landing gear configurations (Horonjeff, 2010)

Figure 2-2: Traditional landing gear configurations [7]

There are even more complex configurations (Figure 10) like those used on Boeing 747, Boeing 777, and Airbus A-380 aircraft

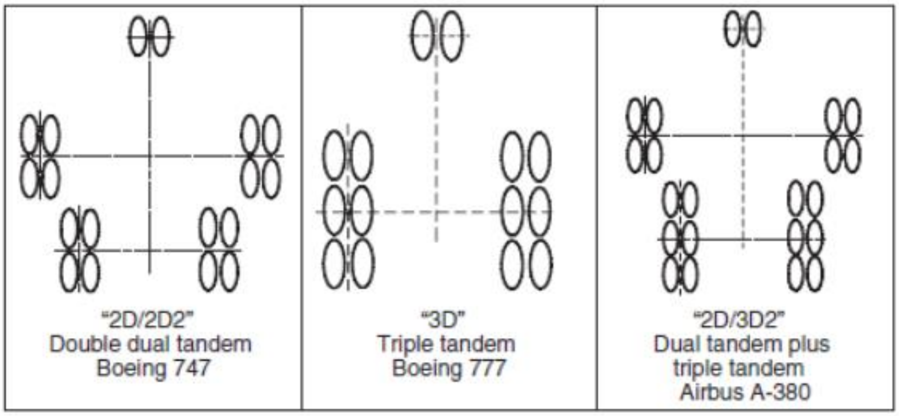


Figure 2-3: Complex landing gear configurations [7]

It is crucial to understand landing gear configurations, as they are the ones that transmit the weight of the aircraft to the pavement, so they have a significant impact on the design of airfield pavements. Briefly, depending on the number of wheels and the distribution of these wheels, the impact on the pavement may be higher or less [6]. Consequently, each manufacturer provides typical aircraft weights and aircraft landing gear configurations that serve as a reference for airport pavement design. Similarly, FAA usually performs tests with different configurations and weights, and the results of these tests are incorporated into the design methods applied by the FAA.

ICAO has adopted letter and numerical codes (Table 2) as standards for the different types of airports and the functions they serve.

Table 2-2:ICAO aerodrome reference codes [7]

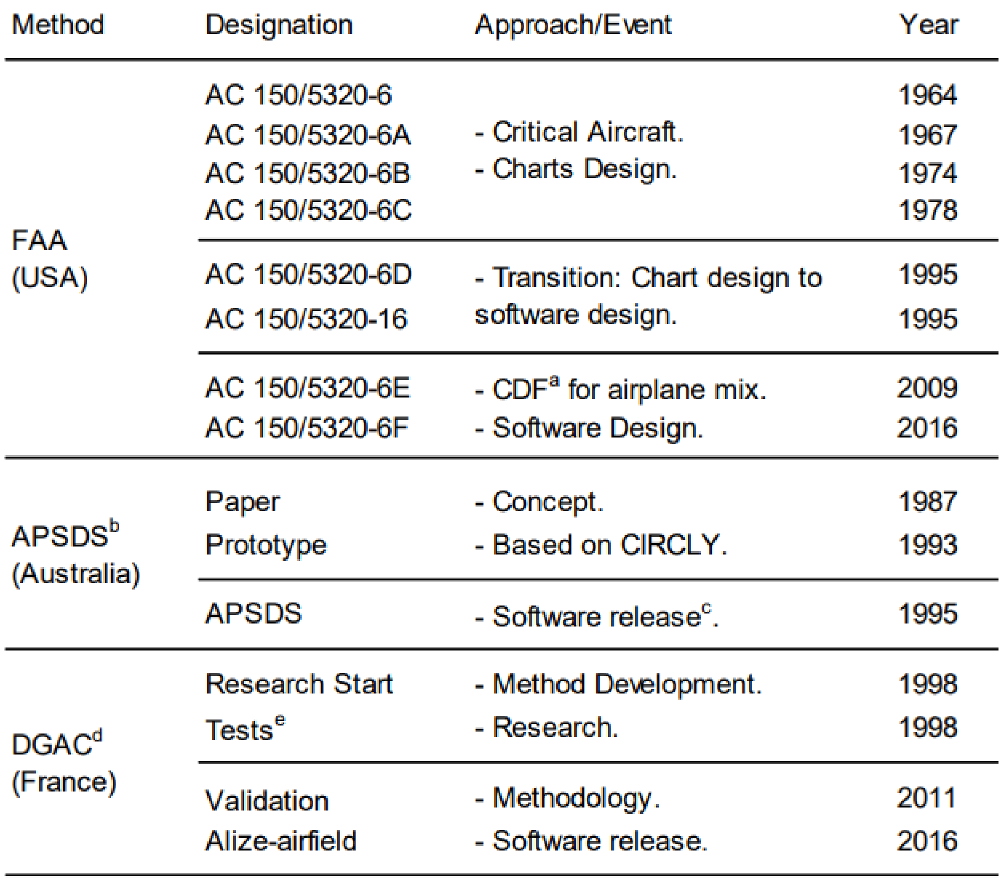
| Code Number | Reference Field Length (m) | Code Letter | Wingspan (m) | Distance between Outside Edges of Main Wheel Gear (m) |
|---|---|---|---|---|
| 1 | < 800 | A | < 15 | < 4.5 |
| 2 | 800 ≤1200 | B | 15 ≤ 24 | 4.5 ≤ 6 |
| 3 | 800 ≤ 1200 | C | 24 ≤ 36 | 6 ≤ 9 |
| 4 | ≥ 1800 | D | 36 ≤ 52 | 9 ≤ 14 |
|  |  | E | 52 ≤ 65 | 9 ≤14 |
|  |  | F | 65 ≤ 80 | 14 ≤ 16 |

An example of using this code was presented by Horonjeff (2010): "…an airport which is designed to accommodate a Boeing 767–200 with an outer main gear wheel span of width of 10.44 m, a wingspan of 48 m, at a maximum takeoff weight of 143 ton, requiring a runway length of about 1830 m at sea level on a standard day, would be classified by ICAO with an aerodrome reference code of 4-D.” [5]

## 2.2Evolution of Design Methods

The main source for airport pavement design is the FAA, and the evolution of design pavements methods are closely linked to the specifications and recommendations of this body. [8] presents a brief historical evolution of FAA methods: “The FAA-specified structural design method of airport pavements has evolved from an empirical CBR-based spreadsheet design method, which was based on the concept of equivalent load and departure to a layered elastic (for flexible pavements) and finite element (for rigid pavements) based methods.” Similarly, in [9], it is mentioned that until 2009 the design was done with the support of abacus and design curves, after this period began to use computational resources. Accordingly, the methodology based on abacuses and design curves evolved into a “spreadsheet” methodology, which automated the processes with computational support. Later, computer software was created to use more complex formulations, such as layered elastic (flexible pavements) and finite element (rigid pavements), so the effort to present the technological evolution related to the design of airport pavements can be represented in Table

**Table 2-3:Evolution of main methods for design airport pavements [9]**



| Method | Designation | Approach/Event | Year |
|---|---|---|---|
| FAA<br>(USA) | AC 150/5320-6 | - Critical Aircraft.<br>- Charts Design. | 1964 |
| | AC 150/5320-6A | | 1967 |
| | AC 150/5320-6B | | 1974 |
| | AC 150/5320-6C | | 1978 |
| | AC 150/5320-6D | - Transition: Chart design to software design. | 1995 |
| | AC 150/5320-16 | | 1995 |
| | AC 150/5320-6E | - CDF[a] for airplane mix. | 2009 |
| | AC 150/5320-6F | - Software Design. | 2016 |
| APSDS[b]<br>(Australia) | Paper | - Concept. | 1987 |
| | Prototype | - Based on CIRCLY. | 1993 |
| | APSDS | - Software release[c]. | 1995 |
| DGAC[d]<br>(France) | Research Start | - Method Development. | 1998 |
| | Tests[e] | - Research. | 1998 |
| | Validation | - Methodology. | 2011 |
| | Alize-airfield | - Software release. | 2016 |

Notes: a. CDF: Cumulative Damage Factor

b. APSDS: Airport Pavement Structural Design System;

c. First Commercial Version 3.0 (1995), currently at version 5.0t (2019);

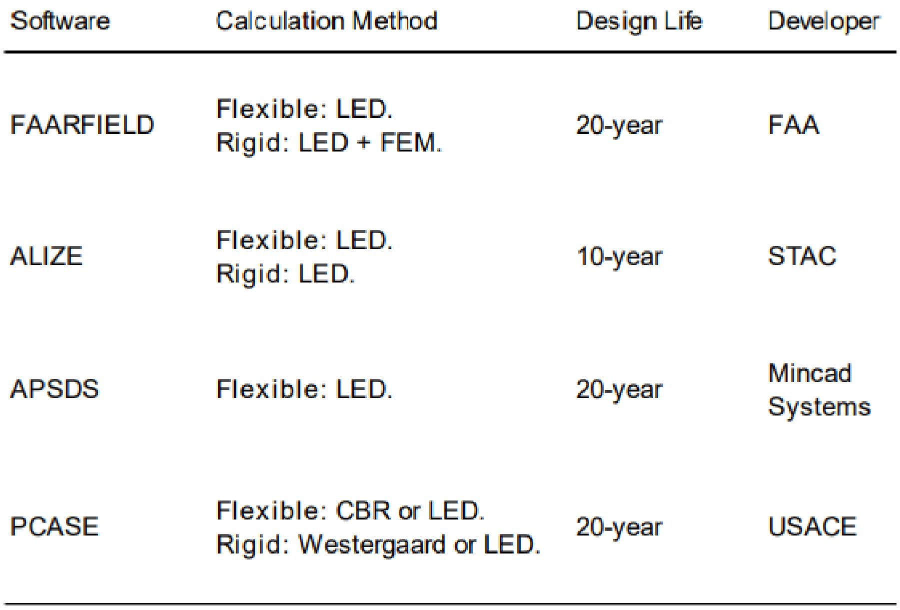
d. DGAC: French Civil Aviation Authority;

e. A380 Pavement Experimental Program

The first studies on airport pavement design were developed by the FAA, and its predecessor agencies, and also the US Army Corps of Engineers (USACE). The Airport Pavement Structural Design System (APSDS), and DGAC (Alize-airfield) methods use this initial knowledge. Also, in 1995 the FAA launched the FAA Layered elastic (LEDFAA). This software was developed to meet the needs of the B-777 aircraft, as the methodology used so far was not satisfactory for aircraft such as the B-777 and A380. The launch of LEDFAA marked the FAA's change in its approach, with the adoption of the software rather than the design charts used so far. Later, FAA Rigid and Flexible Iterative Elastic Layered Design (FAARFIELD) replaced LEDFAA, adding the functionality of the previous software and adding new modules.

There are several methods for airport pavement design, with varying levels of acceptance and use. At this point, we can highlight the efforts of the FAA (USA) for the development of design methodologies and the construction of airport pavements. Other agencies have also advanced in this area, such as LCPC (France), Mincad Systems (Australia), and USACE (USA). Currently, methods have evolved to the application of software. So, the applications developed by the most prominent researchers in the area can be highlighted: FAARFIELD, ALIZE, APSDS and PCASE [6].

**Table 2-4:Main applications for airport pavement design**



| Software | Calculation Method | Design Life | Developer |
|---|---|---|---|
| FAARFIELD | Flexible: LED.<br>Rigid: LED + FEM. | 20-year | FAA |
| ALIZE | Flexible: LED.<br>Rigid: LED. | 10-year | STAC |
| APSDS | Flexible: LED. | 20-year | Mincad Systems |
| PCASE | Flexible: CBR or LED.<br>Rigid: Westergaard or LED. | 20-year | USACE |

Therefore, the trend is the use of LED and FEM based calculation methods, and even Alize airfield has been developing a new module to use FEM in its calculations [6]. Regarding design life, it is usual to design pavements to 20-year. However, the method developed by

STAC (France) uses 10-year as standard. Finally, the software developed by Mincad Systems (Australia) is for flexible pavements only.

### 2.2.1 Initial approach (AC 150/5320-6 to AC 150/5320-6D)

Since the 1950s, the USACE has worked on the development of airport pavement design methods. To this end, the California Bearing Ratio (CBR) and Westergaard have been adopted for flexible and rigid pavements, respectively. It is noteworthy that many airports and aviation authorities maintain the basis of USACE methods in the design, specification, and construction of airport pavements [10]. Applying the CBR method determines the required thickness of the subbase, base, and surface layer by inserting the results of a moderately simple soil test into a set of charts and design curves [11]. In [8]it was presented the Equation below that relates CBR to pavement thickness:

$$t = \propto (Ac)^{1/2}[-0.0481 - 1.1562 (\log \frac{CBR}{P}) - 0.6414 (\log \frac{CBR}{P})^2 \; 2 \; 0.473 (\log \frac{CBR}{P})^3]$$

Where:

- $\propto$ is the load repetition factor;
- Ac is the tire contact area, $in^2$;
- CBR is the CBR of the layer being considered;
- P is the tire pressure (psi) at depth t used in the calculation of the ESWL.

this formula was developed assuming that the deflection caused by the Equivalent Single Wheel Load (ESWL) is the same as that of multiple gears, provided that the areas of contact with the pavement are the same [8]. Consequently, this method assumes that what matters is the contact area and not the landing gear configuration. The main disadvantage of this design method is the inaccurate representation of landing gear configurations of some specific aircraft, where it was realized that the structure response to dynamic loads could not be correctly represented by an ESWL [8]. For the design of rigid pavements, the FAA has adopted as a standard a set of charts and design curves to determine the thickness of the pavement layers, and these curves were developed based on Westergaard theories [6]. These theories were first developed in the 1920s and were focused on calculating stresses and deflections in concrete pavements due to applied loading [6].This theory developed by Westergaard, some simplifications were adopted, such as:

- The pavement slab was a thin slab supported by a subgrade that is considered elastic only in the vertical direction;
- The concrete slab is a homogeneous, isotropic elastic solid;
- The wheel load of an aircraft is distributed over an elliptical area.

From 1974 the FAA began to consider the weights and landing gear configurations of the aircraft fleet that can regularly use the pavement of the airport. In this methodology, one should determine the total number of annual departures and transform them into equivalent annual departures, this equivalent aircraft was named design aircraft. That would not necessarily be the heaviest aircraft, but the one with the most effort applied to the pavement, depending on its gross weight, the number of repetitions planned for its take-off, and the type of landing gear [5].

The remaining aircraft from the traffic mix were converted to the critical aircraft according to the Equation:

$$\text{Log } R_1 = \log R_2 \left(\frac{W2}{W1}\right)^{0.5}$$

Where:

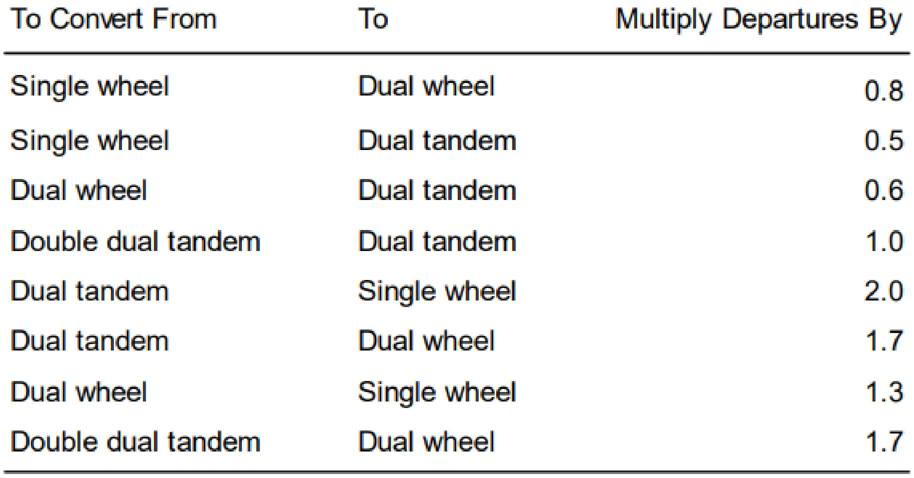
R1 is the equivalent annual departures by the design aircraft;

R2 is the annual number of departures by an aircraft in terms of design aircraft landing gear configuration; W1 is the wheel load of the design aircraft;

W2 is the wheel load of the aircraft being converted.

If the aircraft has a different landing gear configurations than the design aircraft, the corresponding impact must be converted, and this transformation is possible by multiplying the annual departures of this aircraft to equivalent annual departures, as shown in Table

Table 2-5: Factors for converting annual departures by aircraft to equivalent annual



| To Convert From | To | Multiply Departures By |
|---|---|---|
| Single wheel | Dual wheel | 0.8 |
| Single wheel | Dual tandem | 0.5 |
| Dual wheel | Dual tandem | 0.6 |
| Double dual tandem | Dual tandem | 1.0 |
| Dual tandem | Single wheel | 2.0 |
| Dual tandem | Dual wheel | 1.7 |
| Dual wheel | Single wheel | 1.3 |
| Double dual tandem | Dual wheel | 1.7 |

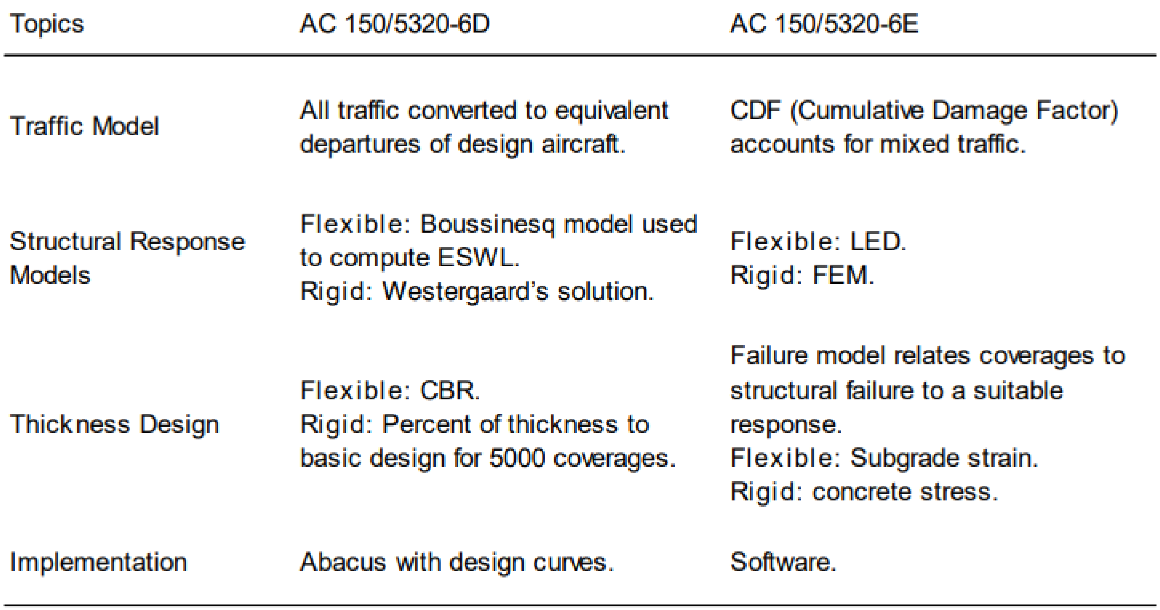
### 2.2.2 Computational implementation (from AC 150/5320-6E)

Computers have become more powerful, cheaper, and more straightforward to use. In this scenario, it made sense to apply this computational capability to methods that could more accurately represent the loads applied by aircraft and the structural response of the pavements. Therefore, in [6], the authors state that for flexible pavements, the most common approach is Layered Elastic Design (LED), while for rigid pavements variations of Westergaard or Finite

Element Method (FEM) is typically applied. In addition to this new computational capability, a new generation of aircraft was launched, with more complex landing gear configurations and higher total gross weight. Therefore, the FAA had to rethink the previous formulation, creating the method that considers the damage of each aircraft to the pavement [5].

For the FAA method, this transition occurred between AC 150/5320-6D and AC 150/5320-6E, as shown in Table 7.

**Table 2-6:AC 150/5320-6D x AC 150/5320-6E (adapted from Brill, 2012)**



| Topics | AC 150/5320-6D | AC 150/5320-6E |
|---|---|---|
| Traffic Model | All traffic converted to equivalent departures of design aircraft. | CDF (Cumulative Damage Factor) accounts for mixed traffic. |
| Structural Response Models | Flexible: Boussinesq model used to compute ESWL.<br>Rigid: Westergaard's solution. | Flexible: LED.<br>Rigid: FEM. |
| Thickness Design | Flexible: CBR.<br>Rigid: Percent of thickness to basic design for 5000 coverages. | Failure model relates coverages to structural failure to a suitable response.<br>Flexible: Subgrade strain.<br>Rigid: concrete stress. |
| Implementation | Abacus with design curves. | Software. |

Therefore, this was a shift in the methodology used so far by the FAA, which was based on a set of charts and design curves in pavements design, this made it possible to adopt the concept of Cumulative Damage Factor (CDF) using a fatigue failure factor methodology. The CDF value ranges from 0 to 1, when CDF = 1, it is assumed that the project life is exhausted. Thus, the CDF represents the life of the pavement, specifying, i.e., a 0.5 (50%) CDF represents that the pavement has received accumulated damage of half of its projected life. According to Miner's hypothesis, CDF is the sum of the damage factors over all the loadings in the traffic mix, so the CDF for a given fleet of aircraft can be determined by Equation:

$$CDF_i=\sum \frac{n_i}{N_i}$$

Where:

ni is the expected coverages of individual aircraft i;

Ni is the allowable coverages of individual aircraft i

The CDF corresponding to the sum of pavement damage caused by all aircraft in the fleet mix and calculated according to the following Equations:

$$\mathrm{CDF}_{\mathrm{total}}=\sum_{i=1}^{Na}\mathrm{CDFi}$$

Or

$$\mathrm{CDF}_{\mathrm{total}}=\sum_{K=1}^{M}\quad\sum_{j=1}^{Nk}\mathrm{CDFi}$$

Where: CDFi is the CDF of each aircraft i in the fleet mix;

Na is the number of aircraft i in the fleet mix; k is summed over M aircraft models;

Nk is the number of different gross weights for aircraft model no. k.

## 2.3. Flexible Pavement design method choice

Many agencies have been adopting standard pavement sections for different ranges of traffic levels and environmental conditions. These standard sections are mostly based on previous experience and are applicable to local materials and budget practice [10]. Although these methods are old, they are still being used by relatively small agencies because of their simplicity, low design cost, and reliability under certain conditions. These methods, however, do not allow for comparison between alternatives. They also do not recognize the varying serviceability with age. These methods also assume average material properties, traffic levels, and environmental conditions. If any of these variables change, this approach loses its validity.

## 2.4 empirical design methods-CBR method

### 2.4.1 History and Development

The California Division of Highways developed the CBR method of design in 1928. The outbreak of World War II required that an immediate decision be made by the U.S. Army concerning the choice of a design method, as there were no methods dedicated to the design of t flexible airfield pavements. Obviously, the COE did not have the time required to develop a completely new method of design. Therefore, it was decided that a review of all existing flexible highway design methods would be made. The method that appeared the most adaptable to airfield use would be adopted and modified. After investigating all available methods for several months, the COE chose the CBR method because of its procedural simplicity, satisfactory performance, and ease in adapting it to airfield design [12].

### 2.4.2 Adaptation of CBR Method to Airfield Pavements

Between the years of 1928 and 1940, the California Highway Department (CHD) studied the adequacy of flexible Pavements. From their observations, they developed the curves shown in Figure 2-1. Curve A was derived from pavements subjected to normally encountered highway conditions and curve B from light traffic conditions [13, p. 45].

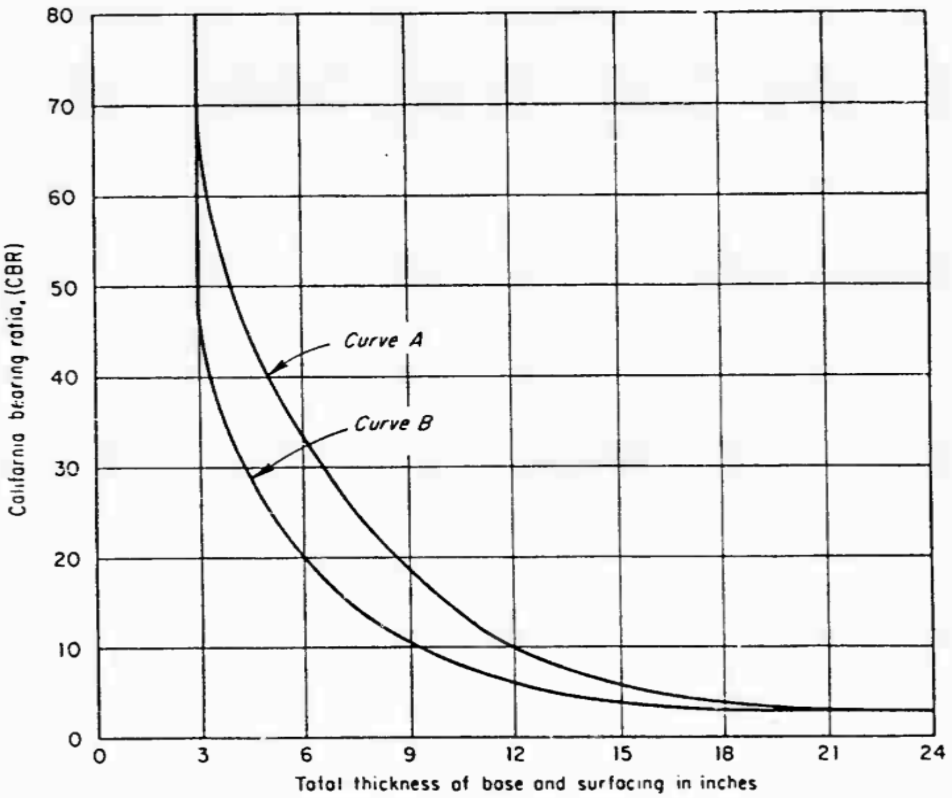


Figure 2-4: Total thickness of base and surfacing in relation to CBR ( [13, p. 56]

The California Highway Department (CHD) also found that curve A was more reliable and therefore, assumed it to represent a 9,000 lb. wheel load. They also reasoned that because aircraft tires operate at larger deformations and the traffic on airfields is less channelized, this curve would also represent a 12,000 lb. aircraft wheel load. Because of the war emergency program, the C0E utilized soil mechanics to extrapolate from the 12,000 lb. curve to curves for larger wheel loads. Curves for larger wheel loads were generated based on the assumption that the pavement acted as a homogeneous layer. Towards the end of World War II, the U.S. Army Air Corps introduced the B-29 bomber. It complicated flexible pavement design, as it had a dual-wheeled gear. The C0E proceeded with an analysis of its effect on flexible pavements and their design. This analysis was based on the fact that a principal cause of pavement failure was strain or deflection. Their investigation and tests concluded that a single-wheel load that produces the same deflection as a multiple-wheel load will produce equivalent or larger strains in the pavement foundation compared to the multiple-wheel load. This very important concept is known as the equivalent single-wheel load (ESWL) and will be discussed further in the next sections.

### 2.4.3 CBR Thickness Design Procedure

In order to design a flexible pavement using the CBR method, the subgrade CBR, minimum pavement component thicknesses, design aircraft type, and the anticipated traffic volume must all be determined. These variables effect the magnitude and distribution of loads, as well as the frequency that the pavement and subgrade will be subjected to stresses [14, p. 16].

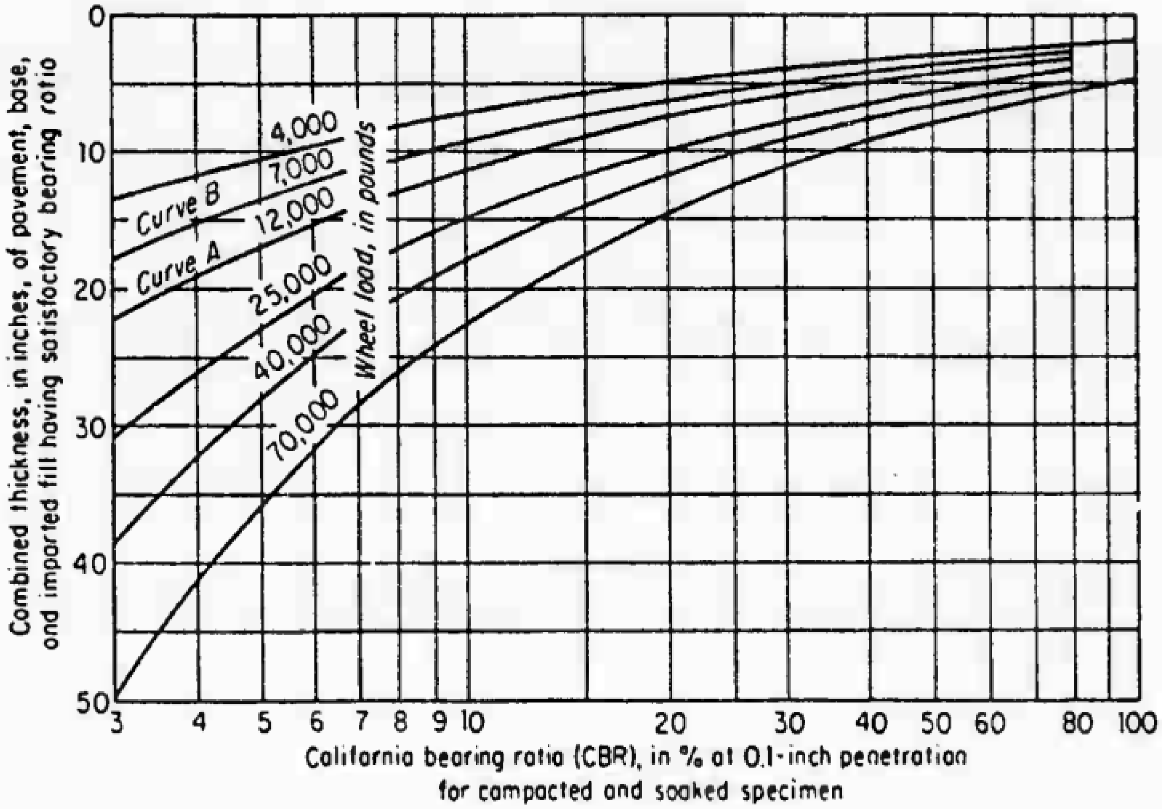


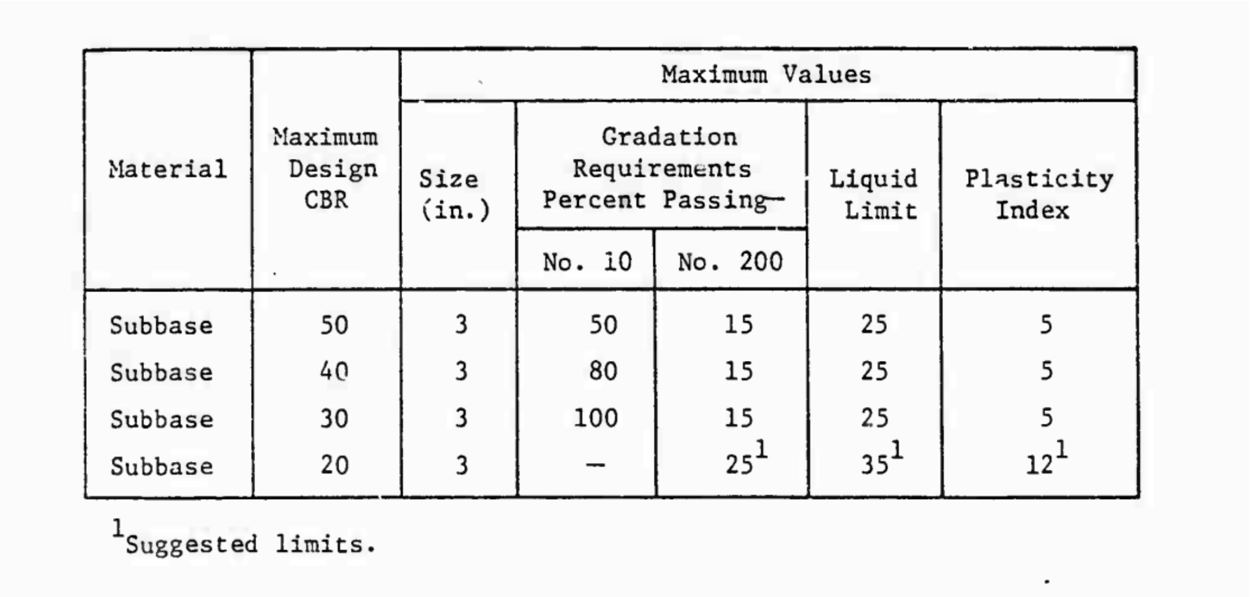
Figure 2-5 : Tentative CBR Design curve [15, p. 65]

The COE CBR design method is the basis for design methods used by the Navy, Air Force, and Army. They are all quite similar. However, each of these military services uses slightly different design criteria due to the varying ranges of aircraft size and landing gear configuration. The Air Force criteria for flexible airfield pavement design appears to be the most general. This is probably due to the very wide range of aircraft that regularly use Air Force airfields. Their aircraft inventory ranges from the single engine Cessna to the enormous C-5A Galaxy. For this reason. Air Force criteria such as pavement thickness minimums and subbase gradation requirements will be utilized in the design.

### 2.4.4 Subgrade and Subbase Design CBR Selection

The CBR design procedure may be considered to be empirical and acquires its validity through the correlation of lab or field (in-situ) CBR test values with known traffic loadings and frequencies. When various soil types are encountered at the site, a range of subgrade CBR values may be found to exist [16, p. 24]. Where this condition exists, some designers select the lowest CBR value for pavement thickness determination when the difference in the high and low CBR value is not too large. When lower than average values are found in isolated locations across the site, the designer should consider replacing these areas with more suitable material before constructing the pavement. The lab determined CBR must also be compared to maximum allowable CBR design values that are determined by the subbase gradation requirements set forth in Table 4-1. For example, suppose that a lab test determined a subbase CBR of 40 and sieve analysis on the same material showed 85" passing the no. 10 sieve. From Table 2-1, the maximum

Table 2-7: Maximum Permissible Subbase CBR [15, p. 28]



| Material | Maximum Design CBR | Maximum Values | | | | |
|---|---|---|---|---|---|---|
| | | Size (in.) | Gradation Requirements Percent Passing No. 10 | Gradation Requirements Percent Passing No. 200 | Liquid Limit | Plasticity Index |
| Subbase | 50 | 3 | 50 | 15 | 25 | 5 |
| Subbase | 40 | 3 | 80 | 15 | 25 | 5 |
| Subbase | 30 | 3 | 100 | 15 | 25 | 5 |
| Subbase | 20 | 3 | — | 25[1] | 35[1] | 12[1] |

[1] Suggested limits.

allowable design CBR will be 30. All gradation and Atterberg limit requirements listed in Table 4-1 must be met. Exceptions to the gradation requirements are permissible when supported by adequate in place CBR tests on similar construction that has been in service for several years.

### 2.4.5 Design Aircraft Selection and Traffic Forecasting

A design aircraft should be selected as a basis for the pavement design. The design aircraft is generally the heaviest or most damaging aircraft that will operate at the airport, or the most frequent user. The design aircraft's weight and landing gear configuration are the primary aircraft characteristics used in the design of flexible airfield pavements utilizing the CBR method [13]. It is essential in the design of an airfield pavement to have realistic estimates of the future demand to which the airport will be subjected. There is a variety of forecasting techniques available, ranging from subjective judgement to sophisticated mathematical models, that can be used to estimate both the number and mix of aircraft that will utilize the design airfield over its life. A forecast such as this generally results in a specified number of aircraft passes or movements of the design aircraft by converting all aircraft types to equivalent design aircraft loadings [13].

### 2.4.6 Minimum Pavement Thickness

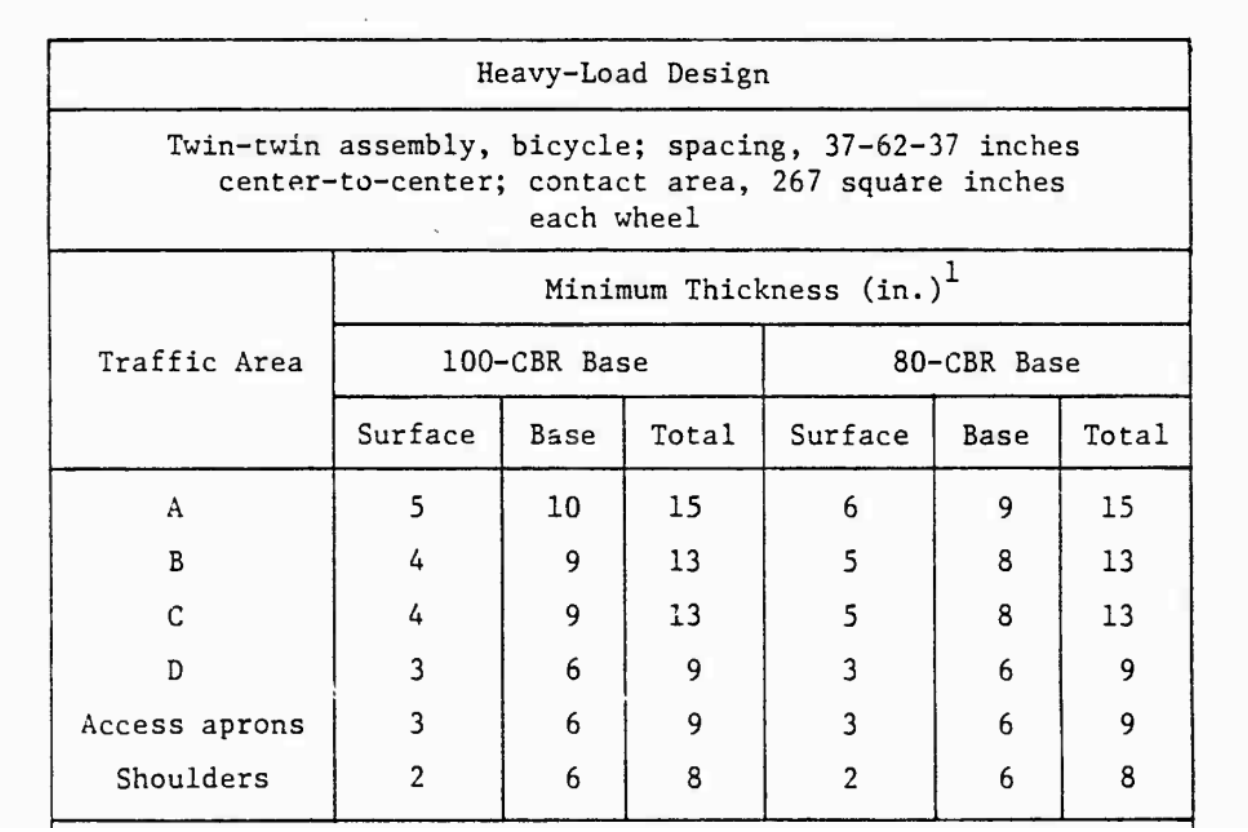
In order to simplify the infinite variety of loading conditions that may exist, the COE has categorized airfields into three major loading conditions. The categories are heavy-Toad, medium-load and light-load. The design gear load for each of these conditions is 255 kips, 100 kips, and 25 kips, respectively.  Being given the traffic area the COE minimum acceptable thicknesses for base and wearing courses for each loading condition. The designer should check to ensure that all CBR designs meet these minimum thickness requirements [17, p. 76].

### 2.4.7Determination of the ESWL

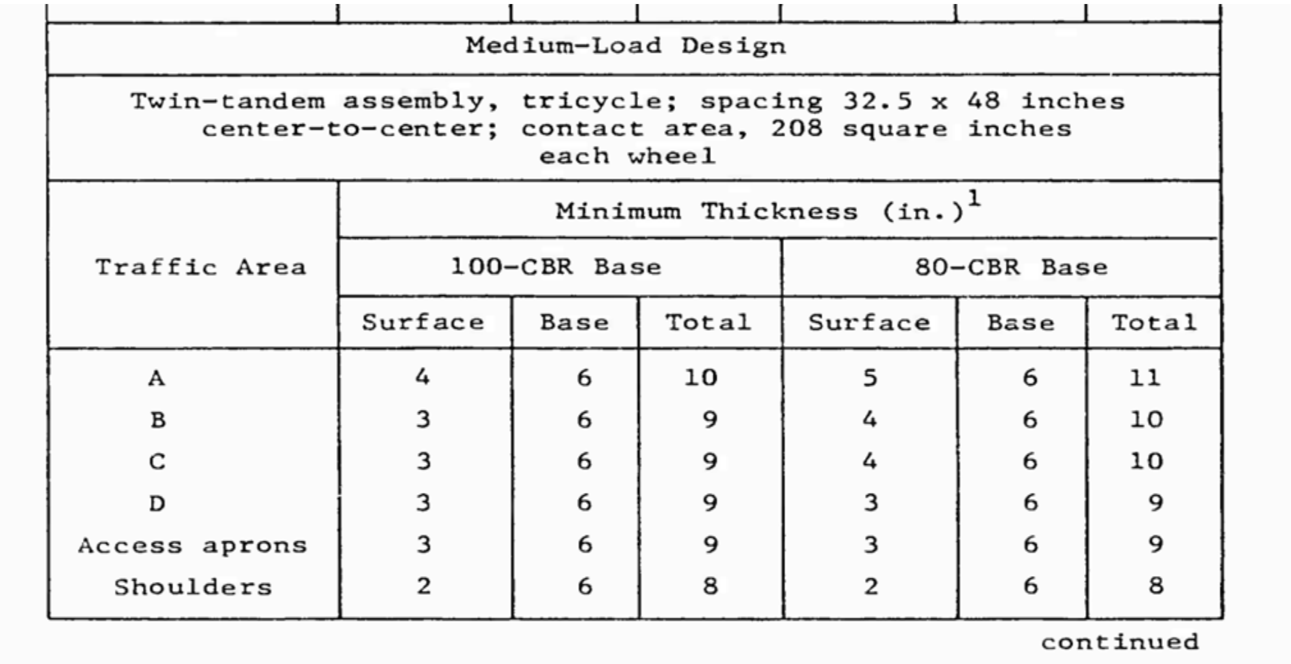
As aircraft became larger and heavier, it was realized that their assembly loads were too large to be delivered to the pavement through a single wheel. To better distribute these loads over the pavement surface, f multiple-wheel assemblies were developed [15].

Because reliable design methods have been formulated based on single wheel loadings, complex landing gear arrangements must be equated to a single wheel configuration, or ESWL. The ESWL replaces for computational purposes the effects of a multiple-wheel assembly with the effects of a single wheel assembly. The ESWL may therefore be defined as a fictitious load acting on a single wheel with the same contact area as one tire of the multiple-wheel assembly, and that produces the same deflection as the multiple-wheel assembly at a given depth in the pavement. Figure 5-3 shows both the multiple-wheel and single-wheel configurations and their respective deflection conditions. The subscript k in Figure 2-3 (a) refers to known conditions under a dual-wheel gear, while the subscript e shown in (b) of the same figure refers to the ESWL loading configuration. The following analysis is also applicable to more complex landing gear configurations.

### Table 2-8: Minimum Surface and Base Thickness Criteria

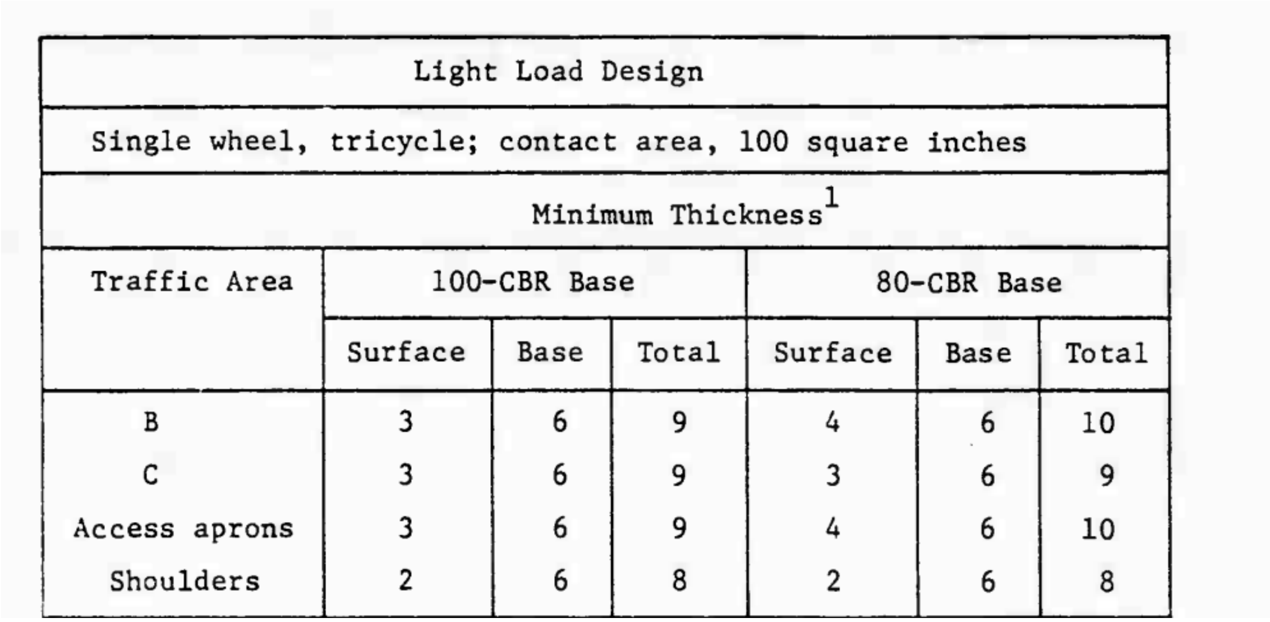


| Heavy-Load Design | | | | | | |
|---|---|---|---|---|---|---|
| Twin-twin assembly, bicycle; spacing, 37-62-37 inches center-to-center; contact area, 267 square inches each wheel | | | | | | |
| Traffic Area | Minimum Thickness (in.)[1] | | | | | |
| | 100-CBR Base | | | 80-CBR Base | | |
| | Surface | Base | Total | Surface | Base | Total |
| A | 5 | 10 | 15 | 6 | 9 | 15 |
| B | 4 | 9 | 13 | 5 | 8 | 13 |
| C | 4 | 9 | 13 | 5 | 8 | 13 |
| D | 3 | 6 | 9 | 3 | 6 | 9 |
| Access aprons | 3 | 6 | 9 | 3 | 6 | 9 |
| Shoulders | 2 | 6 | 8 | 2 | 6 | 8 |

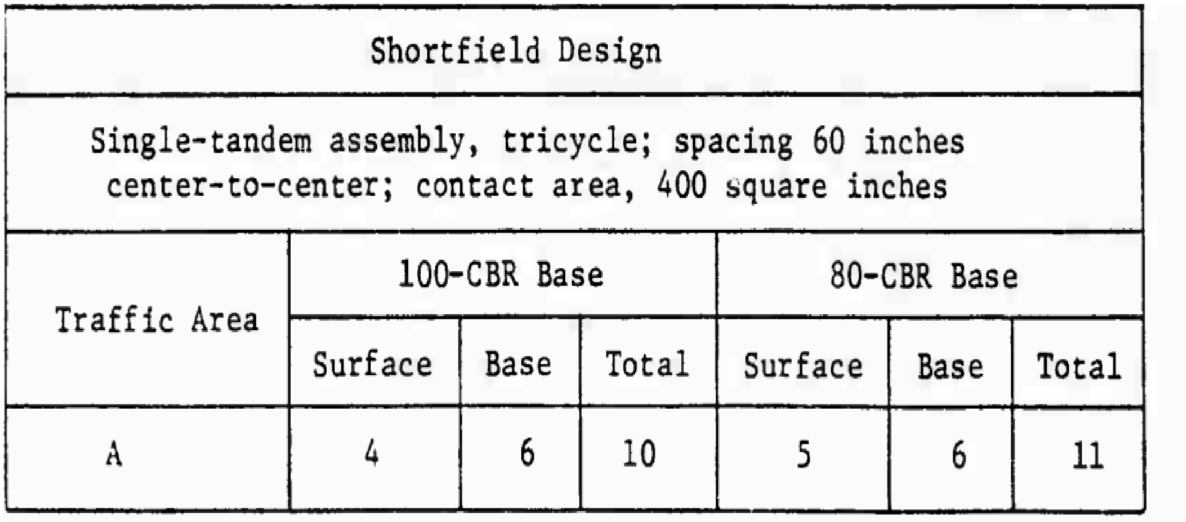


| Medium-Load Design | | | | | | |
|---|---|---|---|---|---|---|
| Twin-tandem assembly, tricycle; spacing 32.5 x 48 inches center-to-center; contact area, 208 square inches each wheel | | | | | | |
| Traffic Area | Minimum Thickness (in.)[1] | | | | | |
| | 100-CBR Base | | | 80-CBR Base | | |
| | Surface | Base | Total | Surface | Base | Total |
| A | 4 | 6 | 10 | 5 | 6 | 11 |
| B | 3 | 6 | 9 | 4 | 6 | 10 |
| C | 3 | 6 | 9 | 4 | 6 | 10 |
| D | 3 | 6 | 9 | 3 | 6 | 9 |
| Access aprons | 3 | 6 | 9 | 3 | 6 | 9 |
| Shoulders | 2 | 6 | 8 | 2 | 6 | 8 |

continued



| Light Load Design | | | | | | |
|---|---|---|---|---|---|---|
| Single wheel, tricycle; contact area, 100 square inches | | | | | | |
| Minimum Thickness[1] | | | | | | |
| Traffic Area | 100-CBR Base | | | 80-CBR Base | | |
| | Surface | Base | Total | Surface | Base | Total |
| B | 3 | 6 | 9 | 4 | 6 | 10 |
| C | 3 | 6 | 9 | 3 | 6 | 9 |
| Access aprons | 3 | 6 | 9 | 4 | 6 | 10 |
| Shoulders | 2 | 6 | 8 | 2 | 6 | 8 |



| Shortfield Design | | | | | | |
|---|---|---|---|---|---|---|
| Single-tandem assembly, tricycle; spacing 60 inches center-to-center; contact area, 400 square inches | | | | | | |
| Traffic Area | 100-CBR Base | | | 80-CBR Base | | |
| | Surface | Base | Total | Surface | Base | Total |
| A | 4 | 6 | 10 | 5 | 6 | 11 |

[1] When underlying subbase layer has a design CBR of 80, the minimum thickness of base course is 6 inches. [15]

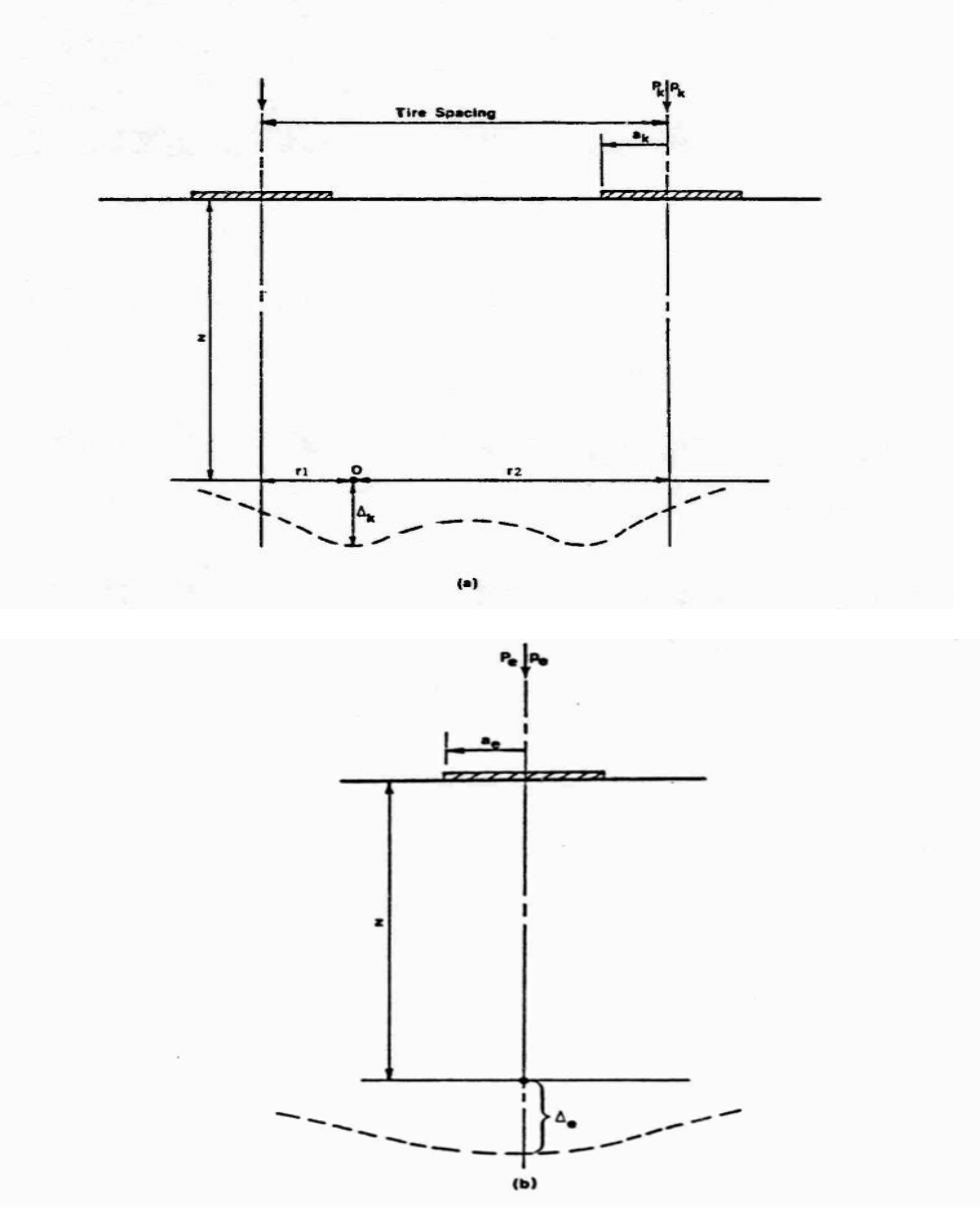


Figure 2-6: ESWL Analysis, (a) Deflection Under Multiple Gear, (b) Deflection Under Equivalent Single Wheel [15]

In Figure 4-3, $a_k$ is the radius of the assumed round, known contact area of one tire for the dual wheel configuration and a is the same for the ESWL configuration tire. Horizontal offset distances from each tire in the known configuration to the computational point in question, 0, are represented by $r_1$and $r_2$.In an elastic, homogeneous medium, the deflection $\Delta$ is expressed as:

$$\Delta = \frac{PaF}{E} \qquad \text{Equation 5.1} \qquad [14]$$

Where Δ=Deflection in inches, P=Load intensity in psi, a=Radius of contact Area Ac in inches, F=Deflection factor.

In equation 5.1 the deflection factor F is a function of the depth and offset radii ratios.

$$F = f\left(\frac{z}{a}, \frac{r}{a}\right) \qquad [14]$$

The total deflection at point 0 for the known multiple gear condition is simply the sum of the deflections contributed by each wheel load. From Equation 5.1 and Figure 5-3.

$$\Delta_k = \Delta_1 + \Delta_2 = \frac{Pk^a k}{E}(f_1 + f_2) \qquad (5.3)$$

$$F = f\left(\frac{z}{ak}, \frac{r}{ak}\right) \qquad (5.4)$$

Similarly, for the ESWL, $\Delta = \frac{Peae}{E} Fe$ (5.5)

$$F = f\left(\frac{z}{ae}, \frac{r}{ae}\right) \qquad (5.6)$$

It is desired that the total deflection under the ESWL equal the total deflection beneath the multiple gear load. Therefore, by equating the two, P , or the ESWL, may be solved for. By equating equations 5.3 and 5.5:

$$\left(\frac{Pkak}{E}\right) \sum F_i = \left(\frac{Pe\,ae}{E}\right) Fi \qquad (5.7)$$

For any multiple-wheel assembly, $P_k$ is known. Therefore, the ESWL analysis is simplified to finding the magnitude and location of the maximum $\sum F_i$ value at a specific depth. For dual-wheel gears, $\sum F_i$ values are calculated under one tire and at the center of gravity of the assembly. For dual-tandem assemblies, $\sum F_i$. values are computed underneath the center of one tire, at the center of a line connecting the two closest tires, and at the center of gravity of the assembly.

### 2.4.8 CBR Design Curve Development

The COE has developed a flexible pavement design method that allows CBR versus thickness curves to be generated for any aircraft with any type of landing gear configuration. The design curve can then be used to determine the thickness of pavement required to protect the subgrade. The equations used in this design process were derived from actual data taken from test sections and operational airfields In Chapter Three, it was stated that the design thickness, t, of a pavement is the standard thickness, T, corrected by a load repetition factor $\alpha_1$This standard thickness can be found by using the following equation:

$$T = \int \frac{E\sin L}{8.1CBR} - \frac{Ac}{\pi} \qquad [14]$$

## 2.5Layered Elastic design methods

The design of airfield pavements is a complex engineering problem that involves the interaction of multiple variables. FAARFIELD uses layered elastic and three-dimensional finite element-based design procedures for new and overlay designs of flexible and rigid pavements respectively [18, p. 12].

### 2.5.1. cumulative damage concept

FAARFIELD is based on the cumulative damage factor (CDF) concept in which the contribution of each aircraft type in a given traffic mix is summed to obtain the total cumulative damage from all aircraft operations in the traffic mix [19].

The cumulative damage factor (CDF) is the amount of structural fatigue life of a pavement that has been used. It is expressed as the ratio of applied load repetitions to allowable load repetitions to failure.

### 2.5.2. Pass-to-Coverage Ratio.

An aircraft seldom travels along a pavement section in a perfectly straight path or along the same path each time. This lateral movement is known as aircraft wander and is modeled with a normal distribution. As an aircraft moves along a taxiway or runway, it may take several trips or passes along the pavement for a specific point on the pavement to receive a coverage of one full-load application.

### 2.5.3. Pavement Life.

Design Life in FAARFIELD refers to structural life, the total number of load cycles a pavement structure will carry before it fails structurally. Functional or useful life is the period of time that the pavement is able to provide an acceptable level of service as measured by performance indicators such as FOD, skid resistance, or roughness. Pavements may have significant remaining functional life, even after they have failed structurally [18].

### 2.5.4. Design Life

It is theoretically possible to perform a pavement design for any service period. To achieve the intended design life requires consideration of many interacting factors including: (1) actual Aircraft mix as compared to traffic considered during design analysis, (2) initial quality of materials and construction, and (3) timely application of routine and preventative pavement maintenance [19, pp. 10-12].

### 2.5.5. Aircraft Traffic Volume

For pavement design use forecasts of annual departures by aircraft type including all aircraft that will use the pavement. Seasonal or other non-regular use aircraft may have significant impact on the pavement structure required. On federally funded projects when occasional or seasonal use aircraft are included in the traffic, include sensitivity analysis comparing the structure needed to accommodate all planes in the fleet to the structure needed for all planes that have at least 250 annual departures. Document and support traffic considered for pavement design in the engineer’s report.

### 2.5.6. Aircraft Traffic Volume

Generally, airfield pavements are designed considering only aircraft departures. The main reason for disregarding arrivals in design is that, typically, the arrival weights are much lighter than the departure weights (due to fuel consumption). If airport operations are such that most aircraft arrive and depart at essentially the same weight (for example, if refueling does not take place), then double the number of departures in FAARFIELD to reflect the number of times the pavement is loaded

### 2.5.7. Total Departures Over Design Life

FAARFIELD evaluates the total number of departures over the design life period. For example, FAARFIELD considers 250 annual departures with a growth rate of 0% and a 20-year design life to be 5,000 total departures. Total departures is calculated using the formula:

$$N = 1 + \frac{r \times L}{200}{}_{p} N_A \times L$$

Where: N is the total lifetime departures, NA is the annual departures, L is the design life (typically 20 years), and r is the growth rate (percent). For example, FAARFIELD considers 225 annual departures at a 1% annual growth rate to be 4,950 total departures over a 20-year design life. It is not always necessary to include all aircraft that use a facility, but it is necessary to consider all of the most demanding aircraft that use a facility. When a few operations of a heavy aircraft control the design of the pavement structure, perform a sensitivity analysis to determine the impact of the operations of that aircraft.

### 2.5.8. Minimum Layer Thickness

Establish minimum layer thicknesses for flexible and rigid pavements respectively, applicable to different aircraft weight classes. The gross weight of the heaviest aircraft in the traffic mix determines minimum thickness requirements, regardless of traffic level. The Software automatically checks the minimum layer thickness requirements for standard materials based on the traffic mix entered, however the user must still verify that all thickness requirements have been met Use the larger of the values from Table 2-4 or the thickness as calculated by Software rounded up to the nearest inch. Additional thickness may be required for frost protection.

Table 2-9: Minimum thicknesses of pavement layers [18]

| Layer Type | FAA Specification Item | Maximum Aircraft Gross Weight Operating on Pavement, lbs (kg) | | |
|---|---|---|---|---|
| | | <60,000 (27,215) | < 100,000 (45,360) | ≥100,000 (45,360) |
| Asphalt Surface[2] | P-401/P-403 | 3 in (75 mm) | 4 in (100 mm) | 4 in (100 mm) |
| Stabilized Base[3] | P-401 or P-403; P-304; P-306[3] | Not Required | Not Required | 5 in (125 mm) |
| Crushed Aggregate Base[5,6] | P-209, P-211 | Not Required | 6 in (150 mm) | 6 in (150 mm) |
| Aggregate Base[5,6] | P-207, P-208, P-210, P-212, P-213, P-219 | 6 in (75 mm) | n/a | n/a |
| Drainable Base (When Used) | P-307, P-407[7] | Not Required | 6 in (150 mm) when used | 6 in (150 mm) when used |
| Subbase[6,8] | P-154 | 6 in (150 mm) (if required) | 6 in (150 mm) (If required) | 6 in (150 mm) (if required) |

### 2.5.9. Material properties consideration

a. Asphalt Mixture Surfacing.
The asphalt material surface or wearing course: limits the penetration of surface water into the base course, provides a smooth, skid resistant surface free from loose particles that could become FOD, and resists the shearing stresses induced by aircraft wheel loads. A dense-graded asphalt mixture meets these requirements [12].

b. Base Course.
The base course distributes the imposed wheel loadings to the pavement subbase and/or subgrade. The best base course materials are composed of select, hard, and durable aggregates. The base course quality depends on material type, physical properties, gradation, and compaction. A properly constructed base course will withstand the stresses produced and resist vertical pressures that may produce consolidation and distortion of the surface course, and resist volume changes caused by fluctuations in moisture content protecting the support layer from failing [18]

c. Aggregate Base Course
The standard aggregate base course for flexible pavement design is Item P-209, Crushed Aggregate Base Course. Item P-208, Aggregate Base Course, may be used as a base for pavements accommodating aircraft fleets with all aircraft less than 60,000 pounds (27,200 kg) gross weight. [18]. The base course may be offset 12 inches (300 mm) from the edge of the asphalt surface course. It is a good construction practice to construct the base course up to 12 inches wider than the asphalt surface course.

d. Subbase Course

A subbase is required as part of the flexible pavement structure on subgrades with a CBR value less than 20. The standard subbase layer, provides the equivalent bearing capacity of a subgrade with a CBR of 20. Subbases may be aggregate or treated aggregate.

The minimum thickness of subbase is 6 inches (150 mm). This minimum is recommended as a practical construction layer thickness for non-stabilized aggregate subbase. Additional thickness may be required to structurally protect subgrade or to provide frost protection to subgrade. If pavement structural design indicates a subbase thickness less than 6 inches (150 mm), subbase may be eliminated.

e. Subgrade

The ability of a particular soil to resist shear and deformation varies with its properties, density, and moisture content. Subgrade stresses decrease with depth, and the controlling subgrade stress is usually at the top of the subgrade. the subgrade thickness is assumed to be infinite and is characterized by a modulus (E)value. Subgrade modulus values for flexible pavement design can be determined in a number of ways. The applicable procedure in most cases is to use CBR values as calculated at in-service moisture content. The software converts the CBR to the design elastic modulus using the following relationship:

$$E=1500\times CBRR \text{ (E in psi)}$$

## 3. RESEARCH METHODOLOGY

### 3.1 Research design

For the purpose of this research six Airfield pavement sections for three major Airports in Rwanda named “New Bugesera International Airport, Existing Kigali International Airport and Kamembe International Airport, will be analyzed using mechanistic-empirical design methods and Empirical CBR design method by the United States Army Corps of Engineer software “Pavement-Transportation Computer Assisted Structural Engineering (PCASE) considering similar traffic loading and Subgrade strength for each individual Airport. Then the computed thicknesses will be analyzed in the FAA airfield pavement design software FAARFIELD (FAA Rigid and Flexible Iterative Elastic Layered Design) to determine the pavement Life considering equivalent converted traffic to analyze each airport pavement design results.

### 3.2 Data Collection

### 3.2.1 Existing pavement data

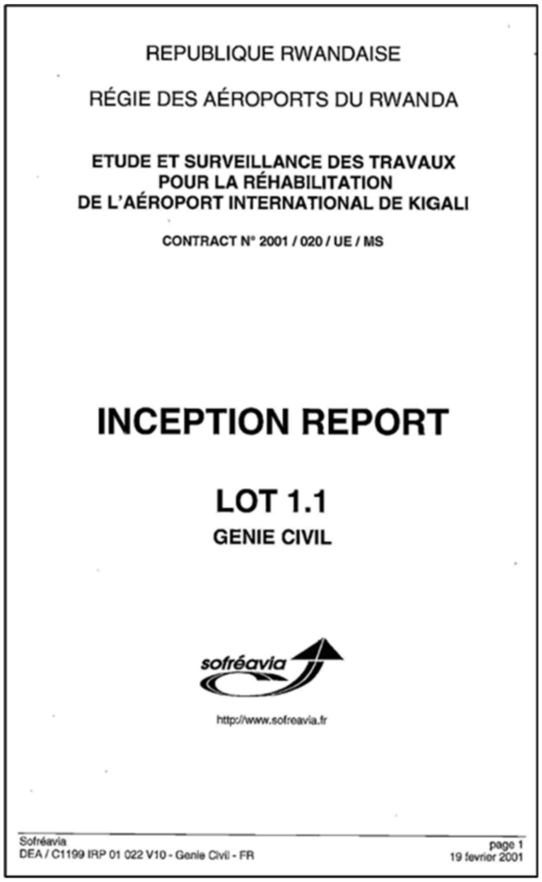
For the Purpose of comparing initially designed pavement using empirical approaches, the existing pavement will be modeled in Layered elastic analysis software to compute the life of pavement with the original designed traffic. The material characteristics of the existing pavement layers will be obtained using the Heavy Falling Weight deflectometer to compute the moduli of various pavement layers for the purpose of re-modelling the existing pavement.

### 3.2.2. Background of Kigali International Airport

Kigali International Airport is the primary airport in Rwanda located in the capital city, Kigali. The airport is located in the center of Rwanda where the aerodrome has an average elevation of 1,485 meters above sea level. The airport mainly serves commercial aircraft operations with a design capacity to handle Code E aircraft with B747-400 being the critical aircraft. The airport has a single runway 3500 meters long, oriented 10-28 and linked to three taxiways: Taxiway Alpha and Charlie which were newly constructed in 2016 and Taxiway Bravo. The airport has also three aprons; one in the north (Apron A) linked to the runway by the Taxiways A and B and two in the south (Apron B&C) linked to the runway by the Taxiway C. The airport has registered progressive traffic growth over the past years, pre-COVID (2016 - 2019) with average passenger growth of 18% and post-COVID (2021 - 2023) with average growth rate of 44%. A conservative projection for 2023 - 2027, average passenger growth is estimated to be approximately 12%, reaching 2.1 million passengers per year by 2027. Factoring in the assumption of RwandAir/Qatar Airways partnership, the growth rate is expected to be much higher than this projected number.

### 3.2.3. pavement investigation campaign

The review of the documents received revealed a study that was performed by SOFREAVIA in preparation for future rehabilitation at KIA in 2001. The study covered an assessment of the existing pavement condition based on a thorough inspection. The findings of the study are summarized below, and the data of existing conditions prevailing at that time will be considered as being for guidance only, and it will be further verified by the sampled cores taken in the Runway, given the fact the runway has undergone an interim rehabilitation after the reviewed study has been conducted.



REPUBLIQUE RWANDAISE

RÉGIE DES AÉROPORTS DU RWANDA

**ETUDE ET SURVEILLANCE DES TRAVAUX**
**POUR LA RÉHABILITATION**
**DE L'AÉROPORT INTERNATIONAL DE KIGALI**

**CONTRACT N° 2001 / 020 / UE / MS**

**INCEPTION REPORT**

**LOT 1.1**
**GENIE CIVIL**

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DEA / C1199 IRP 01 022 V10 - Genie Civil - FR
page 1
19 fevrier 2001

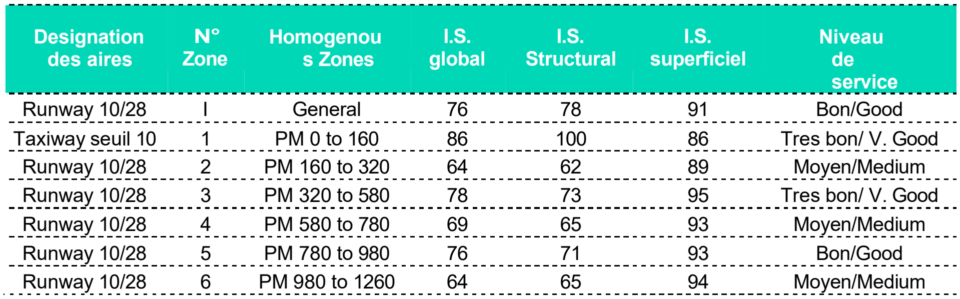
3-1 Inception report

As stated in the above-referenced study, the inspected pavement comprised the runway 10/28 (3500 m x 60 m) and the turning pads at each of the two runway ends, the Central Taxiway Linking between the Apron area and the Runway (i.e. Taxiway Bravo), and the Apron (i.e. Apron A). It was reported that all the aforementioned facilities have a flexible pavement and no rigid/PCC pavement had been reported.

The reported inspection included the findings of a pavement visual assessment and the results of a coring campaign to assess the existing structures. The results of the pavement visual inspection for the Runway are presented in terms of Runway Service Index as shown in the table below. In general, the level of service of the runway pavement was globally "Bon" (Good), with a note that numerous executed maintenance activities may have hidden the real surface condition which has deteriorated/degraded over time. The structural index was judged to be "Passable" (or Fair to

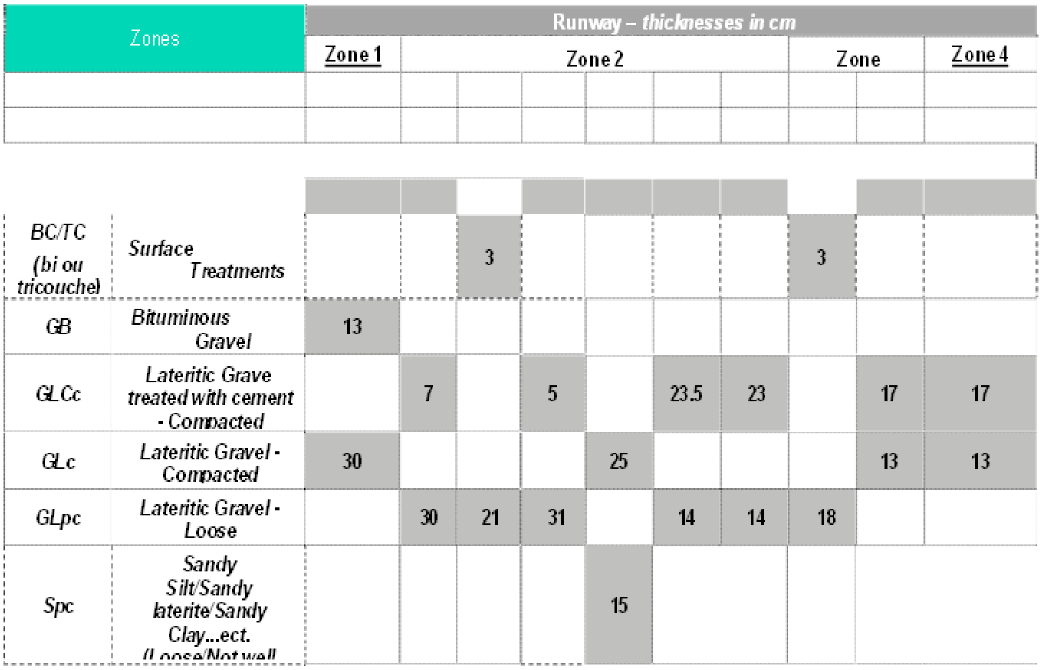
Poor) as water was seeping into the structure leading to accelerated aging and deterioration of layers, with some areas that were reported to be in need to be completely purged for being extremely deteriorated.

Table 3-1: Pavement condition Index report [20, pp. 24-26]



| Designation des aires | N° Zone | Homogenous Zones | I.S. global | I.S. Structural | I.S. superficiel | Niveau de service |
|---|---|---|---|---|---|---|
| Runway 10/28 | I | General | 76 | 78 | 91 | Bon/Good |
| Taxiway seuil 10 | 1 | PM 0 to 160 | 86 | 100 | 86 | Tres bon/ V. Good |
| Runway 10/28 | 2 | PM 160 to 320 | 64 | 62 | 89 | Moyen/Medium |
| Runway 10/28 | 3 | PM 320 to 580 | 78 | 73 | 95 | Tres bon/ V. Good |
| Runway 10/28 | 4 | PM 580 to 780 | 69 | 65 | 93 | Moyen/Medium |
| Runway 10/28 | 5 | PM 780 to 980 | 76 | 71 | 93 | Bon/Good |
| Runway 10/28 | 6 | PM 980 to 1260 | 64 | 65 | 94 | Moyen/Medium |

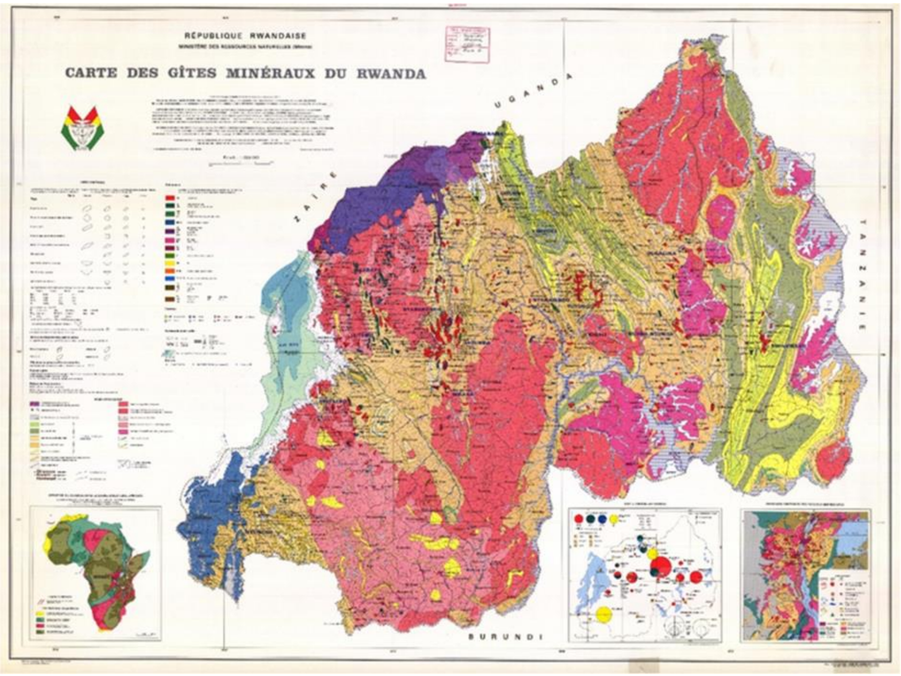
Table 3-2:Existing Pavement materials [20]



| Zones | | Runway – *thicknesses in cm* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Zone 1 | Zone 2 | | | | | | Zone | Zone 4 |
| *BC/TC (bi ou tricouche)* | *Surface Treatments* | | | 3 | | | | | 3 | | |
| *GB* | *Bituminous Gravel* | 13 | | | | | | | | | |
| *GLCc* | *Lateritic Grave treated with cement - Compacted* | | 7 | | 5 | | 23.5 | 23 | | 17 | 17 |
| *GLc* | *Lateritic Gravel - Compacted* | 30 | | | | 25 | | | | 13 | 13 |
| *GLpc* | *Lateritic Gravel - Loose* | | 30 | 21 | 31 | | 14 | 14 | 18 | | |
| *Spc* | *Sandy Silt/Sandy laterite/Sandy Clay...ect. (Loose/Not well* | | | | | 15 | | | | | |

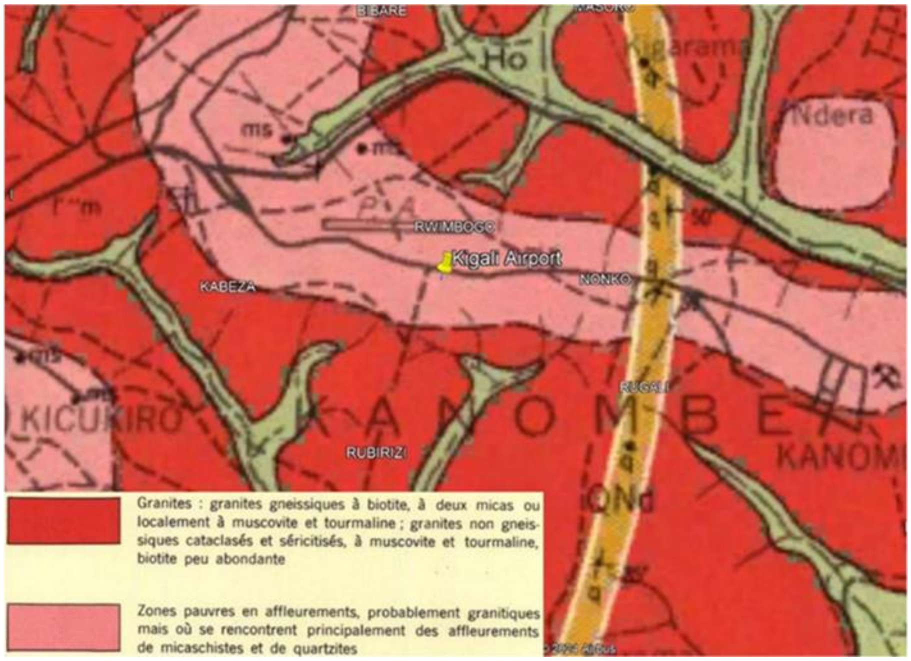
### 3.2.4. Review of geological conditions of the project site

The geology of Rwanda generally is made up of sandstones alternating with shales, which are all assigned to the Mesoproterozoic Burundian Supergroup as shown in the figure below, sometimes intercalated by granitic intrusions. In the east of the country, the geology consists of predominate older granites and gneisses. Neogene volcanics are found in the northwestern and southwestern parts of Rwanda. Young alluvials and lake sediments occur along the rivers and lakes. In various localities of Rwanda, for instance to the south and southwest of Butare and in the Congo- Nile watershed to the southwest of Rwengeri, pre-Burundian migmatites and gneisses accompanied by crystalline whitish quartzites occur. Generally, the stratigraphic sequences established in Rwanda can be identified with those, which appear in neighboring Burundi. The sedimentary succession of the Burundian Supergroup can be subdivided into the following units: the Lower Series (la Série Inférieure), the Byumba Series, and the Miyove Series; each of these can subdivided into formations of quartzites and various undifferentiated rocks. The base of the Lower Series is the most developed formation, characterized by black sericitic shales. The metamorphic rocks in the east of the country probably represent metamorphosed Burundian formations. All these sedimentary sequences indicate a former shallow marine, high-energetic environment, as often shown by the oblique stratification, the conglomerates, and the symmetric ripple marks within the layers



3-2 Geological map of Rwanda

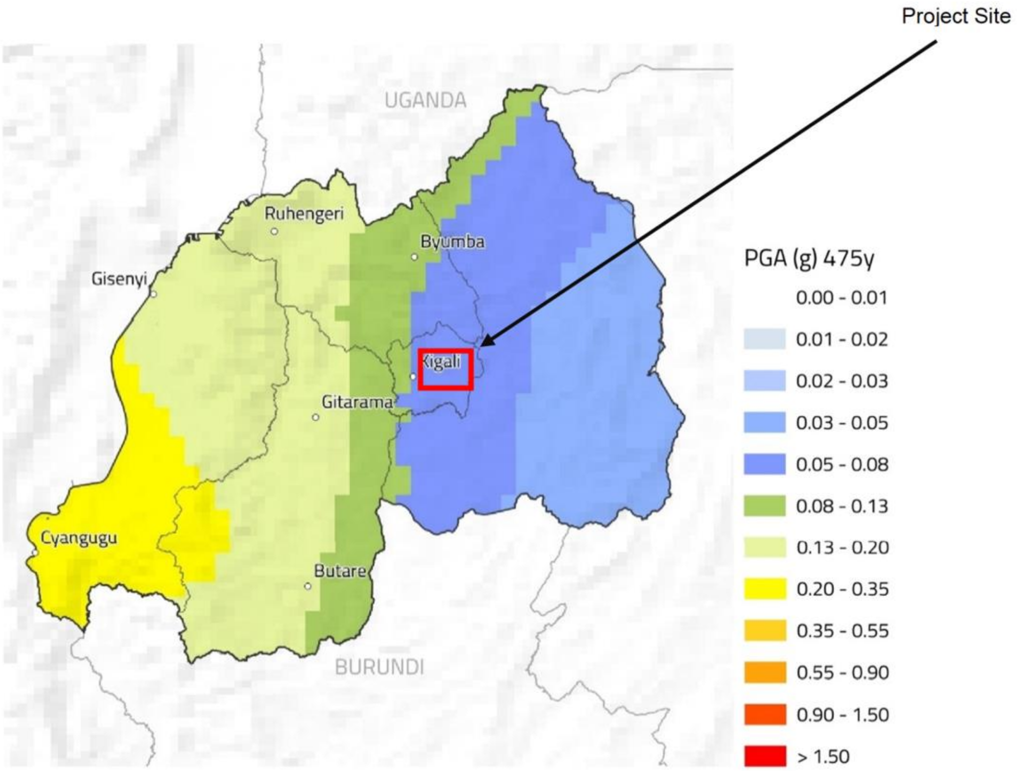
Based on the available geological map, the project site is covered mainly of granites: gneissic granites with biotite, two micas, or locally muscovite and tourmaline; sericitized sub-granular granites with muscovite, tourmaline and low abundance biotite and poor areas of granitic origin showing the outcropping of mica schists and quartzites as shown in the following figure:



3-3: Geological Map covering the Project Site

### 3.2.5. seismic data

The project site is located on a medium seismic zone as shown in the Seismic Hazard Map (Figure 11). The range of PGA is between 0.05 and 0.08 g.



**3-4: Seismic Hazard Map of Rwanda, Global Earthquake Model (GEM), (2018**

### 3.2.6. Layers thickness data

Table 3-3*:* Summary of Existing Pavements Layer Thicknesses.

| Item | Location | Layer Thickness | | |
|---|---|---|---|---|
| | | **AC Layer (cm)** | **Aggregate Base (cm)** | **Aggregate Subbase (cm)** |
| **1** | Apron A | 20 | 45 | - |
| **2** | VIP Apron | 20 | 45 | - |
| **3** | General Aviation Apron | 6 | 30 | - |
| **4** | Apron B | 20 | 15 | 40 |
| **5** | Apron C | 20 | 15 | 40 |
| **6** | Turning Pad / Runway End 10 | 40 | 30 | - |

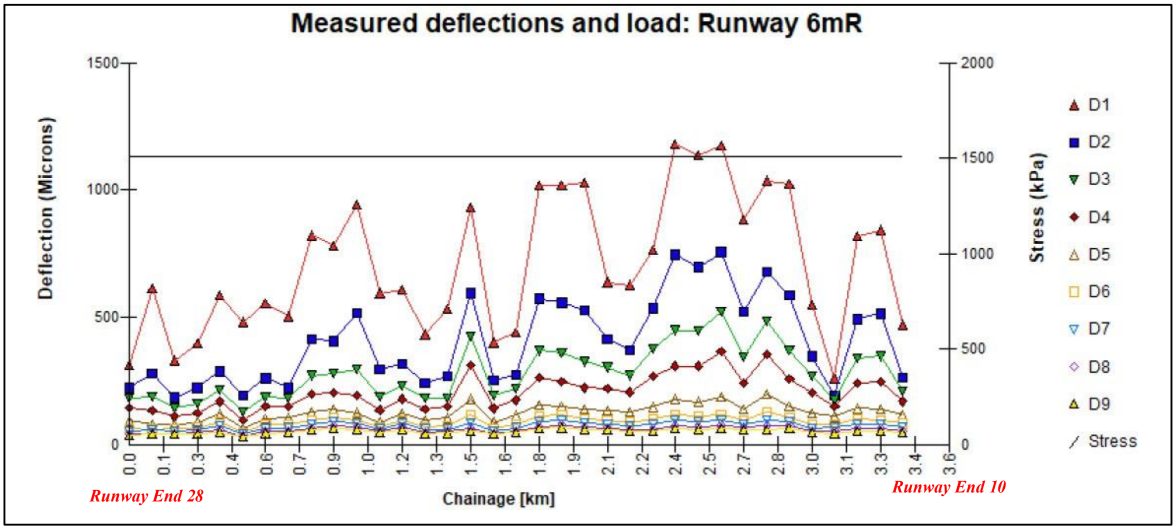
| | | | | |
|---|---|---|---|---|
| **7** | Runway (excluding turning pad at runway End 10 and the stretch between stations 0+500<br>to 0+1000) | 19 | 30 | - |
| **8** | Runway stretch between stations 0+600 and 0+1000 | 13 | 30 | - |
| **9** | TWY Alpha (first 100 m at intersection with Apron A) | 14 | 30 | - |
| **10** | TWY Alpha (except for first 100 m at intersection with Apron A) | 24 | 30 | - |
| **11** | TWY Bravo | 17 | 40 | - |
| **12** | TWY Charlie | 20 | 15 | 40 |

### 3.2.7. Heavy Falling weight deflectometer test

All HFWD test points were included in a detailed back-analysis procedure to determine the effective stiffness of each distinct pavement layer. A pavement structure can be satisfactorily modelled as a (non-)linear elastic multi-layered structure. This model enables the different pavement layers to be analyzed. The subgrade approach allows for a non- linear variation in material stiffness with depth. In addition, the model searches for a depth to a stiff layer below which there is no influence on the measured surface deflections.

The HFWD-generated load-deflection data was analyzed using the so-called "mechanical-empirical" methodology, through a specially developed software package designed to accomplish the task in the best and most efficient manner available. The system is "analytical" in the sense that actual, in-situ material properties and wheel load responses are derived through a reverse, layered analysis technique, as described below. It is still "empirical" however in the sense that the relationships between the load related response of these mechanistic or analytical properties and future pavement performance are based upon past experience (observed performance) and associated (laboratory) research. The software package employed was the BAKFAA software package. BAKFAA is listed in Table 16 of FAA AC 150/5370-11B meeting the requirements for use in the back-calculation process.

A full record of the deflection data is obtained and presented in the factual report of the HFWD testing survey. This data is used for conducting the back calculation for determining the back-calculation of the various layer moduli for the pavement under analysis. A sample of the measured deflection data is presented in the figures below:



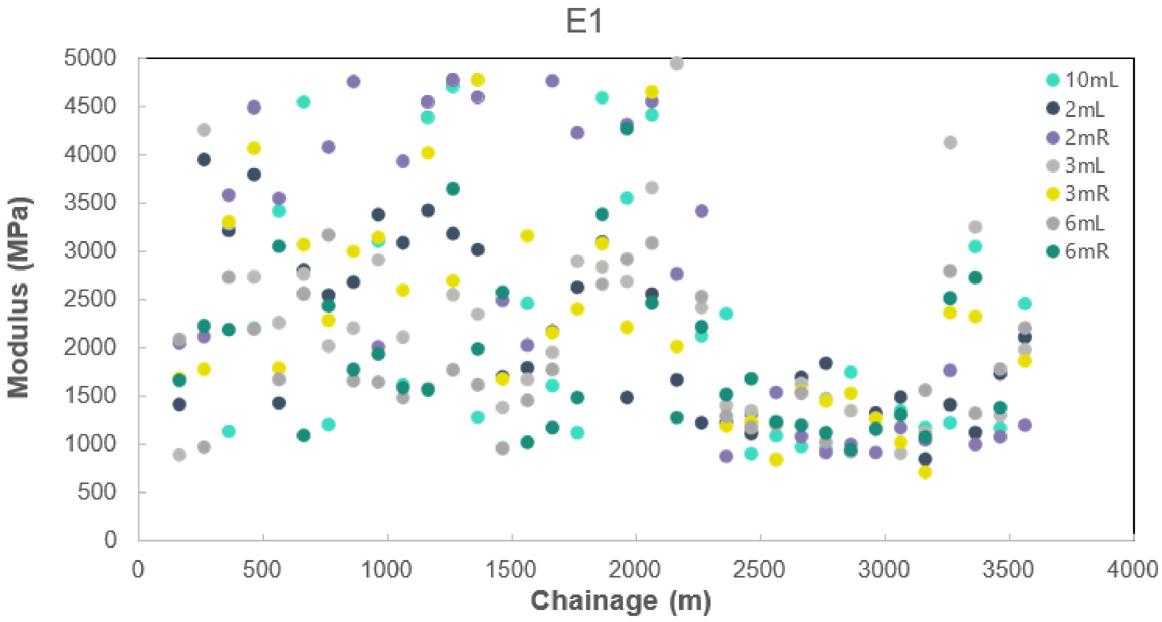
3-5: Graphical presentation deflections Runway 6mR Track

Based on conducted analysis, the back-calculated moduli for the various layers of the asphalt pavement sections in each of the assessed airfield facilities is presented by the following parameters:

- E1 = stiffness Asphalt Concrete (AC) Surface
- $E1^{30}$ = stiffness AC at Reference Temperature calculated to be 30ºC. being used for pavement analysis.
- E2 = stiffness Crushed Aggregate Base Course (CABC)
- E3 = stiffness Aggregate Subbase Course (ASC)
- E4 = stiffness Subgrade
- h1 = thickness AC
- h2 = thickness CABC
- h3 = thickness ASC.

The Back-calculated Modulus of Elasticity of the subgrade “E4” have to be multiplied by a Correction or Adjustment Factor of 0.33 (as per the recommendations of the relevant international standards for Non-Destructive Testing and HFWD Back-calculation procedures), prior to adopting it in the HFWD Analysis and further calculation of the CBR. This is applied to account for variability and possibility of having some scattered weak, soft spots that could be present within the subgrade soil mass and that may not be sufficiently consolidated, compacted or confined. This parameter will be referred to in the analysis as the Corrected E4 value and it will be used to characterize the existing subgrade property for the pavement rehabilitation design.

For the case of the Runway, the testing was conducted over various tracks offset from the centerline as presented in the figures below where averages per station over the various tracks is considered as summarized in the table below.



3-6: Backcaulcated E1 moduli along Runway Alignment for various HFWD testing tracks.

As presented in the figures above, the data shows a scatter in the three moduli values along the Runway alignment. For the asphalt concrete layers, the average back-calculated modulus “E1” per station is in the range of 1066 MPa to 3795 MPa with an overall average modulus of 2293 MPa and a standard deviation of 824 MPa showing a 15th percentile value of 1239 MPa. For the case of the granular layers, the average back-calculated modulus is in the range of 284 MPa to 3780 MPa with an overall average value of 1282 MPa and a 15th percentile of 409 MPa which is considered on the upper side for similar material. For the characterization of the existing subgrade values, the corrected modulus will be considered in the design of the pavement rehabilitation works where the analysis shows that it is in the range of 139 MPa to 385 MPa with a 15th percentile of 175 MPa, which verifies the adoption of a design **CBR value of 15%** for the pavement rehabilitation design as stated in the above sections of this research.

Table 3-4: Summary of Back-calculated AC, Granular Layer, and Subgrade Moduli based on HFWDF testing

| **Chainage** | **E1 (MPa)** | **E2 (MPa)** | **E4 (MPa)** | **Corrected E4 (MPa)** |
|---|---|---|---|---|
| 1565 | 1929 | 402 | 632 | 208 |
| 1665 | 2215 | 320 | 666 | 220 |
| 1765 | 2875 | 917 | 586 | 193 |
| 1865 | 3555 | 1374 | 681 | 225 |
| 1965 | 3050 | 1418 | 618 | 204 |
| 2065 | 3612 | 1793 | 421 | 139 |
| 2165 | 3268 | 1652 | 712 | 235 |
| 2265 | 2948 | 1205 | 653 | 215 |
| 2365 | 1395 | 1298 | 807 | 266 |
| 2465 | 1239 | 599 | 833 | 275 |
| 2565 | 1128 | 1509 | 782 | 258 |
| 2665 | 1367 | 1029 | 699 | 231 |
| 2765 | 1241 | 1351 | 762 | 251 |
| 2865 | 1191 | 2395 | 841 | 277 |
| 2965 | 1167 | 1887 | 915 | 302 |
| 3065 | 1209 | 1916 | 1063 | 351 |
| 3165 | 1066 | 1730 | 920 | 304 |
| 3265 | 2301 | 1898 | 1030 | 340 |
| 3365 | 2101 | 3397 | 1078 | 356 |
| 3465 | 1962 | 2302 | 1164 | 384 |
| 3565 | 1957 | 2251 | 964 | 318 |
| **Average** | **2293.2** | **1282.2** | **705.8** | **232.9** |
| **Standard Deviation** | **823.8** | **881.5** | **192.4** | **63.5** |
| **Minimum** | **1066.0** | **284.9** | **421.4** | **139.1** |
| **Maximum** | **3795.1** | **3780.5** | **1163.7** | **384.0** |
| **15th Percentile** | **1239.4** | **409.2** | **529.7** | **174.8** |

### 3.2.8. pavement design traffic and loading criteria for Kigali International Airport

The total number of air traffic movements (total departures) that are used in the pavement design are shown in the following set of tables:

**Table 3-5:KIA  Traffic Data (2023)**

| Aircraft | Aircraft in FAARFIELD | Maximum Take-Off Weight (Kg) | Annual Average Departures |
|---|---|---|---|
| **A220** | A220-300 | 67,585 | 89 |
| **A320** | A320-200 opt | 78,400 | 209 |
| **A321** | A321XLR | 101,000 | 91 |
| **A310** | A310-200 | 142,900 | 18 |
| **A330** | A330-900 WV920 | 251,900 | 2720 |
| **A340** | A340-600 WV101 | 381,200 | 2 |
| **A350** | A350 | 308,900 | 47 |
| **B737** | B737-9 MAX | 88,541 | 8122 |
| **B757** | B757-300 | 122,920 | 15 |
| **B767** | B767-400 ER | 204,570 | 20 |
| **B747** | B747-400 | 397,800 | 15 |
| **B777** | B777 | 352,442 | 189 |
| **B787** | B787-9 | 255,372 | 503 |
| **AN26/74** | D-75 | 36,500 | 12 |
| **AN12** | D-150 | 61,000 | 24 |
| **AN124** | An-124 | 397,995 | 22 |
| **Beechcraft** | Beechcraft King Air 350 | 6,849 | 72 |
| **ATR43** | ATR 42-500 | 18,770 | 45 |
| **C208** | Cessna 208B Grand Caravan | 3,969 | 1152 |
| **C550** | Cessna Citation II/Bravo C550/551 | 6,804 | 45 |
| **C680** | Cessna Citation X | 16,329 | 4 |
| **DH8** | Q100/Dash 8 Series 100 | 15,740 | 4043 |
| **CRJ9** | CRJ900 | 38,555 | 1844 |
| **CRJ1/2** | CRJ100/200 | 21,636 | 4 |
| **CL30/60** | D-50 | 21,863 | 80 |
| **DA** | S-5 | 2,300 | 329 |
| **E190** | EMB-190 STD | 47,950 | 1768 |
| **E35L** | D-50 | 22,500 | 4 |
| **GALX/GLF4** | Gulfstream-G-IV | 34,019 | 37 |
| **GLF/GLEX** | D-35 | 16,080 | 220 |
| **FA7X** | D-75 | 31,751 | 69 |

|  |  |  |  |
|---|---|---|---|
| **Falcon** | Dassault Falcon 900B/C | 20,638 | 58 |
| **F50** | Fokker 50 | 20,820 | 37 |
| **Pilatus** | S-10 | 4,740 | 117 |
| **P92** | S-3 | 1,213 | 314 |
| **Q400** | Q400/Dash 8 Series 400 | 29,347 | 417 |
| **MD87/DC 9** | MD-83 | 73,016 | 4 |
| **MD11** | MD-11 | 287,129 | 3 |
| **L410** | S-15 | 6,600 | 3 |
| **L145/160** | ERJ-145 XR | 24,200 | 7 |
| **IL76** | 2D-400 | 170,000 | 44 |
| **FA50** | Dassault Falcon 50/50EX | 17,599 | 37 |

Table 3-6:Aircraft traffic Mix for Apron A

| Aircraft | Aircraft in FAARFIELD | Maximum Take-Off Weight (Kg) | Annual Averag Moven nts |
|---|---|---|---|
| **A330** | A330-900 WV920 | 251,900 | 1623 |
| **A350** | A350 | 308,900 | 34 |
| **B747** | B747-400 | 397,800 | 7 |
| **B777** | B777 | 352,442 | 136 |
| **B787** | B787-9 | 255,372 | 338 |
| **AN12** | D-150 | 61,000 | 14 |
| **AN124** | An-124 | 397,995 | 14 |
| **IL76** | 2D-400 | 170,000 | 28 |
| **A220** | A220-300 | 67,585 | 34 |
| **A320** | A320-200 opt | 78,400 | 68 |
| **A321** | A321XLR | 101,000 | 34 |
| **B737** | B737-9 MAX | 88,541 | 2366 |
| **CRJ9** | CRJ900 | 38,555 | 541 |
| **GLF/GLEX** | D-35 | 16,080 | 68 |
| **E190** | EMB-190 STD | 47,950 | 541 |

Table 6-8: Aircraft traffic mix and annual movements for General Aviation Apron.

| Aircraft | Aircraft in FAARFIELD | Maximum Take-Off Weight (Kg) | Annual Average Movements |
|---|---|---|---|

|  |  |  |  |
|---|---|---|---|
| **Beechcraft** | Beechcraft King Air 350 | 6,849 | 15 |
| **C208** | Cessna 208B Grand Caravan | 3,969 | 370 |
| **C550** | Cessna Citation II/Bravo C550/551 | 6,804 | 15 |
| **CL30/60** | D-50 | 21,863 | 26 |
| **DA** | S-5 | 2,300 | 74 |
| **GALX/GLF4** | Gulfstream-G-IV | 34,019 | 12 |
| **Falcon** | Dassault Falcon 900B/C | 20,638 | 19 |
| **Pilatus** | S-10 | 4,740 | 37 |
| **P92** | S-3 | 1,213 | 74 |
| **FA50** | Dassault Falcon 50/50EX | 17,599 | 15 |
| **Helicopters** | S-3 | 1,200 | 19 |
| **AN26/74** | D-75 | 36,500 | 4 |
| **DH8** | Q100/Dash 8 Series 100 | 15,740 | 1330 |
| **FA7X** | D-75 | 31,751 | 23 |
| **F50** | Fokker 50 | 20,820 | 15 |

Table 6-9: Aircraft traffic mix and annual Movements for Aprons B and C.

| **Aircraft** | **Aircraft in FAARFIELD** | **Maximum Take-Off Weight (Kg)** | **Annual Average Movements** |
|---|---|---|---|
| **Beechcraft** | Beechcraft King Air 350 | 6,849 | 8 |
| **C208** | Cessna 208B Grand Caravan | 3,969 | 193 |
| **C550** | Cessna Citation II/Bravo C550/551 | 6,804 | 8 |
| **CL30/60** | D-50 | 21,863 | 14 |
| **DA** | S-5 | 2,300 | 39 |
| **GALX/GLF4** | Gulfstream-G-IV | 34,019 | 6 |
| **Falcon** | Dassault Falcon 900B/C | 20,638 | 10 |
| **Pilatus** | S-10 | 4,740 | 20 |
| **P92** | S-3 | 1,213 | 39 |

| | | | |
|---|---|---|---|
| **FA50** | Dassault Falcon 50/50EX | 17,599 | 8 |
| **Helicopters** | S-3 | 1,200 | 10 |
| **AN26/74** | D-75 | 36,500 | 2 |
| **DH8** | Q100/Dash 8 Series 100 | 15,740 | 693 |
| **FA7X** | D-75 | 31,751 | 12 |
| **F50** | Fokker 50 | 20,820 | 8 |
| **Q400** | Q400/Dash 8 Series 400 | 29,347 | 77 |
| **B737** | B737-9 MAX | 88,541 | 693 |

### 3.2.9. pavement design traffic and loading criteria for NBIA

The traffic loading for New Bugesera International Airport is projected by simulating Existing Kigali International Airport with a traffic growth of 1% for aircraft with Maximum takeoff weight weight greater or equal to 75 Tones.

Table 3-7 Aircraft Mix for New Bugesera International Airport(projected for 2045)

| | Aircraft in FAARFIELD | Maximum Take-Off Weight (Kg) | Annual Average Departures |
|---|---|---|---|
| **A220** | A220-300 | 67,585 | 120 |
| **A320** | A320-200 opt | 78,400 | 250 |
| **A321** | A321XLR | 101,000 | 105 |
| **A310** | A310-200 | 142,900 | 18 |
| **A330** | A330-900 WV920 | 251,900 | 3300 |
| **A340** | A340-600 WV101 | 381,200 | 15 |
| **A350** | A350 | 308,900 | 60 |
| **B737** | B737-9 MAX | 88,541 | 9100 |
| **B757** | B757-300 | 122,920 | 25 |

|  |  |  |  |
|---|---|---|---|
| **B767** | B767-400 ER | 204,570 | 32 |
| **B747** | B747-400 | 397,800 | 22 |
| **B777** | B777 | 352,442 | 200 |
| **B787** | B787-9 | 255,372 | 503 |
| **AN26/74** | D-75 | 36,500 | 12 |
| **AN12** | D-150 | 61,000 | 24 |
| **AN124** | An-124 | 397,995 | 35 |
| **Beechcraft** | Beechcraft King Air 350 | 6,849 | 72 |
| **ATR43** | ATR 42-500 | 18,770 | 45 |
| **C208** | Cessna 208B Grand Caravan | 3,969 | 1152 |
| **C550** | Cessna Citation II/Bravo C550/551 | 6,804 | 45 |
| **C680** | Cessna Citation X | 16,329 | 4 |
| **DH8** | Q100/Dash 8 Series 100 | 15,740 | 4043 |
| **CRJ9** | CRJ900 | 38,555 | 1844 |
| **CRJ1/2** | CRJ100/200 | 21,636 | 4 |
| **CL30/60** | D-50 | 21,863 | 80 |
| **DA** | S-5 | 2,300 | 329 |
| **E190** | EMB-190 STD | 47,950 | 1768 |
| **E35L** | D-50 | 22,500 | 4 |
| **GALX/GLF4** | Gulfstream-G-IV | 34,019 | 37 |
| **GLF/GLEX** | D-35 | 16,080 | 220 |
| **FA7X** | D-75 | 31,751 | 69 |
| **Falcon** | Dassault Falcon 900B/C | 20,638 | 58 |
| **F50** | Fokker 50 | 20,820 | 37 |

| | | | |
|---|---|---|---|
| **Pilatus** | S-10 | 4,740 | 117 |
| **P92** | S-3 | 1,213 | 314 |
| **Q400** | Q400/Dash 8 Series 400 | 29,347 | 417 |
| **MD87/DC9** | MD-83 | 73,016 | 4 |
| **MD11** | MD-11 | 287,129 | 3 |
| **L410** | S-15 | 6,600 | 3 |
| **L145/160** | ERJ-145 XR | 24,200 | 7 |
| **IL76** | 2D-400 | 170,000 | 60 |
| **FA50** | Dassault Falcon 50/50EX | 17,599 | 37 |

### 3.2.10. Kamembe Airport

Kamembe is located in Ruzizi District, about 5 km southwest of Cyangugu city which lies at the southern end of Lake Kivu. Kamembe is connected by a 170 km long road from Kigali. The existing Airport is located near Kamembe (Western Province) at approximately 2km from Kivu Lake and Democratic Republic of Congo border, and about 5km from Kamembe town. The airport was constructed about 57 years ago but resurfacing works (surface treatment) was done on the taxiway and the apron. Also, expansion of the runway in its present location is a challenge due to lack of space and mountainous terrain. The existing airport has 1500m X 45m flexible (asphalt) runway and oriented in 02-20 direction. The runway at present is open to Visual Flight Rules (VFR) operations only. RWY 20 for Landings and RWY 02 for Take offs are recommended in the Aeronautical Information Publication (AIP)

Total10 trial pits were dug all along the existing runway edges as well in extension portion. Out of total 10trial pits, 3 were dug on the edge of existing runway starting from chainage 7m to 1500m trial pits were dug in the extension portion towards 02 end. Two Trial pits were also dug in the apron area. The locations of test pits were selected with reference to the proposed location of key facilities such as runway, taxiway and apron. For convenience the locations of trial pits were finalized with reference to the runway chainage considering end of the existing runway as 0m chainage increasing towards 02 end of runway. The general properties of the sub grade material along the existing runway are summarized in as below in situ results summary.

Analysis of Sub Grade CBR Results and Determination of Design CBR In-situ conditions: - It is observed that insitu compaction is considerably less than MDD (with little variance from 86% to 87%) and that Laboratory CBR in soaked condition at 95% compaction is reported to be between 5% to 17.5% (It is observed that almost 9 out of 17 Trial Pits have reported field

CBR as between 5% to 7%). Accordingly, it can be mentioned that the CBR at the field compaction is most likely to be near to the lowest value obtained from the laboratory tests. Both density and CBR tests are representatives of poor in-situ condition of soil. According to sub grade CBR results (samples compacted to 95% of modified proctor optimum density after immersed in water for four days) the minimum CBR is 5%. Further the CBR (samples compacted to 95% of modified proctor optimum density after immersed in water for four days) . one standard deviation below **the mean is 5.5.**

### 3.2.11. pavement design traffic and loading for Kamembe Airport

Table 3-8:Aircraft Mix for Kamembe Airport (2020)

| Aircraft | Aircraft in FAARFIELD | Maximum Take-Off Weight (Kg) | Annual Average Movements |
|---|---|---|---|
| **AN12** | D-150 | 61,000 | 14 |
| **AN124** | An-124 | 397,995 | 14 |
| **IL76** | 2D-400 | 170,000 | 28 |
| **A220** | A220-300 | 67,585 | 34 |
| **A320** | A320-200 opt | 78,400 | 68 |
| **A321** | A321XLR | 101,000 | 34 |
| **B737** | B737-9 MAX | 88,541 | 2366 |
| **CRJ9** | CRJ900 | 38,555 | 541 |
| **GLF/GLEX** | D-35 | 16,080 | 68 |
| **Q400** | Q400/Dash 8 Series 400 | 47,950 | 541 |

### 3.3 Pavement design Approaches

The design of flexible pavement draws back in the second world war when the CBR design method was established by the US army corps of engineers for design of military airfields. Later on, the United States Federal Aviation Administration (FAA) adopted the method to be used for general civil airports. The international Civil Aviation Organization latter accepted the CBR as the standardized methods of designing airfield pavement in early 1950s.with the evolution of technology and larger aircraft coming in use, the previous CBR methods were progressively updated until its replacement to a new elastic design methods taking into account stresses due to traffics loads and strains in the materials.

### 3.3.1 Empirical design methodology

An empirical approach is one which is based on the results of experiments or experience. Generally, it requires a number of observations to be made in order to ascertain the relationships between input variables and outcomes. It is not necessary to firmly establish the scientific basis for the relationships between variables and outcomes as long as the limitations with such an approach are recognized. Specifically, it is not prudent to use empirically derived relationships to describe phenomena that occur outside the range of the original data used to develop the relationship. In some cases, it is much more expedient to rely on experience than to quantify the exact cause and effect of certain phenomena.

### 3.3.2 Mechanistic empirical design methodology

Mechanics is the science of motion and the action of forces on bodies. Thus, a mechanistic approach seeks to explain phenomena only by reference to physical causes. In pavement design, the phenomena are the stresses, strains and deflections within a pavement structure, and the physical causes are the loads and material properties of the pavement structure. The relationship between these phenomena and their physical causes is typically described using a mathematical model. Various mathematical models can be (and are) used; the most common is a layered elastic model [21].

Along with this mechanistic approach, empirical elements are used when defining what value of the calculated stresses, strains and deflections result in pavement failure. The relationship between physical phenomena and pavement failure is described by empirically derived equations that compute the number of loading cycles to failure.

The basic advantages of a mechanistic-empirical pavement design method over a purely empirical one are [14]:

- It can be used for both existing pavement rehabilitation and new pavement construction
- It accommodates changing load types
- It can better characterize materials allowing for:
    - Better utilization of available materials
    - Accommodation of new materials
    - An improved definition of existing layer properties
- It uses material properties that relate better to actual pavement performance
- It provides more reliable performance predictions
- It better defines the role of construction
- It accommodates environmental and aging effects on materials

The benefit of a mechanistic-empirical approach is its ability to accurately characterize in situ material (including subgrade and existing pavement structures). This is typically done by using a portable device (like an FWD) to make actual field deflection measurements on a pavement structure to be overlaid. These measurements can then be input into equations to determine existing pavement structural support (often called “backcalculation”) and the approximate remaining pavement life. This allows for a more realistic design for the given conditions [21].

## 3.4. Design methods to be used

### 3.4.1 FAA Layered elastic analysis design methods.

LEAF is a layered elastic analysis computer program developed for use as a component in Federal Aviation Administration (FAA) airport pavement design and analysis application computer programs.

The basic set of structural responses which are calculated from the layered elastic equations are vertical stress, σz, radial stress, σr, tangential stress, σt, vertical-radial shear stress, τzr, vertical deflection, w, and radial deflection, us illustration of the type of computation required, the FAA has developed the computer software FAAFIELD with the design philosophy of mechanistic-empirical approach.

The design of airport pavements is a complex engineering problem that involves the interaction of multiple variables. FAARFIELD uses layered elastic and three-dimensional finite element-based design procedures for new and overlay designs of flexible and rigid pavements respectively. For flexible pavement design, FAARFIELD uses the maximum vertical strain at the top of the subgrade and the maximum horizontal strain at the bottom of all asphalt layers as the predictors of pavement structural life.

### 3.4.2 PCASE Layered elastic design methods

The PCASE is Pavement-Transportation Computer Assisted Structural Engineering software developed and in use by the US Army corps of engineers for design of airfield and Roadway pavements.

# 4. DATA ANALYSIS AND INTERPRETATION

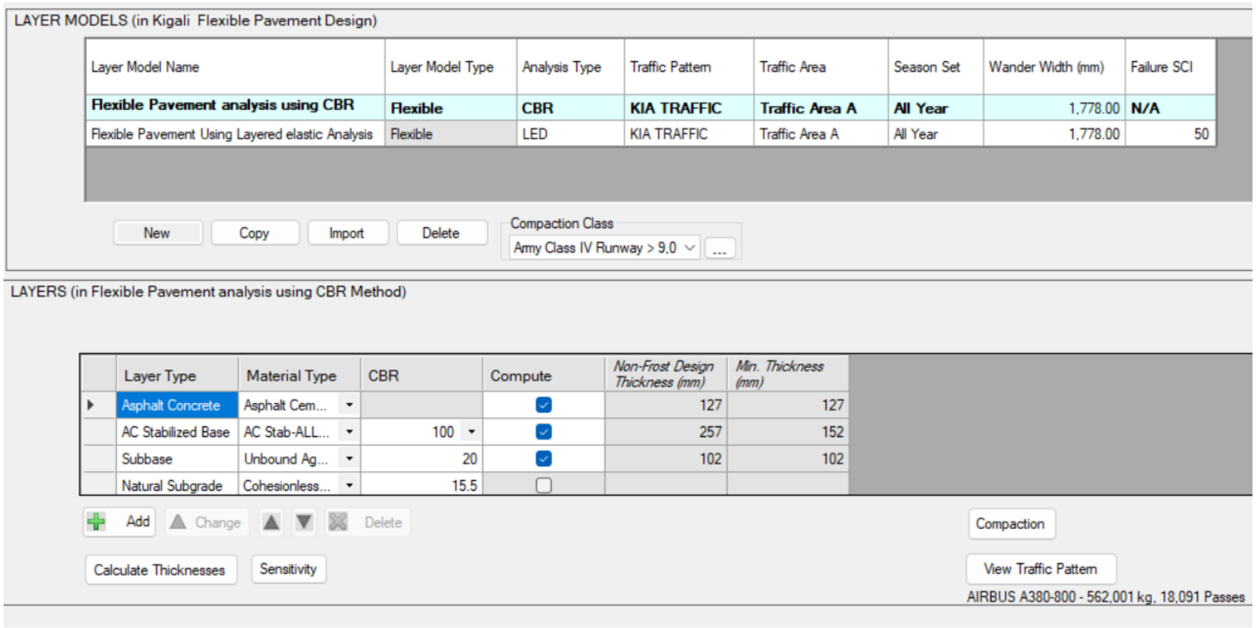
## 4.1Kigali international Airport pavement analysis and design

### 4.1.1Kigali Pavement design method using PCASE-CBR Method

Flexible Pavement. Flexible pavements are so designated due to their flexibility under load and their ability to withstand small degrees of deformation. The design of a flexible pavement structure is based on the requirement to limit the deflections under load and to reduce the stresses transmitted to the natural subsoil. The principal components of the pavement include a bituminous concrete surface, graded crushed aggregate base course, stabilized material, drainage layer, separation layer, and subbase courses. A bituminous concrete surface course is hot mixed bituminous concrete designed as a structural member with weather and abrasion resisting properties. It may consist of wearing and binder or intermediate course.

Pavement design considerations:

- The design CBR is 15.5%
- Aircraft Traffic Mix to be considered are in data Table 3-5
- The wearing course is HMA layer
- The HMA Stabilized base course will be used
- The traffic Area A in PCASE software is main pavement area (Runways, Taxiways and Aprons)
- The subbase course is uncrushed aggregate with Minimum CBR of 20
- The design period is 20 years



LAYER MODELS (in Kigali  Flexible Pavement Design)

| Layer Model Name | Layer Model Type | Analysis Type | Traffic Pattern | Traffic Area | Season Set | Wander Width (mm) | Failure SCI |
|---|---|---|---|---|---|---|---|
| **Flexible Pavement analysis using CBR** | **Flexible** | **CBR** | **KIA TRAFFIC** | **Traffic Area A** | **All Year** | **1,778.00** | **N/A** |
| Flexible Pavement Using Layered elastic Analysis | Flexible | LED | KIA TRAFFIC | Traffic Area A | All Year | 1,778.00 | 50 |

Compaction Class: Army Class IV Runway > 9,0

LAYERS (in Flexible Pavement analysis using CBR Method)

| Layer Type | Material Type | CBR | Compute | *Non-Frost Design Thickness (mm)* | *Min. Thickness (mm)* |
|---|---|---|---|---|---|
| Asphalt Concrete | Asphalt Cem... |  | ☑ | 127 | 127 |
| AC Stabilized Base | AC Stab-ALL... | 100 | ☑ | 257 | 152 |
| Subbase | Unbound Ag... | 20 | ☑ | 102 | 102 |
| Natural Subgrade | Cohesionless... | 15.5 | ☐ |  |  |

AIRBUS A380-800 - 562,001 kg, 18,091 Passes

Figure 4-1: Summarized results from PCASE CBR method)-KIA

From the above Figure 4-1 the resulted pavement section for KIA using empirical CBR method, are as follow: The HMA wearing course is 127mmwhich is equal to the minimum recommended , Asphalt Concrete Stabilized Base course is 257mm is greater than the minimum recommended and the unbound aggregate subbase is 102mm equal to the minimum to be provided.

Table 4-1: PCASE-CBR thickness design for KIA

| **Pavement layer** | **Thickness in mm** |
|---|---|
| Wearing surface | 127 |
| Stabilized Base | 257 |
| Uncrushed aggregate-subbase | 102 |
| **Total thickness above Subgrade** | **486** |

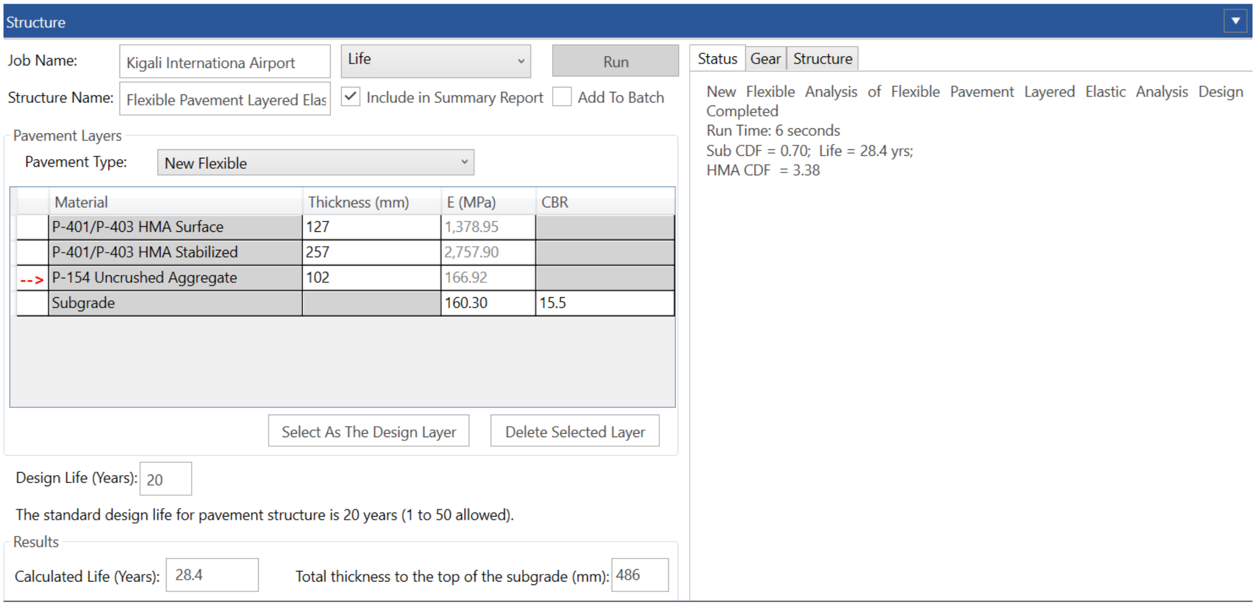
From Above

Table 4-1,the wearing surface course(HMA) is 127mm thick, crushed aggregate base course is 257mm thick,refering to Table 5-2,the minimum thickness of HMA wearing course as per FAA is 100mm(127>100),base course minimum thickness is 150mm(257>150) and subbase course minimum thickness is 150mm(102<150mm).we can see that the subbase course course falls below the minimum recommended thickness by Current Advisory circular. The minimum thicknesses are set bases on constructability and environmental considerations.it was practically shown that compacting a granular layer less than 15cm thick is inefficient.

And from Figure4-2 the design life for this pavement is 28.4 years, according to FAA, the design of flexible pavement exceeding 20 years is not recommended, this is due to environmental deterioration of flexible pavement layers with time. Attempting to design for a period higher than 20 years, might lead to uneconomical initial construction period with very low reliability to meet the intended service life.

#### 4.1.1bFAA Pavement Life computation using FAAFIELD.

The FAA has developed the computer program FAA Rigid and Flexible Iterative Elastic Layer Design (FAARFIELD) to assist with pavement design. For flexible pavement design, FAARFIELD uses the maximum vertical strain at the top of the subgrade and the maximum horizontal strain at the bottom of all asphalt layers as the predictors of pavement structural life. FAARFIELD provides the required thickness for all individual layers of flexible pavement (surface, base, and subbase) required to support a given aircraft traffic mix for the structural design life over a given subgrade.



Job Name: Kigali Internationa Airport

Life

Structure Name: Flexible Pavement Layered Elas

☑ Include in Summary Report ☐ Add To Batch

Pavement Layers

Pavement Type: New Flexible

| | Material | Thickness (mm) | E (MPa) | CBR |
|---|---|---|---|---|
| | P-401/P-403 HMA Surface | 127 | 1,378.95 | |
| | P-401/P-403 HMA Stabilized | 257 | 2,757.90 | |
| --> | P-154 Uncrushed Aggregate | 102 | 166.92 | |
| | Subgrade | | 160.30 | 15.5 |

Design Life (Years): 20

The standard design life for pavement structure is 20 years (1 to 50 allowed).

Calculated Life (Years): 28.4

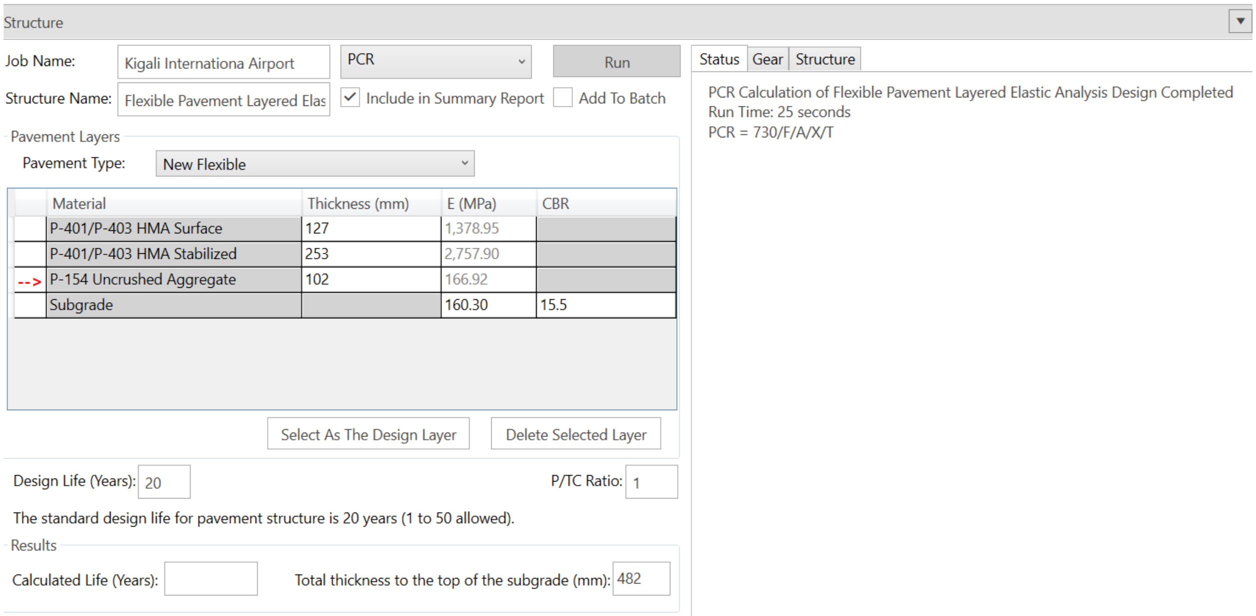
Total thickness to the top of the subgrade (mm): 486

New Flexible Analysis of Flexible Pavement Layered Elastic Analysis Design Completed
Run Time: 6 seconds
Sub CDF = 0.70; Life = 28.4 yrs;
HMA CDF = 3.38

Figure4-2 Analy sis of the design Life for PCASE-CBR of this pavement using FAAFIELD-KIA

From the figure Figure4-2 above the analysis of design life for the designed pavement section using Empirical -CBR Method, the computed design life is 28.4 years, this is slightly higher than the 20 years design life intended during the design.

### 4.1.1.C ACR/PCR Analysis for PCASE-CBR Pavement section



Job Name: Kigali Internationa Airport

PCR

Structure Name: Flexible Pavement Layered Elas

☑ Include in Summary Report ☐ Add To Batch

Pavement Layers

Pavement Type: New Flexible

| | Material | Thickness (mm) | E (MPa) | CBR |
|---|---|---|---|---|
| | P-401/P-403 HMA Surface | 127 | 1,378.95 | |
| | P-401/P-403 HMA Stabilized | 253 | 2,757.90 | |
| --> | P-154 Uncrushed Aggregate | 102 | 166.92 | |
| | Subgrade | | 160.30 | 15.5 |

Design Life (Years): 20

P/TC Ratio: 1

The standard design life for pavement structure is 20 years (1 to 50 allowed).

Calculated Life (Years):

Total thickness to the top of the subgrade (mm): 482

PCR Calculation of Flexible Pavement Layered Elastic Analysis Design Completed
Run Time: 25 seconds
PCR = 730/F/A/X/T

**Figure 4-3:PCR computation for PCASE-CBR pavement section**

The analysis of the Aircraft classification Rating, Pavement classification Rating is the pavement strength reporting methodology. The ACR is defined as twice Derived Single Wheel Load (DSWL) Expressed in hundreds of Kilograms, the pavement classification rating (PCR) is an index rating (1/50th) of the mass, expressed in kilograms, which an evaluation shows it can be borne by the pavement when applied by a standard (1.50 MPa tire pressure) single wheel. The PCR rating established for a pavement indicates that the pavement is capable of supporting aircraft having an aircraft classification rating (ACR) of equal or lower magnitude. The ACR in comparison to the PCR must be the aircraft ACR established for the particular pavement type and subgrade category of the rated pavement, as well as for the particular aircraft mass and characteristics. From the Above you can see that one aircraft has a ACR higher than the PCR.

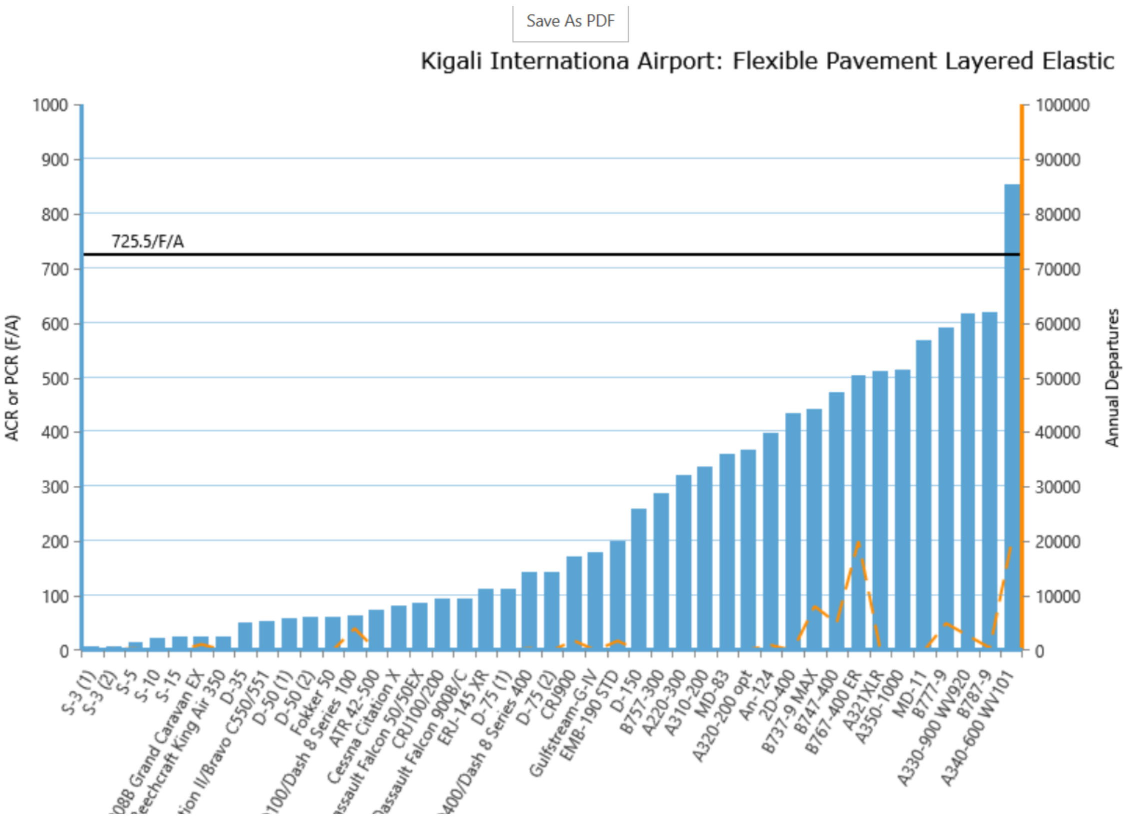
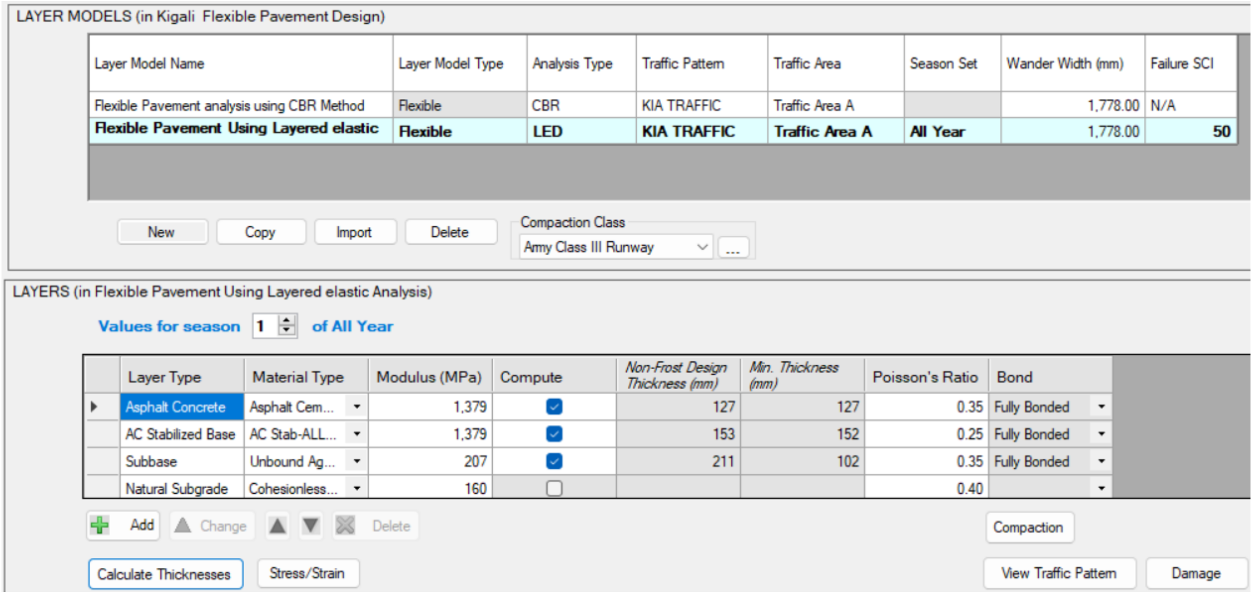


Figure 4-4 ACR-PCR Graph

### 4.1.2Kigali Pavement design method using PCASE-LED Method

Pavement design considerations:

- The design CBR is 15.5%
- Aircraft Traffic Mix to be considered are in data Table 3-5
- The wearing course is HMA layer
- The HMA Stabilized base course will be used
- The traffic Area A in PCASE software is main pavement area (Runways, Taxiways and Aprons)
- The subbase course is uncrushed aggregate with Minimum CBR of 20
- The design period is 20 years



LAYER MODELS (in Kigali Flexible Pavement Design)

| Layer Model Name | Layer Model Type | Analysis Type | Traffic Pattern | Traffic Area | Season Set | Wander Width (mm) | Failure SCI |
|---|---|---|---|---|---|---|---|
| Flexible Pavement analysis using CBR Method | Flexible | CBR | KIA TRAFFIC | Traffic Area A |  | 1,778.00 | N/A |
| **Flexible Pavement Using Layered elastic** | **Flexible** | **LED** | **KIA TRAFFIC** | **Traffic Area A** | **All Year** | 1,778.00 | **50** |

Compaction Class: Army Class III Runway

LAYERS (in Flexible Pavement Using Layered elastic Analysis)

**Values for season** 1 **of All Year**

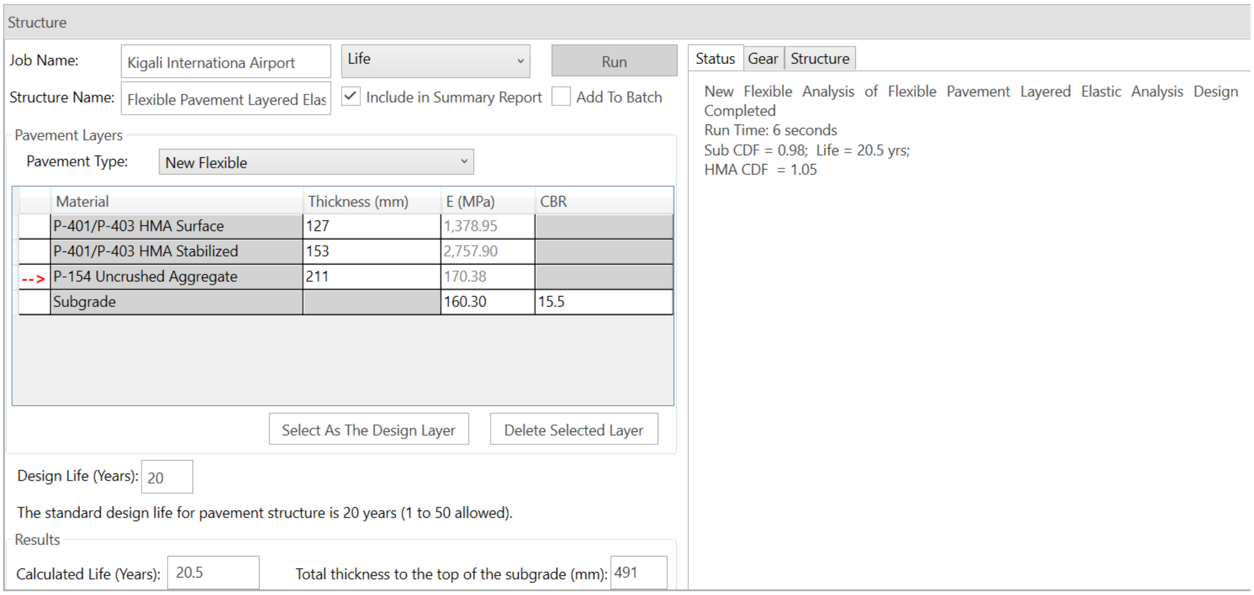
| Layer Type | Material Type | Modulus (MPa) | Compute | *Non-Frost Design Thickness (mm)* | *Min. Thickness (mm)* | Poisson's Ratio | Bond |
|---|---|---|---|---|---|---|---|
| Asphalt Concrete | Asphalt Cem... | 1,379 | ☑ | 127 | 127 | 0.35 | Fully Bonded |
| AC Stabilized Base | AC Stab-ALL... | 1,379 | ☑ | 153 | 152 | 0.25 | Fully Bonded |
| Subbase | Unbound Ag... | 207 | ☑ | 211 | 102 | 0.35 | Fully Bonded |
| Natural Subgrade | Cohesionless... | 160 | ☐ |  |  | 0.40 |  |

Figure 4-5 Summarized results from PCASE-LED method-KIA

From the above Figure 4-5 the resulted pavement section for KIA using Mechanistic empirical LED method, are as follow: The HMA wearing course is 127mm which is equal to the minimum recommended , Asphalt Concrete Stabilized Base course is 211 mm is greater than the minimum recommended and the unbound aggregate subbase is 102mm equal to the minimum to be provided.

Table 4-2:Pavement design thicknesses using PCASE-LED

| Pavement layer | Thickness in mm |
|---|---|
| Wearing surface | 127 |
| Stabilized Base | 153 |
| Uncrushed aggregate-subbase | 211 |
| **Total thickness above Subgrade** | **491** |



Job Name: Kigali Internationa Airport

Life

Structure Name: Flexible Pavement Layered Elas

☑ Include in Summary Report ☐ Add To Batch

Pavement Layers

Pavement Type: New Flexible

| | Material | Thickness (mm) | E (MPa) | CBR |
|---|---|---|---|---|
| | P-401/P-403 HMA Surface | 127 | 1,378.95 | |
| | P-401/P-403 HMA Stabilized | 153 | 2,757.90 | |
| --> | P-154 Uncrushed Aggregate | 211 | 170.38 | |
| | Subgrade | | 160.30 | 15.5 |

Design Life (Years): 20

The standard design life for pavement structure is 20 years (1 to 50 allowed).

Results

Calculated Life (Years): 20.5

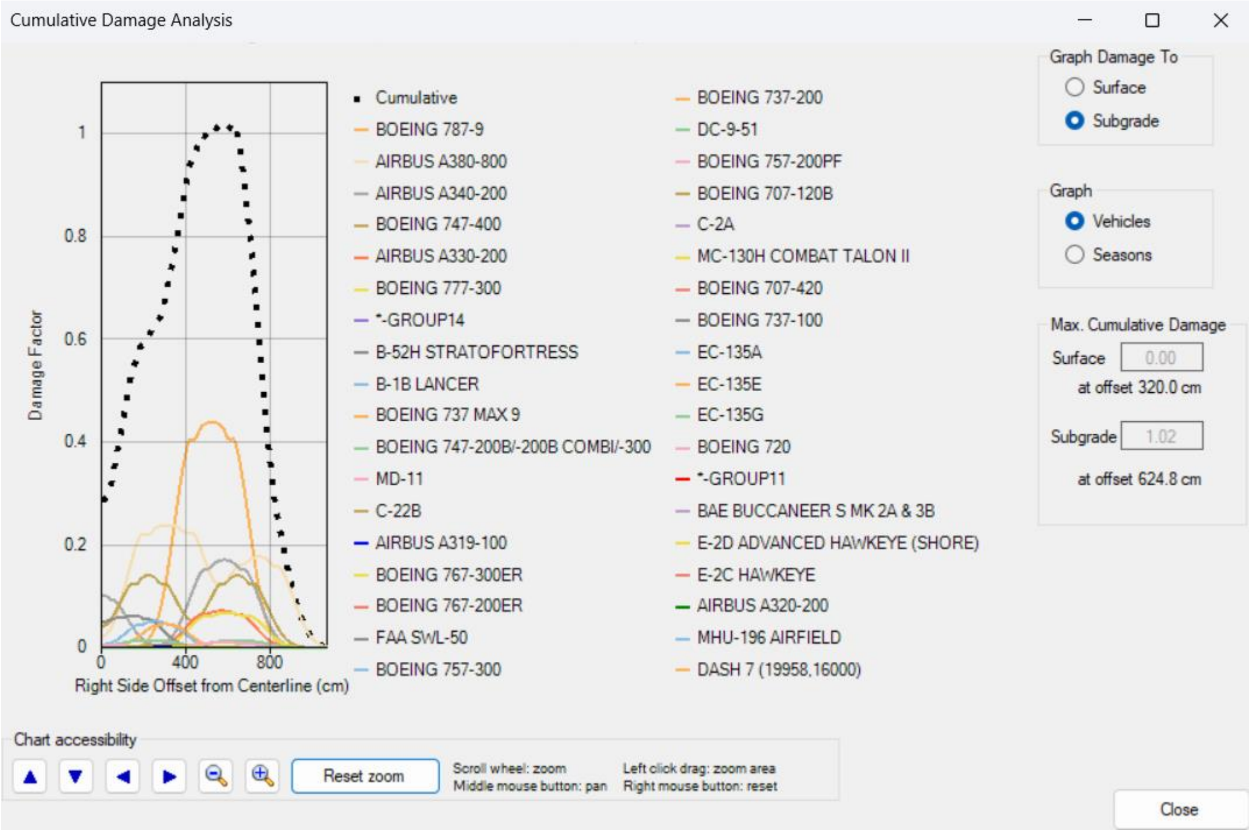
Total thickness to the top of the subgrade (mm): 491

New Flexible Analysis of Flexible Pavement Layered Elastic Analysis Design Completed
Run Time: 6 seconds
Sub CDF = 0.98; Life = 20.5 yrs;
HMA CDF = 1.05

**Figure 4-6 Analysis of the design Life for PCASE-LED of this pavement using FAAFIELD-KIA**

From Above Table 4-2,the wearing surface course(HMA) is 127mm thick, crushed aggregate base course is 153 mm thick,refering to Table 5-2,the minimum thickness of HMA wearing course as per FAA is 100mm(127>100),base course minimum thickness is 150mm(153>150) and subbase course minimum thickness is 150mm(212>150mm).we can see that all flexible pavement layers fall above the minimum recommended thickness by Current Advisory circular. The minimum thicknesses are set bases on constructability and environmental considerations.it was practically shown that compacting a granular layer less than 15cm thick is inefficient.

And from Figure 4-6 the design life for this pavement is 20.5 years, according to FAA, which is closer to 20 years design life designed in PCASE, we can see that with two different softwares using LED method, the design life and the computed service life is the same. From Figure 4-7 the stress-strain is expressed as cumulative damage model where each individual aircraft damage contribution is added up to obtain to total damage of the entire traffic mix ,at which the software iterate the thickness to have a CDF ration of 1,the critical aircraft(the most damaging ) in the traffic mix is BOEING T87-9 AS shown in the Figure 4-7.



Graph Damage To
○ Surface
● Subgrade

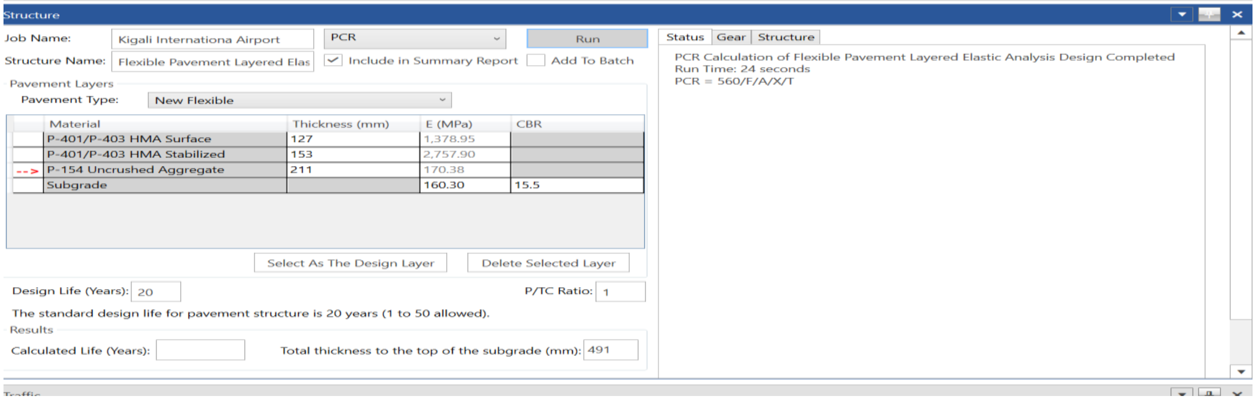
Graph
● Vehicles
○ Seasons

Max. Cumulative Damage
Surface 0.00
at offset 320.0 cm
Subgrade 1.02
at offset 624.8 cm

Figure 4-7:stress-strain in terms of cumulative damage model

From the figure Figure 4-7the Boeing 787-9 has the most damage, the cumulative damage is the overall damage of each individual aircraft and is represented as a dash line.

### 4.1.2a ACR/PCR Analysis for PCASE-LED Pavement section



Job Name: Kigali Internationa Airport
PCR
Structure Name: Flexible Pavement Layered Elas
☑ Include in Summary Report
☐ Add To Batch

Pavement Layers
Pavement Type: New Flexible

| | Material | Thickness (mm) | E (MPa) | CBR |
|---|---|---|---|---|
| | P-401/P-403 HMA Surface | 127 | 1,378.95 | |
| | P-401/P-403 HMA Stabilized | 153 | 2,757.90 | |
| --> | P-154 Uncrushed Aggregate | 211 | 170.38 | |
| | Subgrade | | 160.30 | 15.5 |

Design Life (Years): 20
P/TC Ratio: 1
The standard design life for pavement structure is 20 years (1 to 50 allowed).

Results
Calculated Life (Years):
Total thickness to the top of the subgrade (mm): 491

PCR Calculation of Flexible Pavement Layered Elastic Analysis Design Completed
Run Time: 24 seconds
PCR = 560/F/A/X/T

Figure 4-8:PCR computation for PCASE-LED pavement section

The PCR analysis for this case as shown in figure Figure 4-8 is 560, the F letter stands for Flexible, the A is the subgrade category is the tire pressure and T is the Technical Evaluation method used. From Figure Figure 4-9 some aircrafts ACR are higher than the PCR, yielding into an overloaded operation.

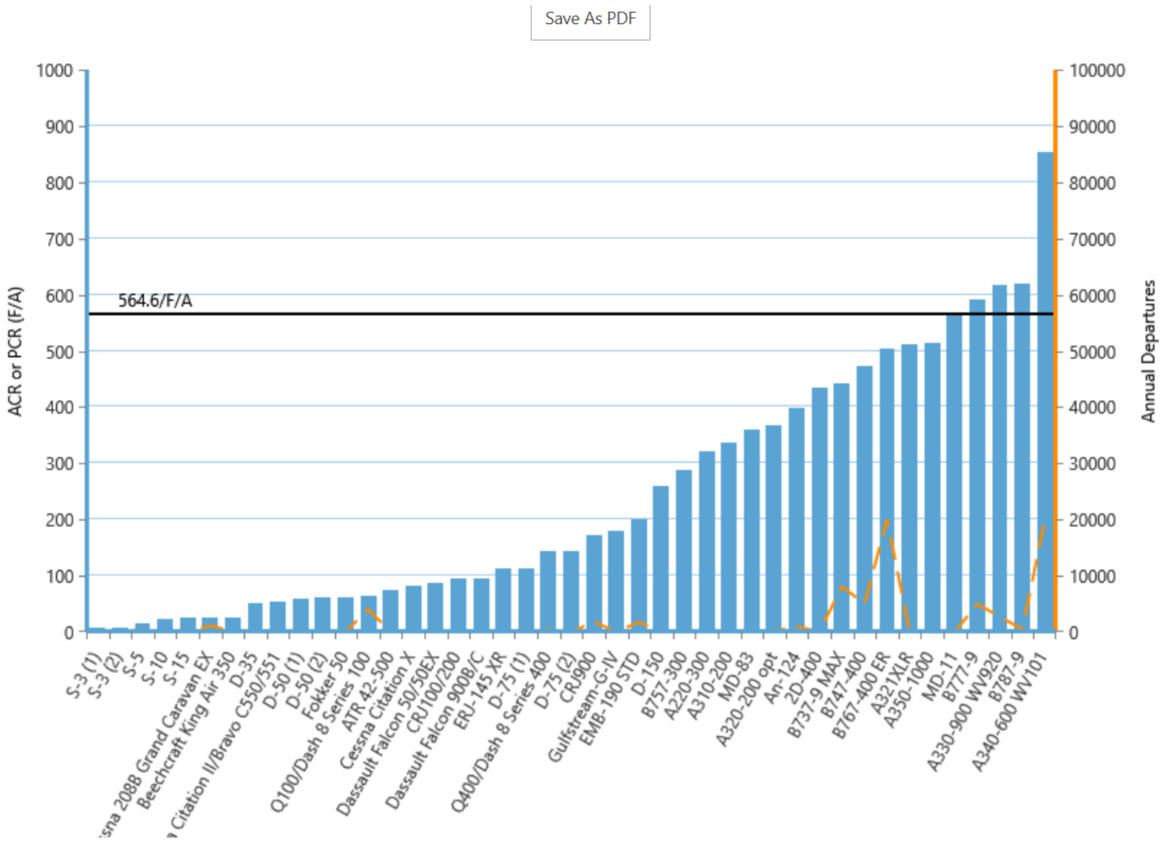


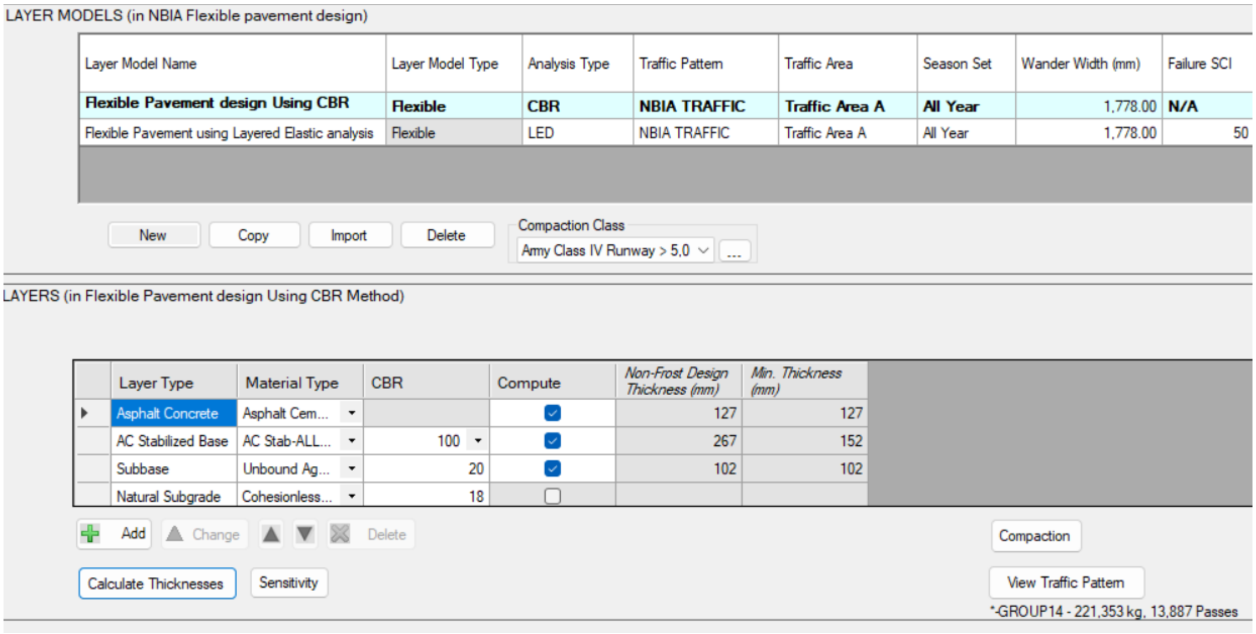
Figure 4-9:ACR-PCR Graph

## 4.3. New Bugesera International Airport pavement analysis and design

### 4.3.1 NBIA Pavement design method using PCASE-CBR METHOD

Pavement design considerations:

- The design CBR is 18%
- Aircraft Traffic Mix to be considered are in data Table 3-7
- The wearing course is HMA layer
- The base course is HMA stabilized
- The subbase course will be uncrushed aggregate
- The design period is 20 years



LAYER MODELS (in NBIA Flexible pavement design)

| Layer Model Name | Layer Model Type | Analysis Type | Traffic Pattern | Traffic Area | Season Set | Wander Width (mm) | Failure SCI |
|---|---|---|---|---|---|---|---|
| **Flexible Pavement design Using CBR** | **Flexible** | **CBR** | **NBIA TRAFFIC** | **Traffic Area A** | **All Year** | 1,778.00 | **N/A** |
| Flexible Pavement using Layered Elastic analysis | Flexible | LED | NBIA TRAFFIC | Traffic Area A | All Year | 1,778.00 | 50 |

Compaction Class: Army Class IV Runway > 5,0

LAYERS (in Flexible Pavement design Using CBR Method)

| Layer Type | Material Type | CBR | Compute | *Non-Frost Design Thickness (mm)* | *Min. Thickness (mm)* |
|---|---|---|---|---|---|
| Asphalt Concrete | Asphalt Cem... | | ☑ | 127 | 127 |
| AC Stabilized Base | AC Stab-ALL... | 100 | ☑ | 267 | 152 |
| Subbase | Unbound Ag... | 20 | ☑ | 102 | 102 |
| Natural Subgrade | Cohesionless... | 18 | ☐ | | |

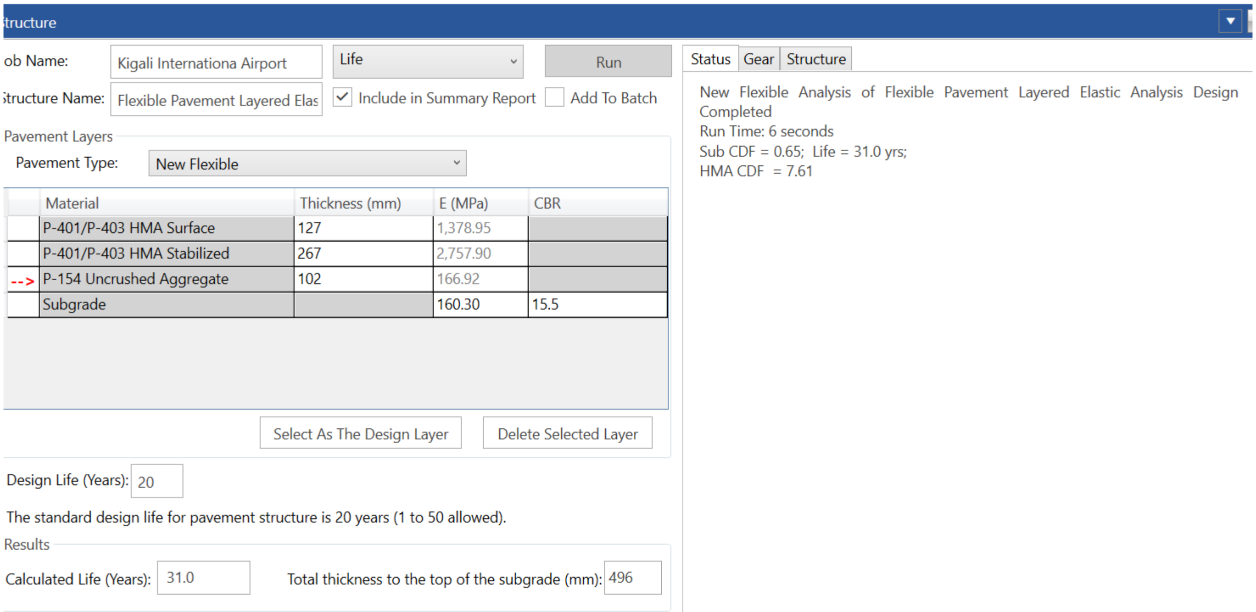
*-GROUP14 - 221,353 kg, 13,887 Passes

Figure 4-10 New Bugesera Int Airport PCASE-CBR Design results extract-NBIA

From the above Figure 4-10 the resulted pavement section for NBIA using empirical LED method, are as follow: The HMA wearing course is 127mm which is equal to the minimum recommended , Asphalt Concrete Stabilized Base course is 267 mm is greater than the minimum recommended and the unbound aggregate subbase is 102mm equal to the minimum to be provided.

Table 4-3:Summarized thickness of layers from PCASE -CBR method-NBIA

| **Pavement layer** | **Thickness in mm** |
|---|---|
| Wearing surface | 127 |
| Stabilized Base | 267 |
| Uncrushed aggregate-subbase | 102 |
| **Total thickness above Subgrade** | **496** |



ob Name: Kigali Internationa Airport

tructure Name: Flexible Pavement Layered Elas

☑ Include in Summary Report ☐ Add To Batch

Pavement Type: New Flexible

|  | Material | Thickness (mm) | E (MPa) | CBR |
|---|---|---|---|---|
|  | P-401/P-403 HMA Surface | 127 | 1,378.95 |  |
|  | P-401/P-403 HMA Stabilized | 267 | 2,757.90 |  |
| --> | P-154 Uncrushed Aggregate | 102 | 166.92 |  |
|  | Subgrade |  | 160.30 | 15.5 |

Design Life (Years): 20

The standard design life for pavement structure is 20 years (1 to 50 allowed).

Calculated Life (Years): 31.0

Total thickness to the top of the subgrade (mm): 496

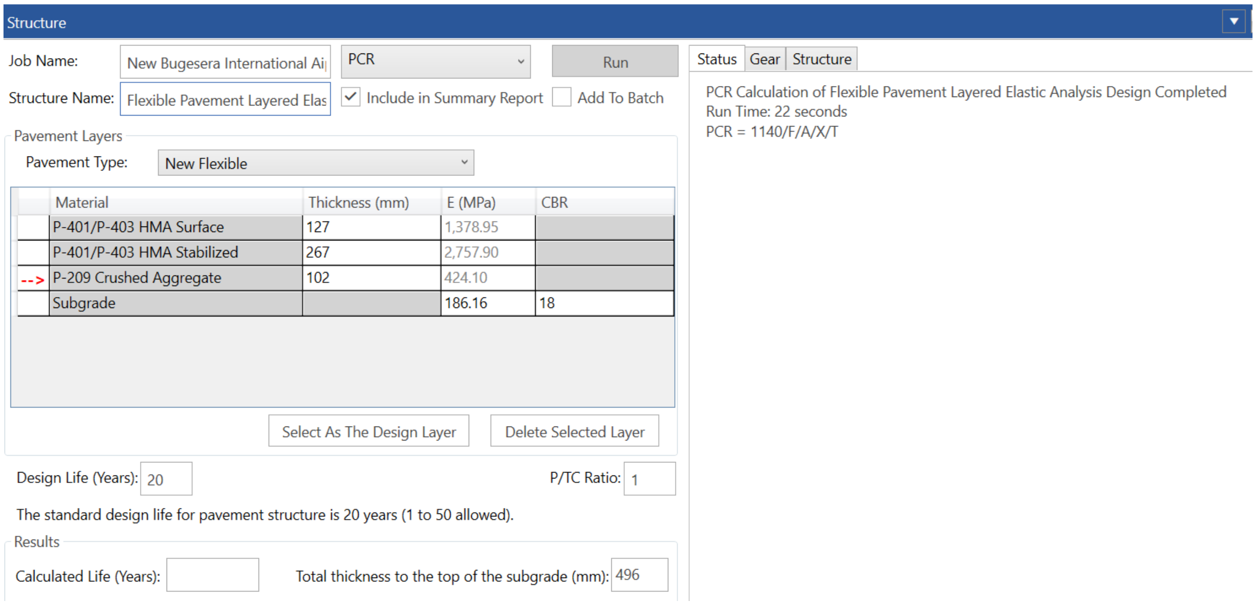
New Flexible Analysis of Flexible Pavement Layered Elastic Analysis Design Completed
Run Time: 6 seconds
Sub CDF = 0.65; Life = 31.0 yrs;
HMA CDF = 7.61

Figure 4-11:Analysis of the design Life from PCASE-CBR of this pavement using FAAFIELD-NBIA

From  Above Table 4-3,the wearing surface course(HMA) is 127mm thick, crushed aggregate base course is 257mm thick,refering to Table 5-2,the minimum thickness of HMA wearing course as per FAA is 100mm(127>100),base course minimum  thickness is 150mm(267>>150) and subbase course minimum thickness is 150mm(102<150mm).we can see that the subbase course course falls below the minimum recommended thickness by Current Advisory circular. The minimum thicknesses are set bases on constructability and environmental considerations.it was practically shown that compacting a granular layer less than 15cm thick is inefficient.

And from Figure 4-11 the computed design life for this pavement is 31 years, according to FAA, the design of flexible pavement exceeding 20 years is not recommended, this is due to environmental deterioration of flexible pavement layers with time. Attempting to design for a period higher than 20 years, might lead to uneconomical initial construction period with very low reliability to meet the intended service life.

### 4.3.2 ACR/PCR Analysis for NBIA PCASE-CBR Pavement section



Job Name: New Bugesera International Ai

PCR

Structure Name: Flexible Pavement Layered Elas

☑ Include in Summary Report ☐ Add To Batch

Pavement Layers

Pavement Type: New Flexible

| | Material | Thickness (mm) | E (MPa) | CBR |
|---|---|---|---|---|
| | P-401/P-403 HMA Surface | 127 | 1,378.95 | |
| | P-401/P-403 HMA Stabilized | 267 | 2,757.90 | |
| --> | P-209 Crushed Aggregate | 102 | 424.10 | |
| | Subgrade | | 186.16 | 18 |

Design Life (Years): 20

P/TC Ratio: 1

The standard design life for pavement structure is 20 years (1 to 50 allowed).

Results

Calculated Life (Years):

Total thickness to the top of the subgrade (mm): 496

PCR Calculation of Flexible Pavement Layered Elastic Analysis Design Completed
Run Time: 22 seconds
PCR = 1140/F/A/X/T

Figure 4-12:PCR computation for PCASE-CBR Pavement section

From the PCR in the above Figure 4-12 the computed PCR is 1140 with the maximum ACR being 860,the pavement section seems to be very robust.

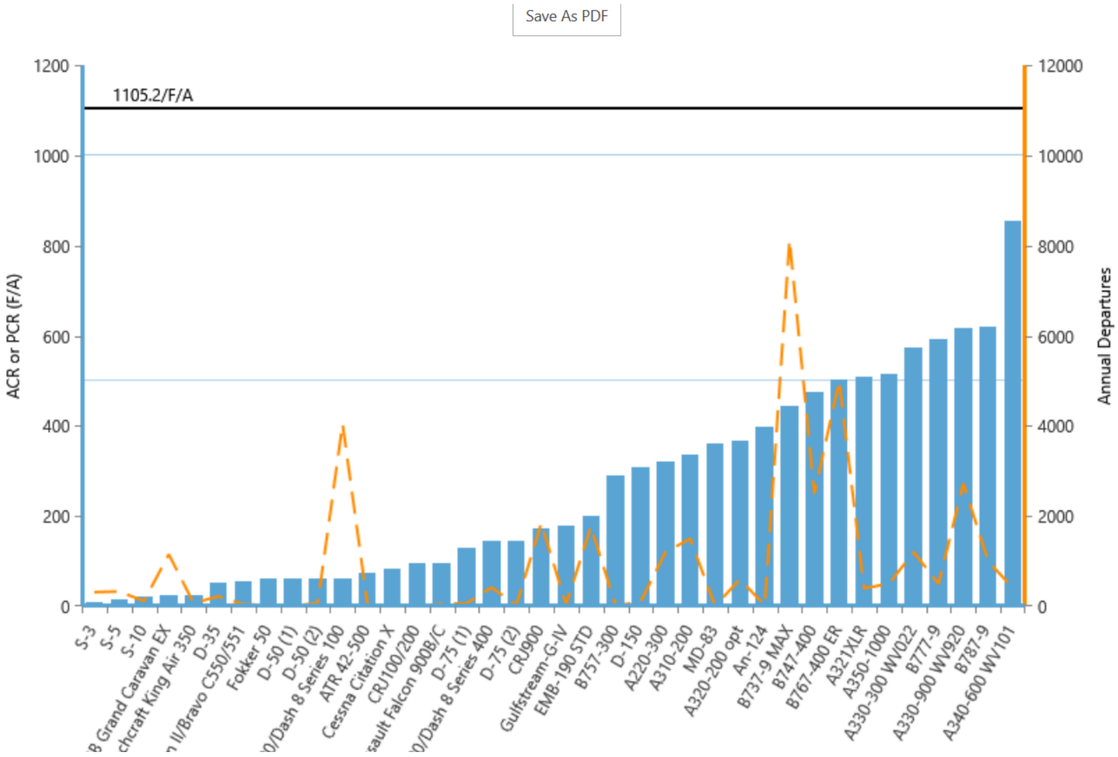
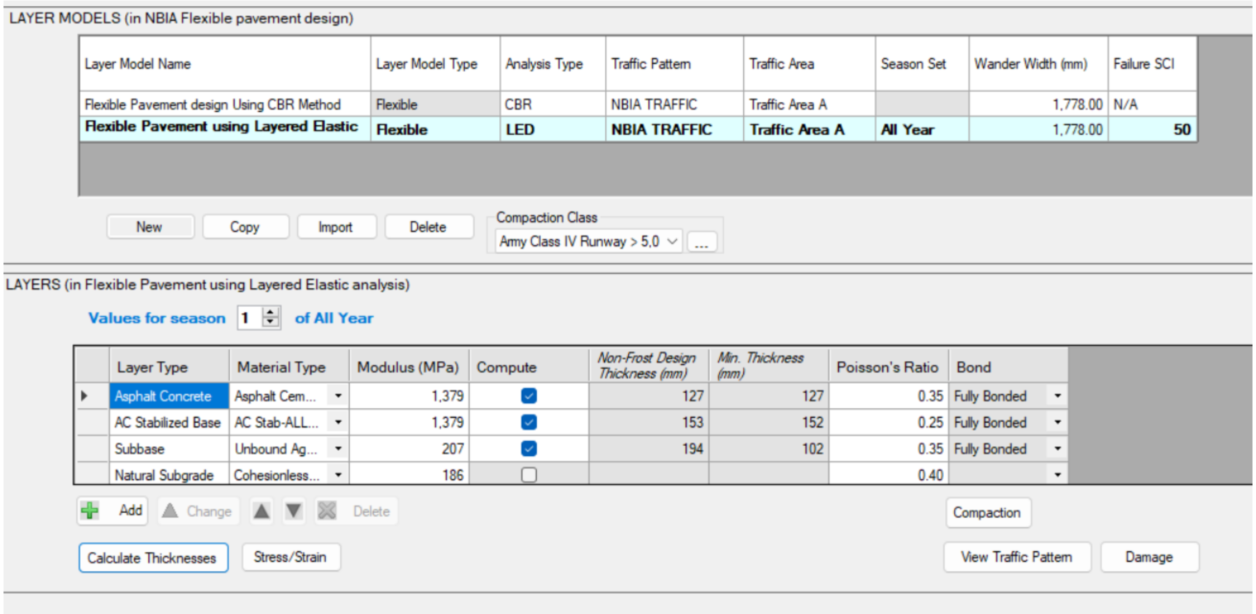


Figure 4-13:ACR-PCR Graph

### 4.3.3. NBIA Pavement design method using PCASE-LED METHOD

Pavement design considerations:

- The design CBR is 18%
- Aircraft Traffic Mix to be considered are in data Table 3-7
- The wearing course is HMA layer
- The base course is HMA stabilized
- The subbase course will be uncrushed aggregate
- The design period is 20 years



LAYER MODELS (in NBIA Flexible pavement design)

| Layer Model Name | Layer Model Type | Analysis Type | Traffic Pattern | Traffic Area | Season Set | Wander Width (mm) | Failure SCI |
|---|---|---|---|---|---|---|---|
| Flexible Pavement design Using CBR Method | Flexible | CBR | NBIA TRAFFIC | Traffic Area A | | 1,778.00 | N/A |
| **Flexible Pavement using Layered Elastic** | **Flexible** | **LED** | **NBIA TRAFFIC** | **Traffic Area A** | **All Year** | 1,778.00 | **50** |

Compaction Class: Army Class IV Runway > 5,0

LAYERS (in Flexible Pavement using Layered Elastic analysis)

**Values for season** 1 **of All Year**

| Layer Type | Material Type | Modulus (MPa) | Compute | *Non-Frost Design Thickness (mm)* | *Min. Thickness (mm)* | Poisson's Ratio | Bond |
|---|---|---|---|---|---|---|---|
| Asphalt Concrete | Asphalt Cem... | 1,379 | ☑ | 127 | 127 | 0.35 | Fully Bonded |
| AC Stabilized Base | AC Stab-ALL... | 1,379 | ☑ | 153 | 152 | 0.25 | Fully Bonded |
| Subbase | Unbound Ag... | 207 | ☑ | 194 | 102 | 0.35 | Fully Bonded |
| Natural Subgrade | Cohesionless... | 186 | ☐ | | | 0.40 | |

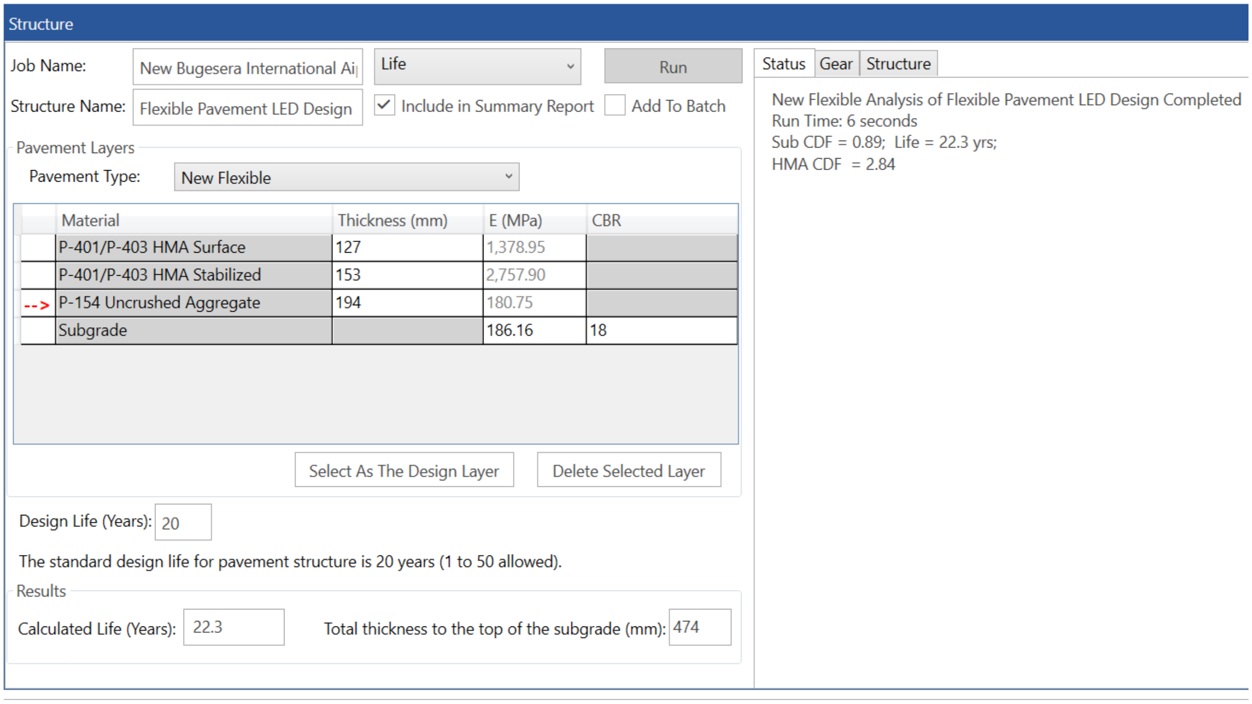
Figure 4-14 :New Bugesera Int Airport PCASE-LED Design results extract-NBIA

From the above Figure 4-14the resulted pavement section for KIA using Mechanistic empirical LED method, are as follow: The HMA wearing course is 127mm which is equal to the minimum recommended , Asphalt Concrete Stabilized Base course is 152 mm slightly equal to the minimum recommended  and the unbound aggregate subbase is 102mm equal to the minimum to be provided. These thicknesses of pavement layers are slightly similar to Kigali yet the traffic for Bugesera is higher, this is the result for slightly higher CBR of the Subgrade.

Table 4-4:Table 4-5:Summarized results from PCASE-LED method-NBIA

| **Pavement layer** | **Thickness in mm** |
|---|---|
| Wearing surface | 127 |
| Stabilized Base | 153 |

|  |  |
|---|---|
| Uncrushed aggregate-subbase | 194 |
| **Total thickness above Subgrade** | **474** |



Job Name: New Bugesera International Ai

Life

Structure Name: Flexible Pavement LED Design

☑ Include in Summary Report ☐ Add To Batch

New Flexible Analysis of Flexible Pavement LED Design Completed
Run Time: 6 seconds
Sub CDF = 0.89; Life = 22.3 yrs;
HMA CDF = 2.84

Pavement Layers

Pavement Type: New Flexible

|  | Material | Thickness (mm) | E (MPa) | CBR |
|---|---|---|---|---|
|  | P-401/P-403 HMA Surface | 127 | 1,378.95 |  |
|  | P-401/P-403 HMA Stabilized | 153 | 2,757.90 |  |
| --> | P-154 Uncrushed Aggregate | 194 | 180.75 |  |
|  | Subgrade |  | 186.16 | 18 |

Design Life (Years): 20

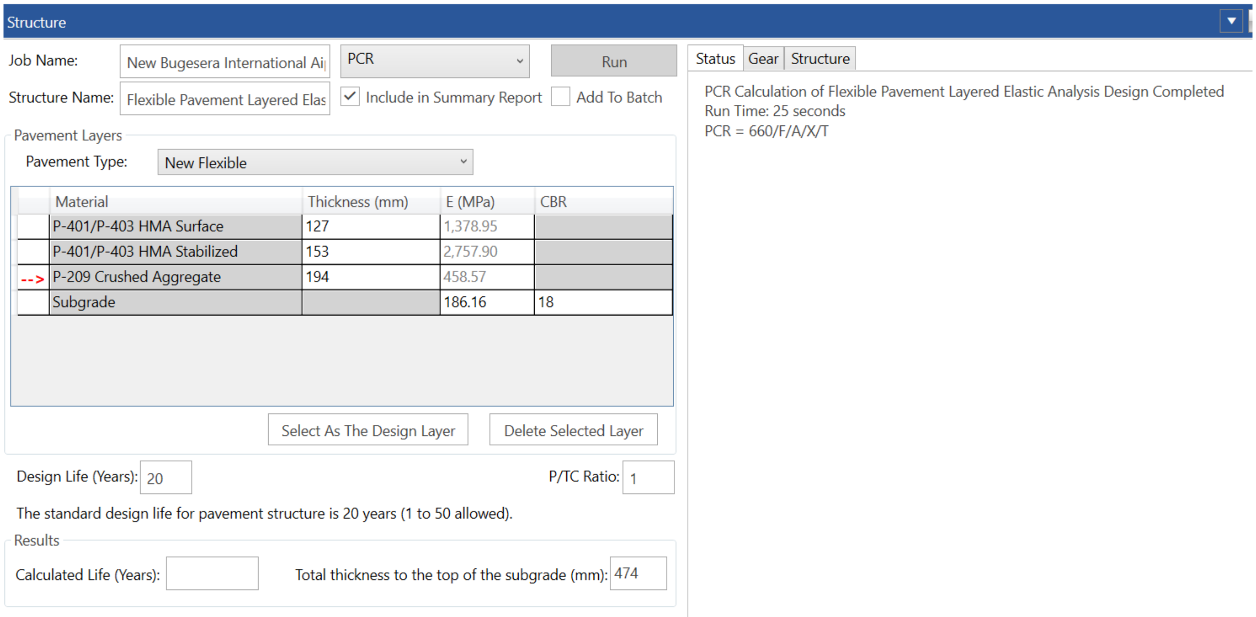
The standard design life for pavement structure is 20 years (1 to 50 allowed).

Results

Calculated Life (Years): 22.3

Total thickness to the top of the subgrade (mm): 474

Figure 4-15:Analysis of the design Life of PCASE-LED results this pavement using FAAFIELD-NBIA



Job Name: New Bugesera International Ai

PCR

Structure Name: Flexible Pavement Layered Elas

☑ Include in Summary Report ☐ Add To Batch

PCR Calculation of Flexible Pavement Layered Elastic Analysis Design Completed
Run Time: 25 seconds
PCR = 660/F/A/X/T

Pavement Layers

Pavement Type: New Flexible

|  | Material | Thickness (mm) | E (MPa) | CBR |
|---|---|---|---|---|
|  | P-401/P-403 HMA Surface | 127 | 1,378.95 |  |
|  | P-401/P-403 HMA Stabilized | 153 | 2,757.90 |  |
| --> | P-209 Crushed Aggregate | 194 | 458.57 |  |
|  | Subgrade |  | 186.16 | 18 |

Design Life (Years): 20

P/TC Ratio: 1

The standard design life for pavement structure is 20 years (1 to 50 allowed).

Results

Calculated Life (Years):

Total thickness to the top of the subgrade (mm): 474

Figure 4-16:PCR Computation for PCASE-LED pavement section

From the figure above the PCR is 660 with the maximum ACR Being 860,according to ICAO,the overloaded operation of one aircraft is permitted.

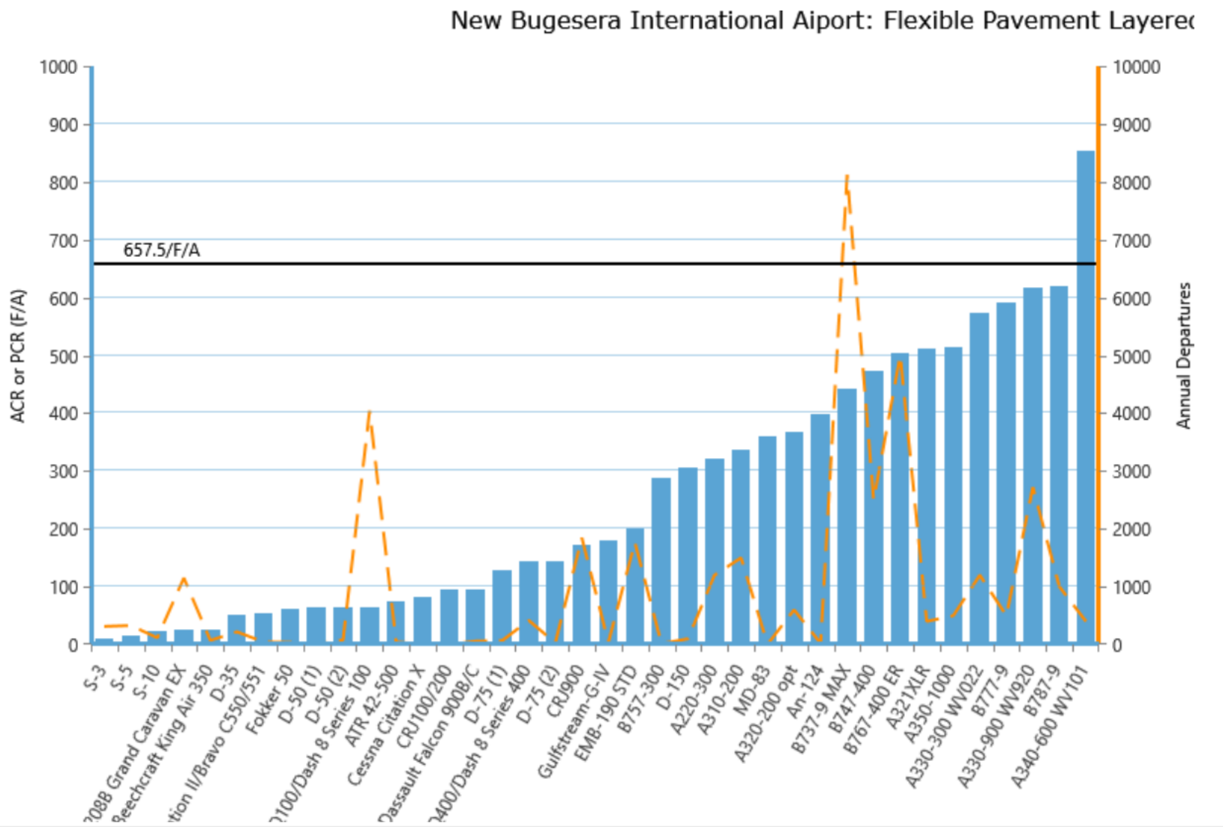
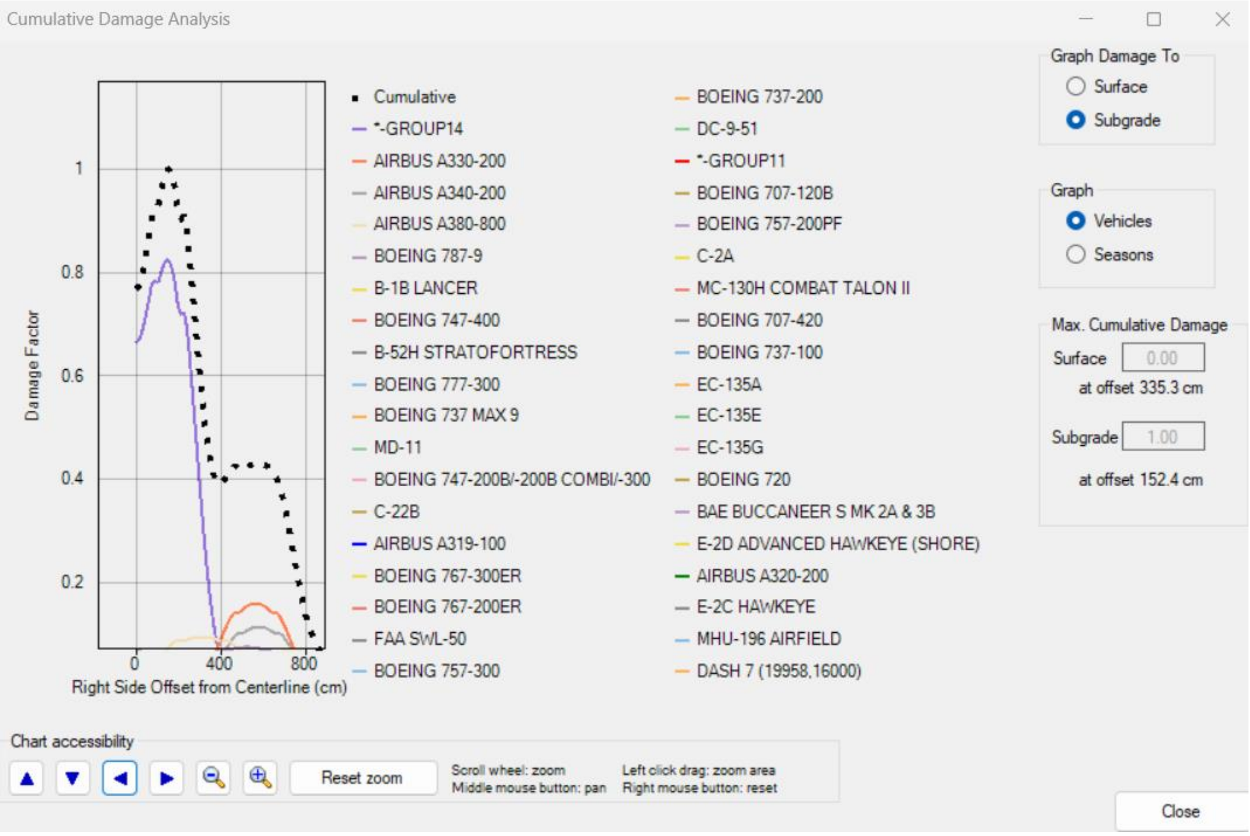


Figure 4-17:ACR-PCR Graph

From  Above Table 4-4,the wearing surface course(HMA) is 127mm thick, crushed aggregate base course is 153 mm thick,refering to Table 5-2,the minimum thickness of HMA wearing course as per FAA is 100mm(127>100),base course minimum  thickness is 150mm(153>150) and subbase course minimum thickness is 150mm(194>150mm).we can see that all flexible pavement layers fall above the minimum recommended thickness by Current Advisory circular. The minimum thicknesses are set bases on constructability and environmental considerations.it was practically shown that compacting a granular layer less than 15cm thick is inefficient.

And from Figure 4-6 the design life for this pavement is 22.3 years, according to FAA, which is closer to 20 years design life designed in PCASE, we can see that with two different softwares using LED method, the design life and the computed service life is nearly the same. From Figure 4-18the stress-strain is expressed as cumulative damage model where each individual aircraft damage contribution is added up to obtain to total damage of the entire traffic mix ,at which the software iterate the thickness to have a CDF ration of 1,the critical aircraft(the most damaging ) in the traffic mix is GROUP 14 as shown in the Figure 4-18.



Graph Damage To
○ Surface
● Subgrade

Graph
● Vehicles
○ Seasons

Max. Cumulative Damage
Surface 0.00
at offset 335.3 cm
Subgrade 1.00
at offset 152.4 cm

Figure 4-18:stress-strain in terms of cumulative damage model

From the figure Figure 4-18 the Group 14 has the most damage, the cumulative damage is the overall damage of each individual aircraft and is represented as a dash line.

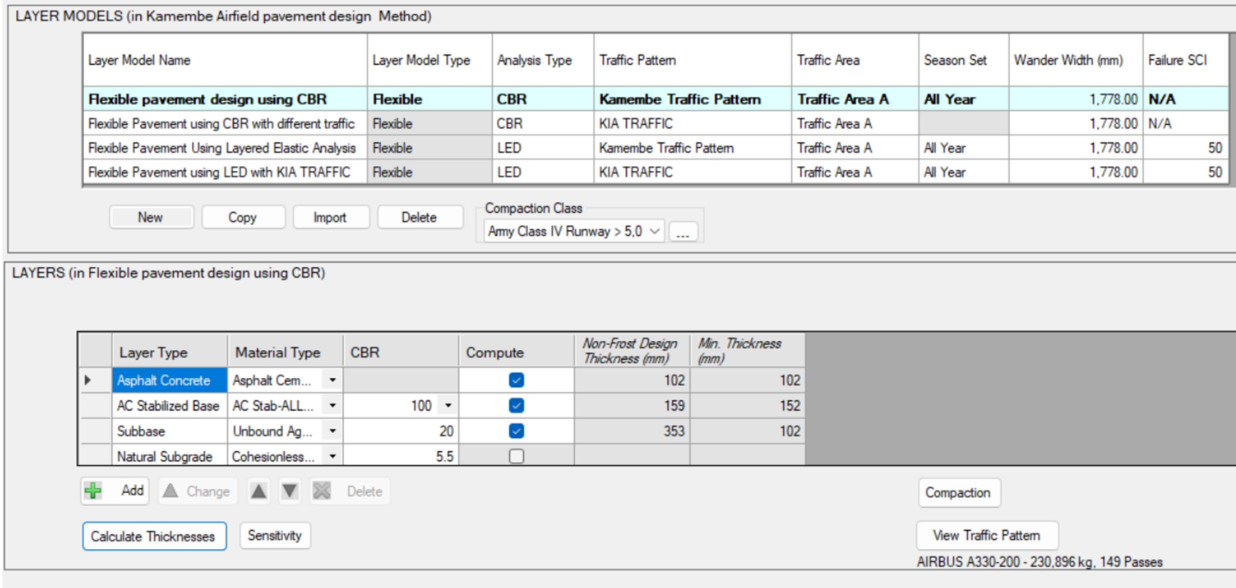
## 4.4. Kamembe Airport pavement analysis and design

### 4.4.1 Kamembe Pavement design method using PCASE-CBR METHOD

Pavement design considerations:

- The design CBR is 5.5%
- Aircraft Traffic Mix to be considered are in data Table 3-8
- The wearing course is HMA layer
- The base course is HMA stabilized

- The subbase course will be uncrushed aggregate
- The design period is 20 years



LAYER MODELS (in Kamembe Airfield pavement design  Method)

| Layer Model Name | Layer Model Type | Analysis Type | Traffic Pattern | Traffic Area | Season Set | Wander Width (mm) | Failure SCI |
|---|---|---|---|---|---|---|---|
| **Flexible pavement design using CBR** | **Flexible** | **CBR** | **Kamembe Traffic Pattern** | **Traffic Area A** | **All Year** | 1,778.00 | **N/A** |
| Flexible Pavement using CBR with different traffic | Flexible | CBR | KIA TRAFFIC | Traffic Area A |  | 1,778.00 | N/A |
| Flexible Pavement Using Layered Elastic Analysis | Flexible | LED | Kamembe Traffic Pattern | Traffic Area A | All Year | 1,778.00 | 50 |
| Flexible Pavement using LED with KIA TRAFFIC | Flexible | LED | KIA TRAFFIC | Traffic Area A | All Year | 1,778.00 | 50 |

Compaction Class: Army Class IV Runway > 5,0

LAYERS (in Flexible pavement design using CBR)

| Layer Type | Material Type | CBR | Compute | *Non-Frost Design Thickness (mm)* | *Min. Thickness (mm)* |
|---|---|---|---|---|---|
| Asphalt Concrete | Asphalt Cem... |  | ☑ | 102 | 102 |
| AC Stabilized Base | AC Stab-ALL... | 100 | ☑ | 159 | 152 |
| Subbase | Unbound Ag... | 20 | ☑ | 353 | 102 |
| Natural Subgrade | Cohesionless... | 5.5 | ☐ |  |  |

AIRBUS A330-200 - 230,896 kg, 149 Passes

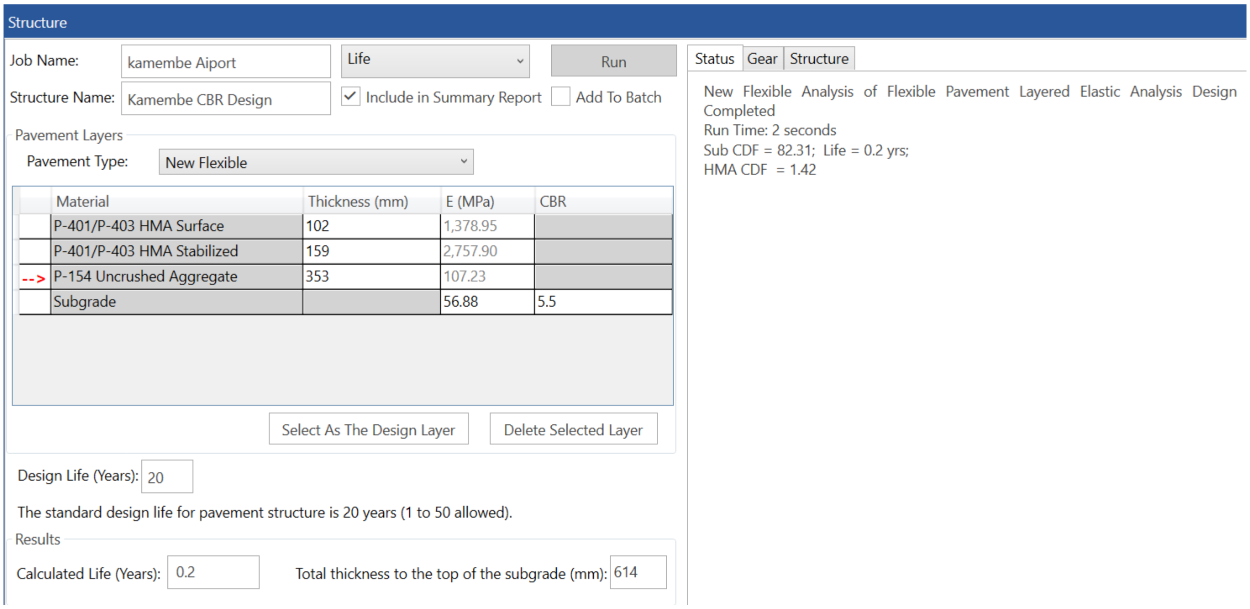
Figure 4-19:Kamembe Airport PCASE-CBR Design results extract-

From the above Figure 4-19the resulted pavement section for Kamembe  using empirical method, are as follow: The HMA wearing course is 102mm which is equal to the minimum recommended , Asphalt Concrete Stabilized Base course is 159 mm slightly equal to the minimum recommended  and the unbound aggregate subbase is 102mm equal to the minimum to be provided. All the thickness are equal to minimum recommended as the traffic is slightly lower, this implies that the environmental damage is higher than the traffic damage

Table 4-6:Kamembe Airport PCASE-CBR Design summary results

| Pavement layer | Thickness in mm |
|---|---|
| Wearing surface | 102 |
| Stabilized Base | 159 |

| | |
|---|---|
| Uncrushed aggregate-subbase | 353 |
| **Total thickness above Subgrade** | **614** |



Job Name: kamembe Aiport

Structure Name: Kamembe CBR Design

Life

☑ Include in Summary Report ☐ Add To Batch

Pavement Layers

Pavement Type: New Flexible

| | Material | Thickness (mm) | E (MPa) | CBR |
|---|---|---|---|---|
| | P-401/P-403 HMA Surface | 102 | 1,378.95 | |
| | P-401/P-403 HMA Stabilized | 159 | 2,757.90 | |
| --> | P-154 Uncrushed Aggregate | 353 | 107.23 | |
| | Subgrade | | 56.88 | 5.5 |

Design Life (Years): 20

The standard design life for pavement structure is 20 years (1 to 50 allowed).

Results

Calculated Life (Years): 0.2

Total thickness to the top of the subgrade (mm): 614

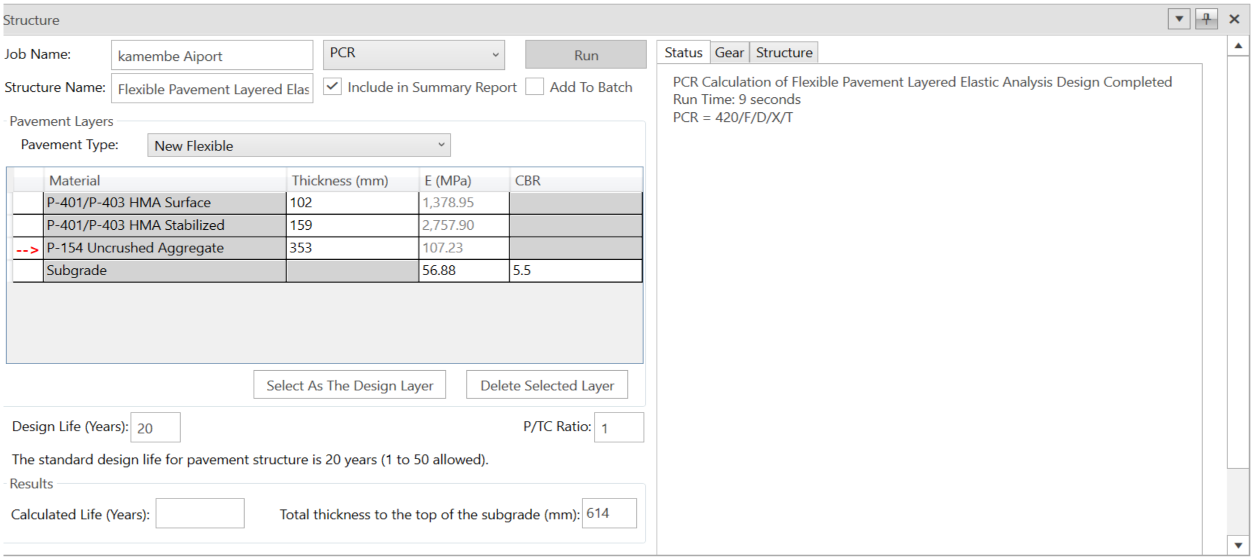
New Flexible Analysis of Flexible Pavement Layered Elastic Analysis Design Completed
Run Time: 2 seconds
Sub CDF = 82.31; Life = 0.2 yrs;
HMA CDF = 1.42

Figure 4-20:Analysis of the design Life of PCASE-CBR RESULTS using FAAFIELD-KAMEMBE

From Above Table 4-6,the wearing surface course(HMA) is 102mm thick, crushed aggregate base course is 159 mm thick,refering to Table 5-2,the minimum thickness of HMA wearing course as per FAA is 100mm(102>100),base course minimum thickness is 150mm(159>150) and subbase course minimum thickness is 150mm(353>>150mm).we can see that all pavement layers thicknesses fall above the minimum pavement requirement by FAA.

And from Figure 4-11 the computed design service life for this pavement is 0.2 which far less than the design life of 20years, this is due to the low CBR values. According to FAA designing pavement using CBR method for a low CBR subgrade was shown to be inefficient.

### 4.4.1aACR/PCR Analysis for KAMEMBE PCASE-CBR Pavement section



Job Name: kamembe Aiport

PCR

Structure Name: Flexible Pavement Layered Elas

☑ Include in Summary Report ☐ Add To Batch

Pavement Type: New Flexible

| | Material | Thickness (mm) | E (MPa) | CBR |
|---|---|---|---|---|
| | P-401/P-403 HMA Surface | 102 | 1,378.95 | |
| | P-401/P-403 HMA Stabilized | 159 | 2,757.90 | |
| --> | P-154 Uncrushed Aggregate | 353 | 107.23 | |
| | Subgrade | | 56.88 | 5.5 |

Design Life (Years): 20

P/TC Ratio: 1

The standard design life for pavement structure is 20 years (1 to 50 allowed).

Calculated Life (Years):

Total thickness to the top of the subgrade (mm): 614

PCR Calculation of Flexible Pavement Layered Elastic Analysis Design Completed
Run Time: 9 seconds
PCR = 420/F/D/X/T

Figure 4-21:PCR computation for PCASE-CBR pavement section

From above Figure 4-21 the computed PCR is 420,and refer to below Figure 4-22 many aircraft has an ACR higher than the PCR,this implies an under designed pavement section .

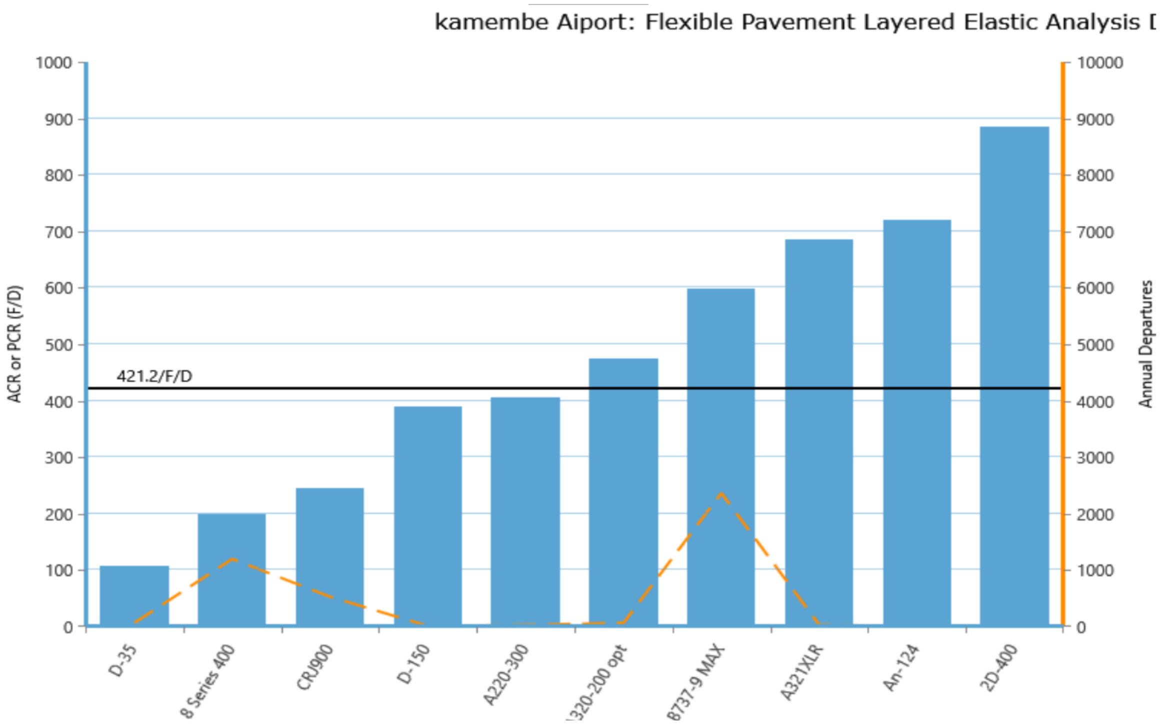


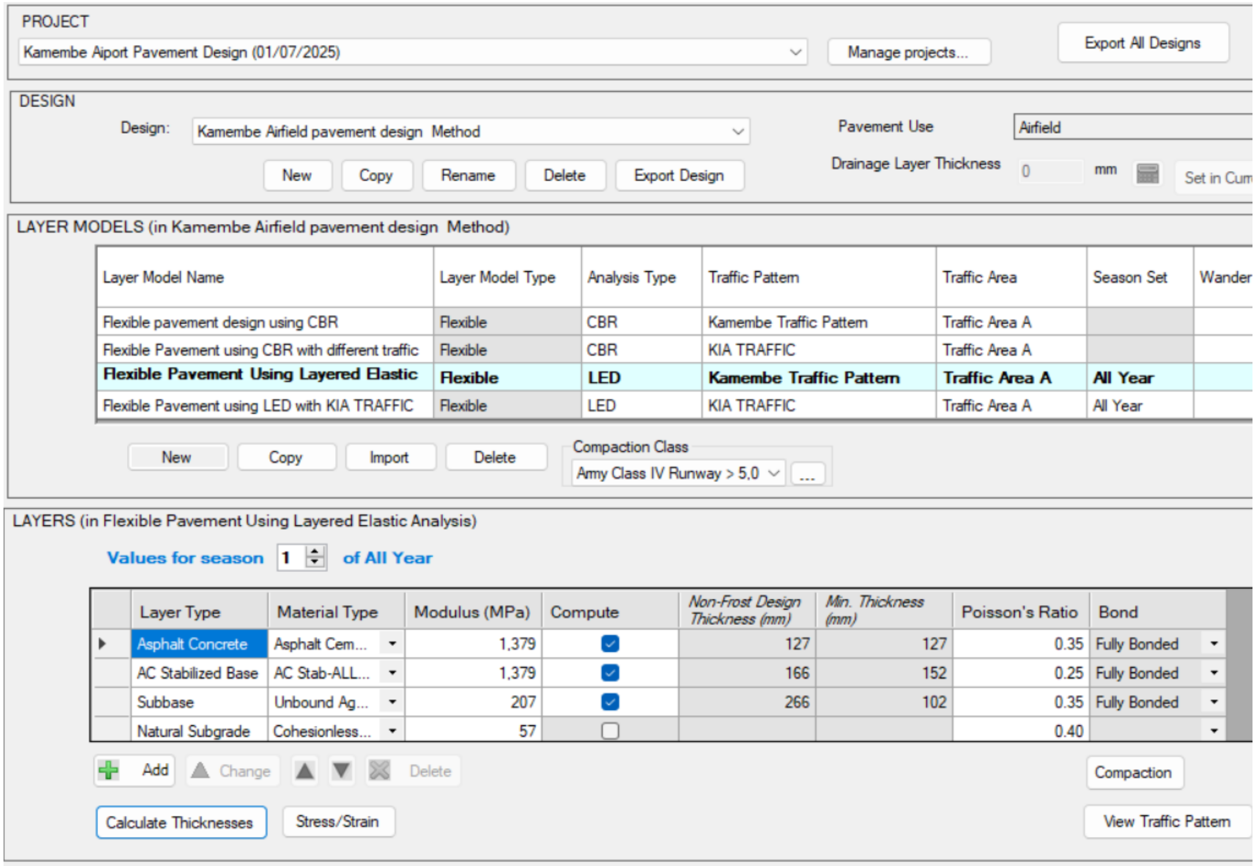
Figure 4-22:ACR-PCR Graph

### 4.4.2 Kamembe Pavement design method using PCASE-LED METHOD

Pavement design considerations:

- The design CBR is 5.5%

- Aircraft Traffic Mix to be considered are in data Table 3-8
- The wearing course is HMA layer
- The base course is HMA stabilized
- The subbase course will be uncrushed aggregate
- The design period is 20 years



Kamembe Aiport Pavement Design (01/07/2025)

Design: Kamembe Airfield pavement design Method

Pavement Use: Airfield

Drainage Layer Thickness: 0 mm

LAYER MODELS (in Kamembe Airfield pavement design Method)

| Layer Model Name | Layer Model Type | Analysis Type | Traffic Pattern | Traffic Area | Season Set | Wander |
|---|---|---|---|---|---|---|
| Flexible pavement design using CBR | Flexible | CBR | Kamembe Traffic Pattern | Traffic Area A | | |
| Flexible Pavement using CBR with different traffic | Flexible | CBR | KIA TRAFFIC | Traffic Area A | | |
| **Flexible Pavement Using Layered Elastic** | **Flexible** | **LED** | **Kamembe Traffic Pattern** | **Traffic Area A** | **All Year** | |
| Flexible Pavement using LED with KIA TRAFFIC | Flexible | LED | KIA TRAFFIC | Traffic Area A | All Year | |

Compaction Class: Army Class IV Runway > 5,0

LAYERS (in Flexible Pavement Using Layered Elastic Analysis)

**Values for season** 1 **of All Year**

| Layer Type | Material Type | Modulus (MPa) | Compute | *Non-Frost Design Thickness (mm)* | *Min. Thickness (mm)* | Poisson's Ratio | Bond |
|---|---|---|---|---|---|---|---|
| Asphalt Concrete | Asphalt Cem... | 1,379 | ☑ | 127 | 127 | 0.35 | Fully Bonded |
| AC Stabilized Base | AC Stab-ALL... | 1,379 | ☑ | 166 | 152 | 0.25 | Fully Bonded |
| Subbase | Unbound Ag... | 207 | ☑ | 266 | 102 | 0.35 | Fully Bonded |
| Natural Subgrade | Cohesionless... | 57 | ☐ | | | 0.40 | |

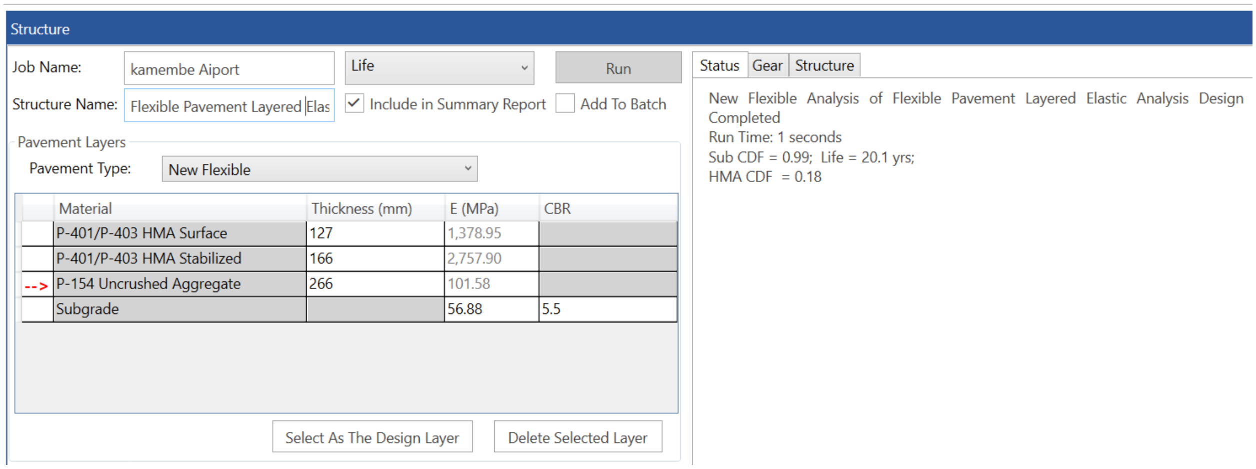
**Figure 4-23:Kamembe Airport PCASE-LED Design results extract**

From the above Figure 4-10 the resulted pavement section for NBIA using Mechnistic empirical LED method, are as follow: The HMA wearing course is 127mm which is equal to the minimum recommended , Asphalt Concrete Stabilized Base course is 166 mm is greater than the minimum recommended and the unbound aggregate subbase is 216mm which is greater than the minimum to be provided.

**Table 4-7:Summarized results from PCASE-LED method-KAMEMBE**

| Pavement layer | Thickness in mm |
|---|---|
| Wearing surface | 127 |
| Stabilized Base | 166 |

|  |  |
|---|---|
| Uncrushed aggregate-subbase | 266 |
| **Total thickness above Subgrade** | **559** |



Job Name: kamembe Aiport

Structure Name: Flexible Pavement Layered Elas

Life

☑ Include in Summary Report ☐ Add To Batch

Pavement Layers

Pavement Type: New Flexible

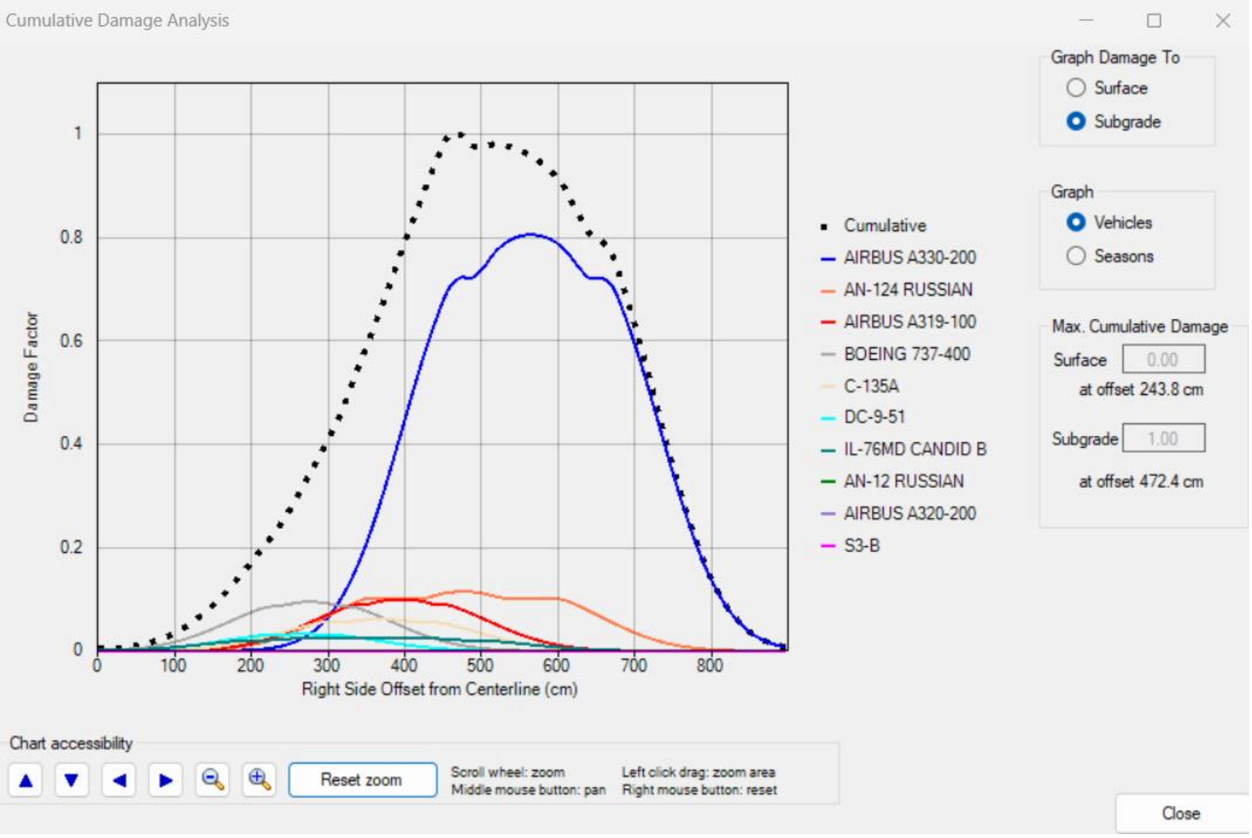
|  | Material | Thickness (mm) | E (MPa) | CBR |
|---|---|---|---|---|
|  | P-401/P-403 HMA Surface | 127 | 1,378.95 |  |
|  | P-401/P-403 HMA Stabilized | 166 | 2,757.90 |  |
| --> | P-154 Uncrushed Aggregate | 266 | 101.58 |  |
|  | Subgrade |  | 56.88 | 5.5 |

New Flexible Analysis of Flexible Pavement Layered Elastic Analysis Design Completed
Run Time: 1 seconds
Sub CDF = 0.99; Life = 20.1 yrs;
HMA CDF = 0.18

**Figure 4-24:Analysis of the design Life from PCASE-LED using FAAFIELD-KAMEMBE**

From Above Table 4-7,the wearing surface course(HMA) is 127mm thick, crushed aggregate base course is 166 mm thick,refering to Table 5-2,the minimum thickness of HMA wearing course as per FAA is 100mm(127>100),base course minimum thickness is 150mm(153>150) and subbase course minimum thickness is 150mm(194>150mm).we can see that all flexible pavement layers fall above the minimum recommended thickness by Current Advisory circular. The minimum thicknesses are set bases on constructability and environmental considerations.it was practically shown that compacting a granular layer less than 15cm thick is inefficient.

And from Figure 4-6 the design life for this pavement is 22.3 years which is closer to 20 years design life designed in PCASE, we can see that with two different softwares using LED method, the design life and the computed service life is nearly the same. From Figure 4-25 the stress-strain is expressed as cumulative damage model where each individual aircraft damage contribution is added up to obtain to total damage of the entire traffic mix ,at which the software iterate the thickness to have a CDF ration of 1,the critical aircraft(the most damaging ) in the traffic mix is AIRBUS A330-200 as shown in the Figure 4-25.



Graph Damage To
○ Surface
● Subgrade

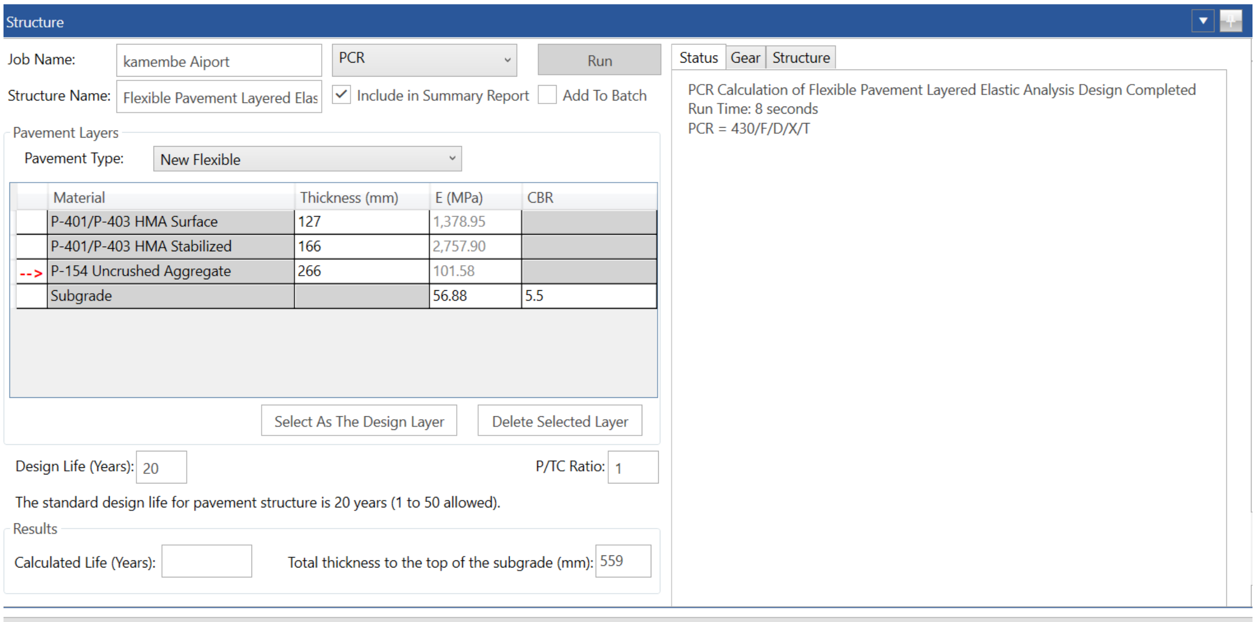
Graph
● Vehicles
○ Seasons

Max. Cumulative Damage
Surface 0.00
at offset 243.8 cm
Subgrade 1.00
at offset 472.4 cm

**Figure 4-25:stress-strain in terms of cumulative damage model**

From Figure 4-25 the most damaging aircraft is Airbus A330-200,with cumulative damage represented by a dashed line.

### 4.4.2aACR/PCR Analysis for KAMEMBE PCASE-CBR Pavement section



Job Name: kamembe Aiport

PCR

Structure Name: Flexible Pavement Layered Elas

☑ Include in Summary Report

☐ Add To Batch

PCR Calculation of Flexible Pavement Layered Elastic Analysis Design Completed
Run Time: 8 seconds
PCR = 430/F/D/X/T

Pavement Layers

Pavement Type: New Flexible

| | Material | Thickness (mm) | E (MPa) | CBR |
|---|---|---|---|---|
| | P-401/P-403 HMA Surface | 127 | 1,378.95 | |
| | P-401/P-403 HMA Stabilized | 166 | 2,757.90 | |
| --> | P-154 Uncrushed Aggregate | 266 | 101.58 | |
| | Subgrade | | 56.88 | 5.5 |

Design Life (Years): 20

P/TC Ratio: 1

The standard design life for pavement structure is 20 years (1 to 50 allowed).

Results

Calculated Life (Years):

Total thickness to the top of the subgrade (mm): 559

Figure 4-26:PCR Computation for PCASE-LED pavement section

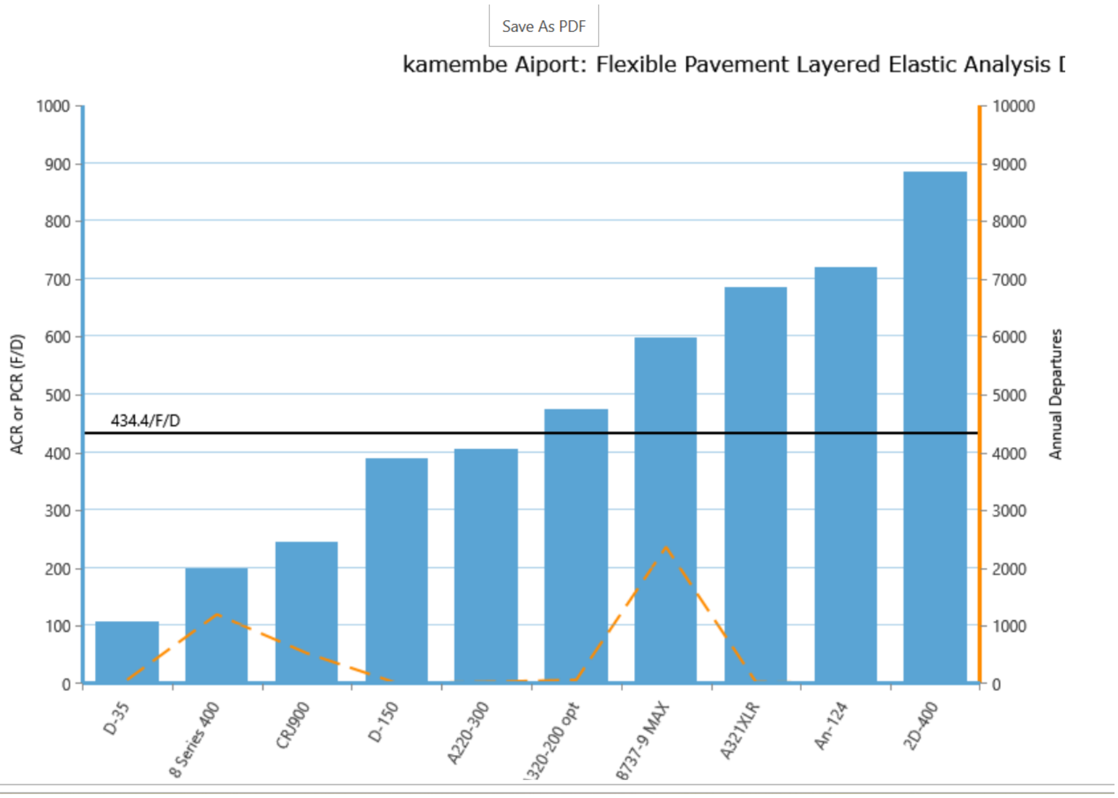


Figure 4-27:ACR-PCR Graph

## 5. OBSERVATIONS, CONCLUSION AND RECOMMENDATIONS

### 5.1Observations

In this comparative study, pavement design sections prepared using the Mechanistic-Empirical Methods represented by the United States Army Corps of Engineer PCASE-LED and the Empirical Pavement Design represented by PCASE-CBR.the resulted Pavement layers were modeled in FAAFIELD considering similar traffic loading and subgrade strength to predict the service life of each pavement section.

From the Analysis and design of pavement structure for the three airports, the output can be summarized in the table below:

Table 5-1:Summary of thicknesses for obtained data

| | | | | | | | | | **Computed service Life using FAARFIELD** | | **Design CBR** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Airport** | **PCASE-CBR METHOD** | | | | **PCASE-LED METHOD** | | | | **PCASE-CBR** | **PCASE-LED** | |
| | **Wearing course** | **Base** | **Sub base** | **Total** | WC | Base | Sub base | Total thick | Life in years | Life in years | |
| **Kigali International Airport** | 127 | 257 | 102 | 486 | 127 | 153 | 211 | 491 | 28.4 | 20.5 | 15.5 |
| **New Bugesera International Airport** | 127 | 267 | 102 | 496 | 127 | 153 | 194 | 494 | 31 | 22.3 | 18 |
| **Kamembe Airport** | 102 | 159 | 353 | 614 | 127 | 166 | 266 | 559 | 0.2 | 20.1 | 5.5 |

From the Above summarized design results in Table 5-1 for thicknesses, we can highlight the following:

For Kigali International Airport using PCASE-CBR method yield into thicker base giving the robust structure that would not structurally fail in the design period of 20 years, however we should be aware that flexible pavement damages from environmental conditions does not depend on the thickness of layers, no matter how thicker the flexible Pavement may be, it will degrade due to environment. We can realize that PCASE-CBR resulted into thicker base(257mm) with thin subbase(102mm) whilst the PCASE-LED Gave a thinner base(153mm) with a thicker subbase(211mm) from the principle of flexible pavement that top layers protect the bottom layers, hence much costly, we are aware that the base course materials (stabilized base for this case) are far much costlier than the subbase materials. This result into an expensive pavement that will still degrade due to environmental conditions and requires either milling and overlay or simply an overlay.

For New Bugesera International Airport Design thicknesses there is a similar case as for KIA, the base for PCASE-CBR design is robust compared to PCASE-LED (267mm-194). this yield in robust pavement structure and costly project.

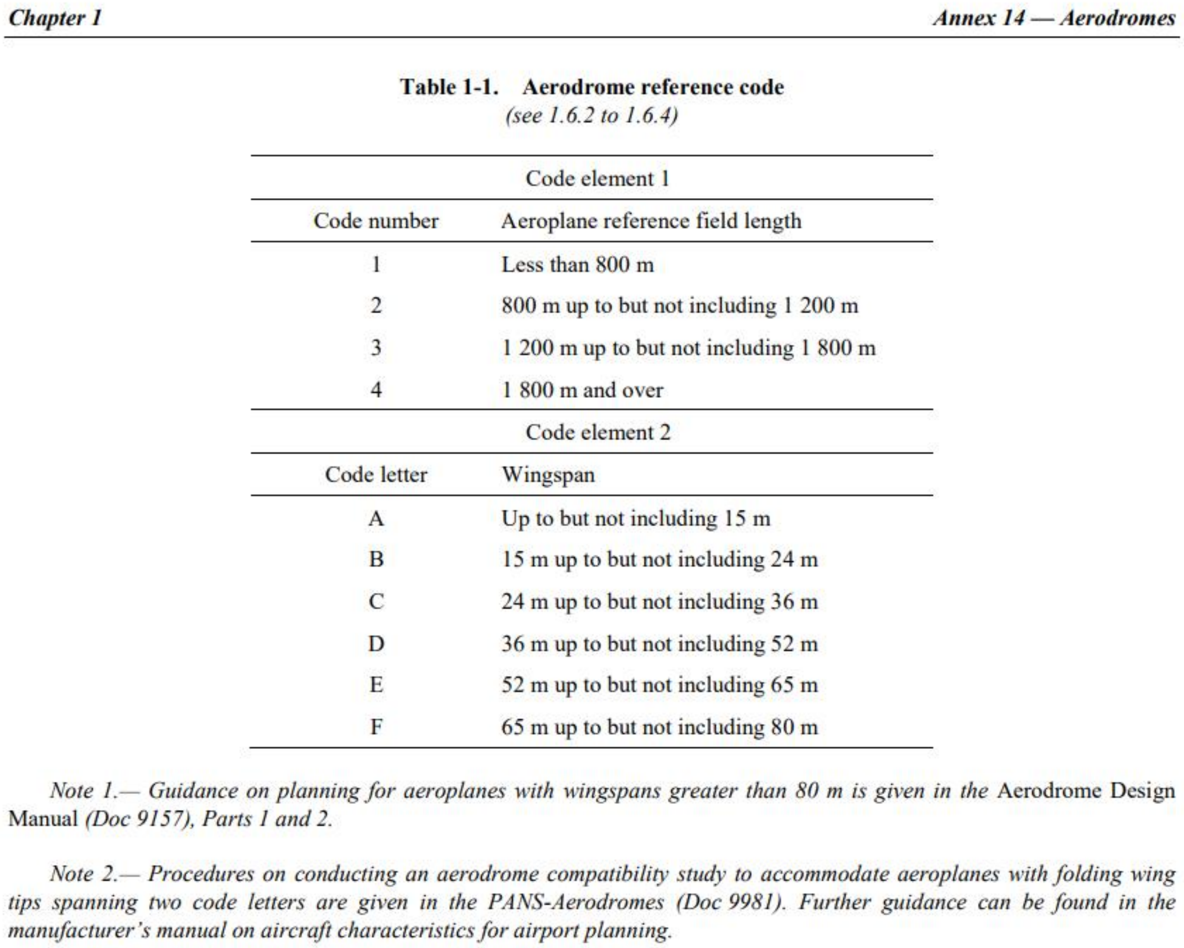
For Kamembe Airport a different case were observed, the PCASE-CBR pavement design resulted into smaller thicknesses compared to PCASE-LED. Kamembe Airport is designed for code C Aircraft (see Table 5-3 ) for Aerodrome reference Code for Aircraft Characteristics based on wingspan). these Aircrafts are much smaller with low loadings, the software yielded into minimum practicable pavement layer's thickness that account constructability and environmental degradation resistance, this implies that for a low loading traffic the pavement may degrade more from environmental conditions than traffic loading. This is the case for Kamember Airport. The PCASE-CBR and PCASE-LED have different minimum Thickness for layers as shown in the minimum layer's thickness in Table 5-1.

**Table 5-2:Minimum thickness of layers.**

| Pavement Layer(s) | PCASE-CBR Minimum thickness in mm | PCASE-LED Minimum thickness in mm |
|---|---|---|
| Wearing Course | 102 | 127 |
| Stabilized Base | 152 | 152 |
| Unbound Aggregate | 102 | 102 |

From the table Above (minimum thickness of Layers) we can easily see that the thicknesses are same for Stabilized Base and unbound Aggregate) whereas the thickness for Wearing course (HMA surface Course is 127mm for PCASE-LED whilst 102mm for PCASE-CBR.the top layer is bituminous layer prone to degradation due to environmental exposure causing both oxidation and wearing out of the binder. With PCASE-LED, the sensitivity analysis takes into account of the effect of stripping and oxidation, that is why much thicker layer is provided, whereas for PCASE-CBR, it only bases on minimum thickness to protect the bottom layer from water ingress.

## Table 5-3:Aerodrome Reference code



*Chapter 1* *Annex 14 — Aerodromes*

**Table 1-1. Aerodrome reference code**
*(see 1.6.2 to 1.6.4)*

| Code element 1 | |
|---|---|
| Code number | Aeroplane reference field length |
| 1 | Less than 800 m |
| 2 | 800 m up to but not including 1 200 m |
| 3 | 1 200 m up to but not including 1 800 m |
| 4 | 1 800 m and over |
| Code element 2 | |
| Code letter | Wingspan |
| A | Up to but not including 15 m |
| B | 15 m up to but not including 24 m |
| C | 24 m up to but not including 36 m |
| D | 36 m up to but not including 52 m |
| E | 52 m up to but not including 65 m |
| F | 65 m up to but not including 80 m |

*Note 1.— Guidance on planning for aeroplanes with wingspans greater than 80 m is given in the* Aerodrome Design Manual *(Doc 9157), Parts 1 and 2.*

*Note 2.— Procedures on conducting an aerodrome compatibility study to accommodate aeroplanes with folding wing tips spanning two code letters are given in the PANS-Aerodromes (Doc 9981). Further guidance can be found in the manufacturer's manual on aircraft characteristics for airport planning.*

From the Above Table, Kigali International Airport runway has 3500m with 60m wide (Code 4E), Bugesera International Airport runway shall be 4000m length with 75m width (Code 4F) whilst Kamembe Airport has Runway of 1500m,35 m width (code 3C).

Existing Pavement Data for Kigali International Airport:

## Table 5-4:existing pavement layers at Kigali International Airport

| Airfield Portion | Surface Course(mm) | Base Couse(mm) | Subbase Course(mm) | Subgrade strength(mm)-CBR | Originally constructed thicknesses-surface course | Year of Construction |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| Runway | 260 | 300 | - | 15.5 | 120 | 1960s |
| Taxiway Alfa | 102 | 120 | 300 | 14.5 | 102 | 2016 |
| Taxiway Bravo | 102 | 100 | 400 | 17 | 102 | 1999 |
| Apron Alfa | 260 | 250 | 268 | 12 | 120 | 1960s |
| Apron Bravo | 102 | 105 | 550 | 8 | 112 | 2012 |

From the Above table of layers thicknesses for existing pavement at Kigali International Airport, you can easily see that the originally constructed runway back 1960s using Empirical method had a thicker base course materials with no subbase materials, the thicknesses of wearing course varied due to overlaying operation done with time to time. Considering Taxiway Alfa built in 2016 the base course material layer is 120mm and subbase course is 300mm, this combination is economical compared to 300mm of base course material. This based solely on initial construction cost of thick layer compared to thin base layer.

Regarding the Tire pressure ,wheel configuration and Aircraft type refer to Aircraft Classification Rating-Pavement Classification Rating (ACR-PCR) in Figure 4-3,Figure 4-4Figure 4-8Figure 4-9Figure 4-12,Figure 4-13,Figure 4-16,Figure 4-17,Figure 4-21,Figure 4-22,Figure 4-26,Figure 4-27. The pavement classification rating (PCR) is an index rating (1/50th) of the mass, expressed in kilograms, which an evaluation shows it can be borne by the pavement when applied by a standard (1.50 MPa tire pressure) single wheel. The PCR rating established for a pavement indicates that the pavement is capable of supporting aircraft having an aircraft classification rating (ACR) of equal or lower magnitude. The ACR in comparison to the PCR must be the aircraft ACR established for the particular pavement type and subgrade category of the rated pavement, as well as for the particular aircraft mass and characteristics.

We can see higher PCR Values for all but kamembe, which implies that the pavement structure is very robust, the tire pressure resistance relies on top surface layers prone to immediate shear deformation.

Minimum thicknesses for LED and PCASE design methodologies

Table 5-5:Minimum thickness for pavement layers.

| Pavement Layer | LED minimum thickness in mm | CBR minimum thickness in mm |
|---|---|---|
| Surface Layer | 100 | 127 |
| Stabilized Base layer (HMA Stabilized) | 12.5 | - |
| Base course(stabilized) | 150 | 152 |

|  |  |  |
|---|---|---|
| Subbase layer | 150 | 102 |

## 5.2 Conclusion

Many airports constructed in past decades were designed using traditional empirical methods. While these pavements often performed adequately, the absence of baseline performance criteria made it difficult to evaluate their cost-effectiveness. As a result, many required overlays within a few years due to surface deterioration—an outcome linked to the lack of preservation strategies. Additionally, limited understanding of material properties and their behaviour under traffic loads led to higher construction costs, with performance outcomes similar to those achieved through mechanistic-empirical (ME) methods.

Although empirically designed pavements may last for extended periods, their performance remains unpredictable due to insufficient analysis of material behaviour and stress-strain relationships. Comparative modelling using PCASE-LED in FAARFIELD demonstrated that pavement sections could reliably meet a 20-year design life. In contrast, designs based on PCASE-CBR resulted in significant overdesign for pavements with moderately strong subgrades (CBR ≥ 10), yielding unrealistic design life predictions. Conversely, weak subgrades (low CBR) led to under-designed sections.

The mechanistic-empirical approach provides a more reliable understanding of material performance, enabling more economical designs with predictable, long-term pavement behaviour

### 5.2.1 Cost benefits analysis of both methods

Mechanistic-Empirical (ME) pavement design is generally more cost-effective over the long term compared to traditional empirical methods, even though it might involve higher upfront **costs.** By integrating detailed information about material properties and environmental conditions, ME design produces pavements that are more durable and require less frequent maintenance or reconstruction throughout their service life. In contrast, empirical methods—while simpler—rely heavily on historical data and may not account for modern traffic demands or climate variations. This can result in pavement designs that are either overly conservative (wasting materials and money) or inadequate (leading to early failure and costly repairs).

Detailed Comparison:

- Empirical Design:
  - Based on historical observations linking pavement thickness, materials, and traffic loads.
  - Example: The 1934 CBR Design Guide.

  - May not accurately capture the effects of modern traffic patterns or environmental changes.
  - Risks include over-design (leading to unnecessary costs) or under-design (causing early failures and increased maintenance expenses).
- Mechanistic-Empirical (ME) Design:
  - Uses mechanistic models to simulate pavement behaviour, supplemented by empirical calibration with real-world performance data.
  - Accounts for factors like material stiffness, strength, climate conditions, and traffic loads.
  - The Mechanistic-Empirical Pavement Design Guide (MEPDG) is a widely used tool.
  - Enables optimized pavement design, improving durability and reliability.

Economic Considerations:

- Initial Costs**:** ME design typically requires more detailed data and analysis, which can increase initial expenses.
- Life-Cycle Costs: Because ME methods more accurately predict pavement performance, they help reduce long-term costs by minimizing repairs, maintenance, and early rehabilitation needs.
- Long-Term Benefits: The improved performance and reliability of ME-designed pavements can lead to significant cost reductions over the pavement's lifecycle for agencies managing Pavement infrastructure.

The summarized cost for each airport is summarized as ,the unit cost considered is based on reasonable estimates:

The Airport SN are as Kigali(1) Bugesera(2) and kamembe is (3) ,considering a 2500m km runway, the cost of pavement layers is summarized as below:

**Table 5-6:Summary of cost for each pavement design methodology**

| **Airport** | **EMPIRICAL PAVEMENT SECTIONS SUMMARY OF COST** | | | | **MECHANISTIC EMPIRICAL PAVEMENT SECTIONS SUMMARY OF COST** | | | |
|---|---|---|---|---|---|---|---|---|
| **SN** | **Wearing Course** | **Base** | **Subbase** | **Total (RWF)** | **Wearing Course** | **Base** | **Subbase** | **Total** |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **KIA(1)** | 2,063,750,000 | 2,570,000,000 | 204,000,000 | **4,837,750,000** | 2,063,750,000 | 1,530,000,000 | 422,000,000 | **4,015,750,000** |
| | | | | | | | | |
| **NBIA(2)** | 2,063,750,000 | 2,670,000,000 | 204,000,000 | **4,937,750,000** | 2,063,750,000 | 1,530,000,000 | 388,000,000 | **3,981,750,000** |
| | | | | | | | | |
| **KMBE (3)** | 1,657,500,000 | 1,590,000,000 | 706,000,000 | **3,953,500,000** | 2,063,750,000 | 1,660,000,000 | 532,000,000 | **4,255,750,000** |

From the Table 5-6 the cost for Empirical design pavement design sections is higher than the Layered Elastic Design methods for the two Kigali International Airport and New Bugesera International Airport, however the Mechanistic Empirical design approach yielded into costlier pavement for Kamembe Airport, this is not an overdesign for LED ,instead it is an under design for CBR Method by referring to computed service design life.

The Layered Elastic design methods are reliable, hence yield into suitable and economic pavement section in the long run, whereas the CBR methods can either under design or overdesign.

### 5.2.2 Gaps of empirical design methods.

The empirical design methods does not have the capability to analyse the effects of tyre pressure ,this is implied in the design methodology that do not provide the tyre pressure during analysis ,refer to Figure 4-7,Figure 4-18, and Figure 4-25.for the analysis of damage model as well as the Pavement Classification Rating(PCR) showing the Tyre pressure(X means high tyre pressure

- **Limited Scope of Input Data:**

Empirical methods often rely on limited datasets, which may not accurately represent the wide range of traffic loads, material properties, and environmental conditions encountered in modern pavement. this includes material testing data.

**Difficulty in Predicting Long-Term Performance:**

Extrapolating from past performance to predict future pavement behaviour can be challenging, particularly when considering the cumulative effects of traffic loading, aging, and environmental factors. No cumulative damage model concepts as done for ME models.

- **Lack of Consideration for Material Variability:**

Empirical methods may not fully capture the variability in material properties and their impact on pavement response. The FAARFIELD has the capability to input new material properties as user defined layer, with the Empirical methods they were developed on assumed materials characteristics that should be met during design and construction.

- **Difficulty in Evaluating New Materials:**

When new materials or construction techniques are introduced, empirical methods may not provide reliable predictions of their performance.

- **Over-reliance on Past Performance:**

While past performance is valuable, it may not be representative of future conditions. This can lead to designs that are either over- or under-designed

### 5.2.3 Comparison between empirical and Mechanistic empirical in summarized table

Table 5-7 detailed comparative parameters for Empirical and Mechanistic Empirical design methos

| Compared parameter | Empirical design methods | Mechanistic Empirical design method |
|---|---|---|
| **Support** | | |
| Paper documentation | Yes | Yes |
| User friendly software | Yes | Yes |
| Need of calculus power | No | Yes |
| **type of pavement and type of analysis** | | |
| Design of all types of new-construction pavements | Yes | Yes |
| Rehabilitation of all types of pavements | No | Yes |
| different accuracy levels depending on inputs | No | Yes |
| **traffic inputs** | | |
| Load spectra | No | Yes |
| Use of design aircraft | Yes | No |
| Traffic wander | No | Yes |
| Traffic speed (load speed) | No | Yes |

| | | |
|---|---|---|
| Analysis of damage caused by special vehicles/aircraft | No | Yes |
| **Climate** | | |
| Possibility of introducing any type of climate state | No | Yes |
| Continuous adaptation of climate parameters during the analyzed period | No | Yes |
| **models for the analysis of materials and structure** | | |
| Non-linear characterization of unbound layers | No | Yes |
| Unbound materials resilient modulus adjusted for moisture variation during pavement life | No, only seasonally variations are considered. | Yes |
| Binder complete characterization | No | Yes |
| Short and long-term hardening consideration | No | Yes |
| Consideration of the variation of the modulus of asphalt mixes at different temperatures and load frequencies | No | Yes |
| Consideration of the viscoelastic behavior of asphalt mixes | No | Not in structural models.<br>Yes, in transfer equations |
| **calibration of structural models** | | |
| Models nationally calibrated and validated | No; only data of the FAA test track | Yes |
| Time length of the performance data used in the calibration | 5 years based on IRI | More than 15 years |
| Time length of the traffic data used in the calibration | Less than 30,000 annual departures | Up to 100,000 annual departures |
| **distresses prediction** | | |
| Accumulated damage prediction nearly in a continuous way (monthly intervals) | No, | Yes, uses cumulative damage concept |
| Permanent deformation of bound and unbound layers | No | Yes |
| Alligator and/or longitudinal fatigue cracking considerations | No | Yes |
| Transverse cracking | No | Yes |
| Roughness | No | Yes |

| **Other related comparisons** | | |
|---|---|---|
| Analysis of stress and strain | No analysis required (purely based on past performance) | Analysis required |
| Material testing | Less testing required | Sophisticated testing required |
| Reliability | Low | High |
| Cost effectiveness | • Higher construction cost in case of overdesign.<br>• Higher M&R cost in case of under design<br>• Lower materials testing cost<br>Overall cost is higher in the long run (considering M&R) | • Optimum construction cost<br>• Lower M&R cost due to predictable performable<br>• Higher cost of materials testing<br>• More economical in the long run |
| Pavement Management and maintenance models | Can't be incorporated during design | May be incorporated |
| Accommodation of differing materials characteristics | Difficult to deviate from materials used during trial sections | Accommodate various material characteristics |

## 5.3 Recommendations

The Layered Elastic Analysis, as a mechanistic-empirical approach, offers several advantages over traditional empirical methods. It accounts for horizontal tensile strain at the bottom of the asphalt layer to reduce fatigue cracking and considers vertical compressive strain at the top of the subgrade to minimize permanent deformation. In contrast, the CBR design method assumes minimal strength for the aggregate subbase, often resulting in overly thick base layers. In this study, the design sections produced using the CBR method yielded significantly thicker bases compared to those derived from the Layered Elastic Design, thereby increasing construction costs. As a result, the following recommendations are proposed:

- ❖ Avoid designing Airfield flexible Pavement on weak subgrades, and if the subgrade strength is low, some kind of improvement should be done. This helps to get reasonable design thickness.
- ❖ The LED recommends to use a slightly lower surface course -100mm compared to 127mm for the CBR method. The stabilized base adds a lot value at low cost compared to thick surface course.
- ❖ Since traffic forecasting is inherently uncertain and can lead to significant variations in pavement thickness depending on the method used, it is recommended to adopt shorter

design lives—ideally not exceeding 20 years—to minimize the impact of these uncertainties.

### 5.3.1 Recommendations for future research

The reliability of flexible pavements depends on design, quality of materials and construction. With the quality materials being very important, I recommend to do more research on using highway local materials with little to no modification of properties for maintenance and rehabilitations airport flexible pavement.

This will reduce the Life Cycle cost of the existing airport pavement.

# 6. REFERENCES

[1] Neufville and Odoni, "Aviation infrastructure evolution," 2019.

[2] I. A. T. Association, "ICAO Aviation statistics through collaborative analysis," 2022.

[3] Belobaba, "The Global Airline Industry," p. 13, 2017.

[4] J. a. F. Calzada, "Route expansion in the European air transport market.," p. 14, 2019.

[5] R. Horonjeff, "Planning and Design of Airports," Airfield Asphlalt Pavement Technology Program(AAPTP), Philadelphie, 2010.

[6] E. a. T. J. Heymsfield, "State of the practice in pavement structural ,codes relevant to airfield pavement design. Engineering Failure Analysis," Asphallt Institute, Lexington, 2019.

[7] I. International Civil Aviation Administration, "Aerodrome pavement design," ICAO, Montreal,Canada, 2022.

[8] R. a. E.-K. T. Mallick, "Pavement Engineering: Principles and Practice," National Asphalt Technology aProgram, 2020.

[9] R. Vieira, "Dimensionamentos de Pavimentos Aeroportuários: A Consideração de Novas Orientações," p. 14, 2015.

[10] G. White, "State of the art: Asphalt for airport pavement surfacing," *International Journal of Pavement Research and Technology,* p. 16, 2021.

[11] FAA, " Airport Pavement Design and Evaluations," *Advisory Circular(AC,* p. 140, 2010.

[12] G. a. M. Garg, "Operational Life of Airport Pavement," Unites States Department of Transportation, Washington DC, r 2004.

[13] C. DOT, "CBR method of flexible Pavement Design," Califonia, 1978.

[14] U. COE, "Flexible Pavement Design," New Jersey, 1973.

[15] U. S. A. C. o. E. U. COE, "Flexible Pavement design manual," New Jersey, 1973.

[16] T. D. o. T. (TxDOT), "Pavement Design Guide," Texas , Austin, 2011.

[17] U. A. C. O. ENGINEERS, "Pavement Design For Airfields,Unified Facility Critieria," Naval Facilities Engineering Command, Wahington D.C, 2001.

[18] A. F. Aviation, "AC 150/5320-6F, Airport Pavement Design and Evaluation," Administartion Federal Aviation, Washington DC, 6/7/2021.

[19] G. G. a. M. Q. Queen, "Operational Life of Airport Pavement," pp. 6-8, December 2004.

[20] Sofreavia, "Pavement condition Index for Kigali international Airport," Sofreavia, Kigali, 2001.

[21] AASHTO, "Mechanistic-Empirical Pavement Design Guide," American Association of State Highway and Transportation Officials, Washington DC, 2008.

[22] Y. H. Huang, Flexible Pavement, New York, 2004.

[23] FDOT, "lexible Pavement Design Manual," Florida Department of Transportation, Florida, January 2005.

[24] Hammitt, "Comparative Performance of Structural Layers in Pavement," Federal Aviation Administration, Washington D.C, December 1974.

[25] A. Institute, "Asphalt Pavements for Highways & Streets, Manual Series," Asphalt Institute, Lexington, KY, USA, 2008.

[26] A. Institute, "User' Guide for Asphalt Pavement Design Software for Highways,," Asphalt Institute, Lexington, KY, USA, 2005.

[27] Mohammed Mahmoud Shallal, "Traffic Loading for Pavement Design," *Building & Road Research ,University of Khartoum,* p. 12, 2010.

# 7. LIST OF APPENDICES

## APPENDIX 1: PCASE-CBR DESIGN REPORT FOR KIGALI INTERNATIONAL AIRPORT

| | | | | | |
|---|---|---|---|---|---|
| PCASE Version: | 7.0.7 2025-02-20 | | | | |
| Design Name: | Kigali Flexible Pavement Design | | | | |
| Layer Model Name: | Flexible Pavement analysis using CBR Method | | | | |
| Drainage Station: | Not selected | | | | |
| Frost Station: | Not selected | | | | |
| Pavement Use: | Airfield | | | | |
| Design Type: | Flexible | | | | |
| Traffic Area: | Traffic Area A | | | | |
| Analysis Type: | CBR | | | | |
| Wander Width (mm): | 1778 | | | | |
| | | | | | |
| | | | | | |
| **Layer Information** | | | | | |
| **Layer Type** | **Material Type** | **Frost Code** | **Analysis** | **Design Thickness (mm)** | **CBR** |
| Asphalt Concrete | Asphalt Cement | NFS | Compute | 127 | |
| AC Stabilized Base | AC Stab-ALL Bituminous | NFS | Compute | 257 | 100 |
| Subbase | Unbound Aggregate | NFS | Compute | 102 | 20 |
| Natural Subgrade | Cohesionless Cut | NFS | Manual | | 15.5 |
| | | | | | |
| | | | | | |
| **Traffic Information** | | | | | |
| Service | Army | | | | |
| Pattern Name: | KIA TRAFFIC | | | | |
| | | | | | |
| | **Weight (kg)** | **Weight (kg)** | **Passes** | **Passes** | **Equivalent Passes** |
| **Vehicles** | **Traffic Area A,B** | **Traffic Area C,D** | **Traffic Area A,B,C** | **Traffic Area D** | |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| *-GROUP11 | 381018 | 285763 | 100 | 1 | 1 |
| *-GROUP14 | 221353 | 166015 | 100 | 1 | 296 |
| AIRBUS A319-100 | 75659 | 56744 | 10000 | 100 | 23 |
| AIRBUS A320-200 | 67999 | 50999 | 2700 | 27 | 1 |
| AIRBUS A330-200 | 230896 | 173172 | 900 | 9 | 683 |
| AIRBUS A340-200 | 275898 | 206923 | 2000 | 20 | 1585 |
| AIRBUS A380-800 | 562001 | 421501 | 5467 | 55 | 5467 |
| ANDOVER C MK 1 & E MK 3 | 24926 | 18694 | 100 | 1 | 1 |
| ANDOVER CC MK 2 QUEENS FLIGHT | 21071 | 15803 | 100 | 1 | 1 |
| AT-38B TALON | 6124 | 4593 | 100 | 1 | 1 |
| B-1B LANCER | 216364 | 162273 | 900 | 9 | 654 |
| B-52H STRATOFORTRESS | 221353 | 166015 | 100 | 1 | 296 |
| BAE BUCCANEER S MK 2A & 3B | 26911 | 20183 | 100 | 1 | 1 |
| BOEING 707-120B | 116728 | 87546 | 9590 | 96 | 1 |
| BOEING 707-420 | 141521 | 106141 | 100 | 1 | 1 |
| BOEING 720 | 104009 | 78007 | 3000 | 30 | 1 |
| BOEING 737 MAX 9 | 88541 | 66406 | 4890 | 49 | 258 |
| BOEING 737-100 | 49895 | 37421 | 9000 | 90 | 1 |
| BOEING 737-200 | 52163 | 39122 | 70000 | 700 | 1 |
| BOEING 747-200B/-200B COMBI/-300 | 377842 | 283382 | 6000 | 60 | 419 |
| BOEING 747-400 | 394625 | 295969 | 15700 | 157 | 3101 |
| BOEING 757-200PF | 116120 | 87090 | 10000 | 100 | 1 |
| BOEING 757-300 | 122470 | 91852 | 13000 | 130 | 3 |
| BOEING 767-200ER | 179169 | 134377 | 1000 | 10 | 33 |
| BOEING 767-300ER | 185519 | 139139 | 1000 | 10 | 69 |
| BOEING 777-300 | 300278 | 225209 | 9000 | 90 | 3286 |
| BOEING 787-9 | 254692 | 191019 | 1000 | 10 | 1743 |
| C-22B | 76657 | 57493 | 11000 | 110 | 45 |

| | | | | | |
|---|---|---|---|---|---|
| C-2A | 27216 | 20412 | 9756 | 98 | 1 |
| CN-235 (CIVIL) | 16500 | 12375 | 100 | 1 | 1 |
| DASH 7 | 19958 | 14969 | 16000 | 160 | 1 |
| DASH 7 | 19958 | 14969 | 100 | 1 | 1 |
| DC-9-51 | 54885 | 41164 | 5650 | 56 | 1 |
| E-2C HAWKEYE | 23541 | 17656 | 100 | 1 | 1 |
| E-2D ADVANCED HAWKEYE (SHORE) | 26082 | 19561 | 100 | 1 | 1 |
| EC-135A | 136804 | 102603 | 100 | 1 | 1 |
| EC-135E | 136804 | 102603 | 100 | 1 | 1 |
| EC-135G | 136804 | 102603 | 100 | 1 | 1 |
| FAA SWL-50 | 22680 | 17010 | 100 | 1 | 2 |
| FALCON DA-20 | 13200 | 9900 | 100 | 1 | 1 |
| MC-130H COMBAT TALON II | 79379 | 59534 | 100 | 1 | 1 |
| MD-11 | 287124 | 215343 | 100 | 1 | 99 |
| MHU-196 AIRFIELD | 36287 | 27216 | 100 | 1 | 1 |
| MIG-29 RUSSIAN | 19700 | 14775 | 100 | 1 | 1 |
| MQ-4C Triton | 14742 | 11056 | 100 | 1 | 1 |
| MQ-9A REAPER | 4763 | 3572 | 100 | 1 | 1 |
| MV-22 OSPREY | 27442 | 20582 | 100 | 1 | 1 |
| AIRBUS A380-800 | 562001 | | | | 18091 |
| | | | | | |

## APPENDIX 2:PCASE-LED DESIGN REPORT FOR KIGALI INTERNATIONAL AIRPORT

| | | | | | | |
|---|---|---|---|---|---|---|
| PCASE Version: | 7.0.7 2025-02-20 | | | | | |
| Design Name: | Kigali Flexible Pavement Design | | | | | |

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| Layer Model Name: | Flexible Pavement Using Layered elastic Analysis |  |  |  |  |  |
| Drainage Station: | Not selected |  |  |  |  |  |
| Frost Station: | Not selected |  |  |  |  |  |
| Pavement Use: | Airfield |  |  |  |  |  |
| Design Type: | Flexible |  |  |  |  |  |
| Traffic Area: | Traffic Area A |  |  |  |  |  |
| Analysis Type: | LED |  |  |  |  |  |
| Wander Width (mm): | 1778 |  |  |  |  |  |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |
| **Layer Information** |  |  |  |  |  |  |
| **Layer Type** | **Material Type** | **Analysis** | **Thickness (mm)** | **Modulus (MPa)** | **Poisson's Ratio** | **Bond** |
| Asphalt Concrete | Asphalt Cement | Compute | 127 | 1378.95 | 0.35 | Fully Bonded |
| AC Stabilized Base | AC Stab-ALL Bituminous | Compute | 153 | 1378.95 | 0.25 | Fully Bonded |
| Subbase | Unbound Aggregate | Compute | 211 | 206.84 | 0.35 | Fully Bonded |
| Natural Subgrade | Cohesionless Cut | Manual | 102 | 160.3 | 0.4 | Fully Bonded |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |
| **Traffic Information** |  |  |  |  |  |  |
| Service | Army |  |  |  |  |  |
| Pattern Name: | KIA TRAFFIC |  |  |  |  |  |
|  |  |  |  |  |  |  |
|  | **Weight (kg)** | **Weight (kg)** | **Passes** | **Passes** |  |  |
| **Vehicles** | **Traffic Area A,B** | **Traffic Area C,D** | **Traffic Area A,B,C** | **Traffic Area D** |  |  |
| *-GROUP11 | 381018 | 285763 | 100 | 1 |  |  |
| *-GROUP14 | 221353 | 166015 | 100 | 1 |  |  |
| AIRBUS A319-100 | 75659 | 56744 | 10000 | 100 |  |  |

| | | | | | | |
|---|---|---|---|---|---|---|
| AIRBUS A320-200 | 67999 | 50999 | 2700 | 27 | | |
| AIRBUS A330-200 | 230896 | 173172 | 900 | 9 | | |
| AIRBUS A340-200 | 275898 | 206923 | 2000 | 20 | | |
| AIRBUS A380-800 | 562001 | 421501 | 5467 | 55 | | |
| ANDOVER C MK 1 & E MK 3 | 24926 | 18694 | 100 | 1 | | |
| ANDOVER CC MK 2 QUEENS FLIGHT | 21071 | 15803 | 100 | 1 | | |
| AT-38B TALON | 6124 | 4593 | 100 | 1 | | |
| B-1B LANCER | 216364 | 162273 | 900 | 9 | | |
| B-52H STRATOFORTRESS | 221353 | 166015 | 100 | 1 | | |
| BAE BUCCANEERS MK 2A & 3B | 26911 | 20183 | 100 | 1 | | |
| BOEING 707-120B | 116728 | 87546 | 9590 | 96 | | |
| BOEING 707-420 | 141521 | 106141 | 100 | 1 | | |
| BOEING 720 | 104009 | 78007 | 3000 | 30 | | |
| BOEING 737 MAX 9 | 88541 | 66406 | 4890 | 49 | | |
| BOEING 737-100 | 49895 | 37421 | 9000 | 90 | | |
| BOEING 737-200 | 52163 | 39122 | 70000 | 700 | | |
| BOEING 747-200B/-200B COMBI/-300 | 377842 | 283382 | 6000 | 60 | | |
| BOEING 747-400 | 394625 | 295969 | 15700 | 157 | | |
| BOEING 757-200PF | 116120 | 87090 | 10000 | 100 | | |
| BOEING 757-300 | 122470 | 91852 | 13000 | 130 | | |
| BOEING 767-200ER | 179169 | 134377 | 1000 | 10 | | |
| BOEING 767-300ER | 185519 | 139139 | 1000 | 10 | | |
| BOEING 777-300 | 300278 | 225209 | 9000 | 90 | | |
| BOEING 787-9 | 254692 | 191019 | 1000 | 10 | | |
| C-22B | 76657 | 57493 | 11000 | 110 | | |
| C-2A | 27216 | 20412 | 9756 | 98 | | |
| CN-235 (CIVIL) | 16500 | 12375 | 100 | 1 | | |
| DASH 7 | 19958 | 14969 | 16000 | 160 | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| DASH 7 | 19958 | 14969 | 100 | 1 | | |
| DC-9-51 | 54885 | 41164 | 5650 | 56 | | |
| E-2C HAWKEYE | 23541 | 17656 | 100 | 1 | | |
| E-2D ADVANCED HAWKEYE (SHORE) | 26082 | 19561 | 100 | 1 | | |
| EC-135A | 136804 | 102603 | 100 | 1 | | |
| EC-135E | 136804 | 102603 | 100 | 1 | | |
| EC-135G | 136804 | 102603 | 100 | 1 | | |
| FAA SWL-50 | 22680 | 17010 | 100 | 1 | | |
| FALCON DA-20 | 13200 | 9900 | 100 | 1 | | |
| MC-130H COMBAT TALON II | 79379 | 59534 | 100 | 1 | | |
| MD-11 | 287124 | 215343 | 100 | 1 | | |
| MHU-196 AIRFIELD | 36287 | 27216 | 100 | 1 | | |
| MIG-29 RUSSIAN | 19700 | 14775 | 100 | 1 | | |
| MQ-4C Triton | 14742 | 11056 | 100 | 1 | | |
| MQ-9A REAPER | 4763 | 3572 | 100 | 1 | | |
| MV-22 OSPREY | 27442 | 20582 | 100 | 1 | | |
| | | | | | | |

## APPENDIX 3: PCASE -CBR DESIGN REPORT FOR NEW BUGESERA INTERNATIONAL AIRPORT

| | | | | | |
|---|---|---|---|---|---|
| PCASE Version: | 7.0.7 2025-02-20 | | | | |
| Design Name: | NBIA Flexible pavement design | | | | |
| Layer Model Name: | Flexible Pavement design Using CBR Method | | | | |
| Drainage Station: | Not selected | | | | |

| | | | | | |
|---|---|---|---|---|---|
| Frost Station: | Not selected | | | | |
| Pavement Use: | Airfield | | | | |
| Design Type: | Flexible | | | | |
| Traffic Area: | Traffic Area A | | | | |
| Analysis Type: | CBR | | | | |
| Wander Width (mm): | 1778 | | | | |
| | | | | | |
| | | | | | |
| **Layer Information** | | | | | |
| **Layer Type** | **Material Type** | **Frost Code** | **Analysis** | **Design Thickness (mm)** | **CBR** |
| Asphalt Concrete | Asphalt Cement | NFS | Compute | 127 | |
| AC Stabilized Base | AC Stab-ALL Bituminous | NFS | Compute | 267 | 100 |
| Subbase | Unbound Aggregate | NFS | Compute | 102 | 20 |
| Natural Subgrade | Cohesionless Cut | NFS | Manual | | 18 |
| | | | | | |
| | | | | | |
| **Traffic Information** | | | | | |
| Service | Army | | | | |
| Pattern Name: | NBIA TRAFFIC | | | | |
| | | | | | |
| | **Weight (kg)** | **Weight (kg)** | **Passes** | **Passes** | **Equivalent Passes** |
| **Vehicles** | **Traffic Area A,B** | **Traffic Area C,D** | **Traffic Area A,B,C** | **Traffic Area D** | |
| *-GROUP11 | 381018 | 285763 | 10000 | 100 | 1 |
| *-GROUP14 | 221353 | 166015 | 5000 | 50 | 5000 |
| AIRBUS A319-100 | 75659 | 56744 | 16000 | 160 | 4 |
| AIRBUS A320-200 | 67999 | 50999 | 21000 | 210 | 1 |
| AIRBUS A330-200 | 230896 | 173172 | 9000 | 90 | 1815 |
| AIRBUS A340-200 | 275898 | 206923 | 6000 | 60 | 1274 |
| AIRBUS A380-800 | 562001 | 421501 | 9700 | 97 | 2578 |
| ANDOVER C MK 1 & E MK 3 | 24926 | 18694 | 2000 | 20 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| ANDOVER CC MK 2 QUEENS FLIGHT | 21071 | 15803 | 600 | 6 | 1 |
| AT-38B TALON | 6124 | 4593 | 690 | 7 | 1 |
| B-1B LANCER | 216364 | 162273 | 4500 | 45 | 914 |
| B-52H STRATOFORTRESS | 221353 | 166015 | 100 | 1 | 100 |
| BAE BUCCANEER S MK 2A & 3B | 26911 | 20183 | 100 | 1 | 1 |
| BOEING 707-120B | 116728 | 87546 | 9590 | 96 | 1 |
| BOEING 707-420 | 141521 | 106141 | 100 | 1 | 1 |
| BOEING 720 | 104009 | 78007 | 3000 | 30 | 1 |
| BOEING 737 MAX 9 | 88541 | 66406 | 4890 | 49 | 52 |
| BOEING 737-100 | 49895 | 37421 | 9000 | 90 | 1 |
| BOEING 737-200 | 52163 | 39122 | 70000 | 700 | 1 |
| BOEING 747-200B/-200B COMBI/-300 | 377842 | 283382 | 6000 | 60 | 80 |
| BOEING 747-400 | 394625 | 295969 | 15700 | 157 | 690 |
| BOEING 757-200PF | 116120 | 87090 | 10000 | 100 | 1 |
| BOEING 757-300 | 122470 | 91852 | 13000 | 130 | 1 |
| BOEING 767-200ER | 179169 | 134377 | 1000 | 10 | 5 |
| BOEING 767-300ER | 185519 | 139139 | 1000 | 10 | 13 |
| BOEING 777-300 | 300278 | 225209 | 9000 | 90 | 768 |
| BOEING 787-9 | 254692 | 191019 | 1000 | 10 | 529 |
| C-22B | 76657 | 57493 | 11000 | 110 | 6 |
| C-2A | 27216 | 20412 | 9756 | 98 | 1 |
| CN-235 (CIVIL) | 16500 | 12375 | 100 | 1 | 1 |
| DASH 7 | 19958 | 14969 | 100 | 1 | 1 |
| DASH 7 | 19958 | 14969 | 16000 | 160 | 1 |
| DC-9-51 | 54885 | 41164 | 5650 | 56 | 1 |
| E-2C HAWKEYE | 23541 | 17656 | 100 | 1 | 1 |
| E-2D ADVANCED HAWKEYE (SHORE) | 26082 | 19561 | 100 | 1 | 1 |
| EC-135A | 136804 | 102603 | 100 | 1 | 1 |
| EC-135E | 136804 | 102603 | 100 | 1 | 1 |
| EC-135G | 136804 | 102603 | 100 | 1 | 1 |
| FAA SWL-50 | 22680 | 17010 | 100 | 1 | 1 |
| FALCON DA-20 | 13200 | 9900 | 100 | 1 | 1 |
| MC-130H COMBAT TALON II | 79379 | 59534 | 100 | 1 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| MD-11 | 287124 | 215343 | 100 | 1 | 28 |
| MHU-196 AIRFIELD | 36287 | 27216 | 100 | 1 | 1 |
| MIG-29 RUSSIAN | 19700 | 14775 | 100 | 1 | 1 |
| MQ-4C Triton | 14742 | 11056 | 100 | 1 | 1 |
| MQ-9A REAPER | 4763 | 3572 | 100 | 1 | 1 |
| MV-22 OSPREY | 27442 | 20582 | 100 | 1 | 1 |
| *-GROUP14 | 221353 | | | | 13887 |
| | | | | | |

## APPENDIX 4: PCASE -LED DESIGN REPORT FOR NEW BUGESERA INTERNATIONAL AIRPORT

| | | | | | | |
|---|---|---|---|---|---|---|
| PCASE Version: | 7.0.7 2025-02-20 | | | | | |
| Design Name: | NBIA Flexible pavement design | | | | | |
| Layer Model Name: | Flexible Pavement using Layered Elastic analysis | | | | | |
| Drainage Station: | Not selected | | | | | |
| Frost Station: | Not selected | | | | | |
| Pavement Use: | Airfield | | | | | |
| Design Type: | Flexible | | | | | |
| Traffic Area: | Traffic Area A | | | | | |
| Analysis Type: | LED | | | | | |
| Wander Width (mm): | 1778 | | | | | |
| | | | | | | |
| | | | | | | |
| **Layer Information** | | | | | | |
| **Layer Type** | **Material Type** | **Analysis** | **Thickness (mm)** | **Modulus (MPa)** | **Poisson's Ratio** | **Bond** |
| Asphalt Concrete | Asphalt Cement | Compute | 127 | 1378.95 | 0.35 | Fully Bonded |
| AC Stabilized Base | AC Stab-ALL Bituminous | Compute | 153 | 1378.95 | 0.25 | Fully Bonded |
| Subbase | Unbound Aggregate | Compute | 194 | 206.84 | 0.35 | Fully Bonded |
| Natural Subgrade | Cohesionless Cut | Manual | 102 | 186.16 | 0.4 | Fully Bonded |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | |
| **Traffic Information** | | | | | | |
| Service | Army | | | | | |
| Pattern Name: | NBIA TRAFFIC | | | | | |
| | | | | | | |
| | **Weight (kg)** | **Weight (kg)** | **Passes** | **Passes** | | |
| **Vehicles** | **Traffic Area A,B** | **Traffic Area C,D** | **Traffic Area A,B,C** | **Traffic Area D** | | |
| *-GROUP11 | 381018 | 285763 | 10000 | 100 | | |
| *-GROUP14 | 221353 | 166015 | 5000 | 50 | | |
| AIRBUS A319-100 | 75659 | 56744 | 16000 | 160 | | |
| AIRBUS A320-200 | 67999 | 50999 | 21000 | 210 | | |
| AIRBUS A330-200 | 230896 | 173172 | 9000 | 90 | | |
| AIRBUS A340-200 | 275898 | 206923 | 6000 | 60 | | |
| AIRBUS A380-800 | 562001 | 421501 | 9700 | 97 | | |
| ANDOVER C MK 1 & E MK 3 | 24926 | 18694 | 2000 | 20 | | |
| ANDOVER CC MK 2 QUEENS FLIGHT | 21071 | 15803 | 600 | 6 | | |
| AT-38B TALON | 6124 | 4593 | 690 | 7 | | |
| B-1B LANCER | 216364 | 162273 | 4500 | 45 | | |
| B-52H STRATOFORTRESS | 221353 | 166015 | 100 | 1 | | |
| BAE BUCCANEER S MK 2A & 3B | 26911 | 20183 | 100 | 1 | | |
| BOEING 707-120B | 116728 | 87546 | 9590 | 96 | | |
| BOEING 707-420 | 141521 | 106141 | 100 | 1 | | |
| BOEING 720 | 104009 | 78007 | 3000 | 30 | | |
| BOEING 737 MAX 9 | 88541 | 66406 | 4890 | 49 | | |
| BOEING 737-100 | 49895 | 37421 | 9000 | 90 | | |
| BOEING 737-200 | 52163 | 39122 | 70000 | 700 | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| BOEING 747-200B/-200B COMBI/-300 | 377842 | 283382 | 6000 | 60 | | |
| BOEING 747-400 | 394625 | 295969 | 15700 | 157 | | |
| BOEING 757-200PF | 116120 | 87090 | 10000 | 100 | | |
| BOEING 757-300 | 122470 | 91852 | 13000 | 130 | | |
| BOEING 767-200ER | 179169 | 134377 | 1000 | 10 | | |
| BOEING 767-300ER | 185519 | 139139 | 1000 | 10 | | |
| BOEING 777-300 | 300278 | 225209 | 9000 | 90 | | |
| BOEING 787-9 | 254692 | 191019 | 1000 | 10 | | |
| C-22B | 76657 | 57493 | 11000 | 110 | | |
| C-2A | 27216 | 20412 | 9756 | 98 | | |
| CN-235 (CIVIL) | 16500 | 12375 | 100 | 1 | | |
| DASH 7 | 19958 | 14969 | 100 | 1 | | |
| DASH 7 | 19958 | 14969 | 16000 | 160 | | |
| DC-9-51 | 54885 | 41164 | 5650 | 56 | | |
| E-2C HAWKEYE | 23541 | 17656 | 100 | 1 | | |
| E-2D ADVANCED HAWKEYE (SHORE) | 26082 | 19561 | 100 | 1 | | |
| EC-135A | 136804 | 102603 | 100 | 1 | | |
| EC-135E | 136804 | 102603 | 100 | 1 | | |
| EC-135G | 136804 | 102603 | 100 | 1 | | |
| FAA SWL-50 | 22680 | 17010 | 100 | 1 | | |
| FALCON DA-20 | 13200 | 9900 | 100 | 1 | | |
| MC-130H COMBAT TALON II | 79379 | 59534 | 100 | 1 | | |
| MD-11 | 287124 | 215343 | 100 | 1 | | |
| MHU-196 AIRFIELD | 36287 | 27216 | 100 | 1 | | |
| MIG-29 RUSSIAN | 19700 | 14775 | 100 | 1 | | |
| MQ-4C Triton | 14742 | 11056 | 100 | 1 | | |
| MQ-9A REAPER | 4763 | 3572 | 100 | 1 | | |
| MV-22 OSPREY | 27442 | 20582 | 100 | 1 | | |

## APPENDIX 5: PCASE-CBR DESIGN REPORT FOR KAMEMBE AIRPORT

| | | | | | |
|---|---|---|---|---|---|
| PCASE Version: | 7.0.7 2025-02-20 | | | | |
| Design Name: | Kamembe Airfield pavement design Method | | | | |
| Layer Model Name: | Flexible pavement design using CBR | | | | |
| Drainage Station: | Not selected | | | | |
| Frost Station: | Not selected | | | | |
| Pavement Use: | Airfield | | | | |
| Design Type: | Flexible | | | | |
| Traffic Area: | Traffic Area A | | | | |
| Analysis Type: | CBR | | | | |
| Wander Width (mm): | 1778 | | | | |
| | | | | | |
| | | | | | |
| **Layer Information** | | | | | |
| **Layer Type** | **Material Type** | **Frost Code** | **Analysis** | **Design Thickness (mm)** | **CBR** |
| Asphalt Concrete | Asphalt Cement | NFS | Compute | 102 | |
| AC Stabilized Base | AC Stab-ALL Bituminous | NFS | Compute | 159 | 100 |
| Subbase | Unbound Aggregate | NFS | Compute | 353 | 20 |
| Natural Subgrade | Cohesionless Cut | NFS | Manual | | 5.5 |
| | | | | | |
| | | | | | |
| **Traffic Information** | | | | | |
| Service | Army | | | | |
| Pattern Name: | Kamembe Traffic Pattern | | | | |
| | | | | | |

| | **Weight (kg)** | **Weight (kg)** | **Passes** | **Passes** | **Equivalent Passes** |
|---|---|---|---|---|---|
| **Vehicles** | **Traffic Area A,B** | **Traffic Area C,D** | **Traffic Area A,B,C** | **Traffic Area D** | |
| AIRBUS A319-100 | 75659 | 56744 | 100 | 1 | 3 |
| AIRBUS A320-200 | 67999 | 50999 | 100 | 1 | 1 |
| AIRBUS A330-200 | 230896 | 173172 | 100 | 1 | 100 |
| AN-12 RUSSIAN | 60999 | 45749 | 100 | 1 | 1 |
| AN-124 RUSSIAN | 391999 | 293999 | 100 | 1 | 36 |
| BOEING 737-400 | 68039 | 51029 | 100 | 1 | 2 |
| C-135A | 136804 | 102603 | 100 | 1 | 3 |
| DC-9-51 | 54885 | 41164 | 100 | 1 | 1 |
| IL-76MD CANDID B | 190010 | 142507 | 100 | 1 | 1 |
| S3-B | 23814 | 17860 | 100 | 1 | 1 |
| AIRBUS A330-200 | 230896 | | | | 149 |

## APPENDIX 6: PCASE-LED DESIGN REPORT FOR KAMEMBE AIRPORT

| | | | | | | |
|---|---|---|---|---|---|---|
| PCASE Version: | 7.0.7 2025-02-20 | | | | | |
| Design Name: | Kamembe Airfield pavement design Method | | | | | |
| Layer Model Name: | Flexible Pavement Using Layered Elastic Analysis | | | | | |
| Drainage Station: | Not selected | | | | | |
| Frost Station: | Not selected | | | | | |

|  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|
| Pavement Use: | Airfield |  |  |  |  |  |
| Design Type: | Flexible |  |  |  |  |  |
| Traffic Area: | Traffic Area A |  |  |  |  |  |
| Analysis Type: | LED |  |  |  |  |  |
| Wander Width (mm): | 1778 |  |  |  |  |  |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |
| **Layer Information** |  |  |  |  |  |  |
| **Layer Type** | **Material Type** | **Analysis** | **Thickness (mm)** | **Modulus (MPa)** | **Poisson's Ratio** | **Bond** |
| Asphalt Concrete | Asphalt Cement | Compute | 127 | 1378.95 | 0.35 | Fully Bonded |
| AC Stabilized Base | AC Stab-ALL Bituminous | Compute | 166 | 1378.95 | 0.25 | Fully Bonded |
| Subbase | Unbound Aggregate | Compute | 266 | 206.84 | 0.35 | Fully Bonded |
| Natural Subgrade | Cohesionless Cut | Manual | 102 | 56.88 | 0.4 | Fully Bonded |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |
| **Traffic Information** |  |  |  |  |  |  |
| Service | Army |  |  |  |  |  |
| Pattern Name: | Kamembe Traffic Pattern |  |  |  |  |  |
|  |  |  |  |  |  |  |
|  | **Weight (kg)** | **Weight (kg)** | **Passes** | **Passes** |  |  |
| **Vehicles** | **Traffic Area A,B** | **Traffic Area C,D** | **Traffic Area A,B,C** | **Traffic Area D** |  |  |
| AIRBUS A319-100 | 75659 | 56744 | 100 | 1 |  |  |
| AIRBUS A320-200 | 67999 | 50999 | 100 | 1 |  |  |
| AIRBUS A330-200 | 230896 | 173172 | 100 | 1 |  |  |
| AN-12 RUSSIAN | 60999 | 45749 | 100 | 1 |  |  |

| | | | | | | |
|---|---|---|---|---|---|---|
| AN-124 RUSSIAN | 391999 | 293999 | 100 | 1 | | |
| BOEING 737-400 | 68039 | 51029 | 100 | 1 | | |
| C-135A | 136804 | 102603 | 100 | 1 | | |
| DC-9-51 | 54885 | 41164 | 100 | 1 | | |
| IL-76MD CANDID B | 190010 | 142507 | 100 | 1 | | |
| S3-B | 23814 | 17860 | 100 | 1 | | |
| | | | | | | |