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COIMBRA

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Airport Pavement Design

Master Dissertation in Urban Mobility Management, supervised by Professor Doutor Adelino Jorge Lopes Ferreira, and presented to the Department of the Faculty of Science and Technology of the University of Coimbra.

February 2020

Faculty of Science and Technology

University of Coimbra

Department of Civil Engineering

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AIRPORT PAVEMENT DESIGN

DIMENSIONAMENTO DE PAVIMENTOS AEROPORTUÁRIOS

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ABSTRACT

Background: In recent years, civil aviation has experienced intense growth, regional or peripheral airports have been built or expanded to operate new routes. In the Portuguese case is no different, the two main airports (Porto and Lisbon) are close to the limit. Furthermore, there is a certain degree of isolation in the Central and Interior regions, being an added value the construction of an Airport to serve these areas. Consequently, this study aims to address the best practices for the design of airport pavements and then apply this knowledge in a case study constituted by the Viseu Aerodrome.

Methods: This dissertation is based on a case study. Therefore, it uses qualitative data in order to explain and explore the design of airport pavements. The text is divided into two parts, the first moment is performed a literature review to obtain a state-of-the-art for the design of airport pavements. Afterward, apply this knowledge to the case study, this approach aims to apply best practices to Portugal.

Results: Three scenarios are presented, maintaining current operation with aircrafts up to 6.4 tons and autonomy of 1000 km, operating aircrafts up to 23 tons and 2500 km range, and aircraft up to 82.2 tons and 6000 km range. In the first scenario, the existing pavement must be reinforced with an overlay that can vary between 5.5 and 7.0 cm. In the second, a new 1800 m runway was designed, with 15.0 cm of the granular layer, 13.0 cm of bituminous layer, and 10.5 cm wear layer. In the final scenario, the new runway should be 2500 m. This pavement should have a structure with 29.5 cm of the granular layer, 13.0 cm of bituminous layer and 10.5 cm of the wear layer. It was also foreseen the possibility of construction of this runway in two stages, the first being precisely the same as the previous project (1800 m in length and a total thickness of 38.5 cm), then the runway should reach the final characteristic, with 2500 m and structural capacity for aircraft up to 82.2 tons. This was possible with a 9.5 cm overlay on the 38.5 cm structure (previous structure).

Conclusions: The pursuit of the sustainability of the airport infrastructure operation is an engineering challenge. In this sense, the runway pavements play an essential role. This dissertation offers a simple and straightforward approach to best practices for airport pavement design. Subsequently, this knowledge of the best airport paving engineering was applied in a case study constituted by the Viseu Aerodrome.

Keywords: Airport, Aerodrome, Pavement Design.

RESUMO

Contexto: Nos últimos anos a aviação civil experimentou um intenso crescimento. Aeroportos regionais e periféricos foram construídos ou ampliados para operar novas rotas. No caso português não é diferente, os dois principais aeroportos (Porto e Lisboa) estão operando próximos do limite. Além disso, existe um certo grau de isolamento nas regiões Centro e Interior de Portugal, sendo uma mais valia a construção de um aeroporto nesta zona. Portanto, este estudo tem como objetivo abordar as melhores práticas para o projeto de pavimentos aeroportuários e, em seguida, aplicar esse conhecimento em um estudo de caso constituído pelo Aeródromo de Viseu.

Método: Esta dissertação baseia-se num estudo de caso. Portanto, utilizam-se dados qualitativos com o objetivo de explicar e explorar o dimensionamento de pavimentos aeroportuários. Deste modo, este documento divide-se em duas partes: em um primeiro momento é realizada uma revisão da literatura para se alcançar o estado da arte para o projeto de pavimentos aeroportuários. Posteriormente, aplica-se esse conhecimento em um estudo de caso, que tem como objetivo exemplificar as melhores práticas à realidade portuguesa.

Resultados: São apresentados três cenários: manter a operação atual com aeronaves de até 6,4 toneladas com autonomia de 1000 km; operar aeronaves de até 23 toneladas com alcance de 2500 km; e aeronaves de 82,2 toneladas e 6000 km de autonomia. No primeiro cenário, o pavimento existente deve ser reforçado com um recapeamento que pode variar entre 5,5 e 7,0 cm. No segundo, uma nova pista de 1800 m foi projetada, com 15,0 cm de camada granular, 13,0 cm de camada betuminosa e 10,5 cm de camada de desgaste. Do mesmo modo, no cenário final a nova pista deve ter 2500 m. Este pavimento deve ter uma estrutura com 29,5 cm de camada granular, 13,0 cm de camada betuminosa e 10,5 cm de camada de desgaste. Também, foi prevista a possibilidade de construção da pista em duas etapas, sendo a primeira exatamente a mesma do projeto anterior (1800 m de comprimento e espessura total de 38,5 cm), devendo a pista atingir a característica final, com 2500 m e capacidade para aeronaves de até 82,2 toneladas. Isso foi possível com uma camada de reforço de 9,5 cm sobre a estrutura de 38,5 cm (estrutura anterior).

Conclusão: A busca pela sustentabilidade operacional em aeroportos é um desafio de engenharia. Neste sentido, os pavimentos das pistas de aterragem e de descolagem desempenham um papel importante. Portanto, este estudo oferece uma abordagem simples e direta às melhores práticas para o dimensionamento de pavimentos aeroportuários. Posteriormente, este conhecimento foi aplicado em um estudo de caso constituído pelo Aeródromo de Viseu.

Palavras-chave: Aeroportos, Aeródromos, Projeto de Pavimentos.

I hereby declare that I am the sole author of this dissertation and that I have not used any sources other than those listed in the bibliography and identified as references. I further declare that I have not submitted this thesis at any other institution in order to obtain a degree.

ACKNOWLEDGMENTS

First and foremost, I would like to thank my supervisor Professor Adelino Ferreira for introducing me to the topic and for his constant support.

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Additionally, I thank the friends who supported me in deciding to leave my comfort zone and pursue bigger goals.

Finally, I would like to thank my wife Millena for the unconditional support.

"We can only see a short distance ahead, but we can see plenty there that needs to be done."

- Alan Turing (1950), Computing machinery and intelligence, p. 460.

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NOMENCLATURE

AAA: Australian Airports Association;

AASTHO: American Association of State Highway and Transportation Officials;

AC: Advisory Circular;

ACI: American Concrete Institute;

ACN: Aircraft Classification Number;

AIP: Aeronautical Information Publication;

APSDS: Airport Pavement Structural Design System;

ASTM: American Society for Testing and Materials;

BAKFAA: FAA Backcalculation Software;

CBR: California Bearing Ratio;

CDF: Cumulative Damage Factor;

CM: Municipal City Hall;

DGAC: French Civil Aviation Authority;

ERDC: Engineer Research and Development Center;

ESWL: Equivalent Single Wheel Load;

FAA: Federal Aviation Administration;

FAARFIELD: FAA Rigid and Flexible Iterative Elastic Layered Design;

FEM: Finite Element Method;

FHWA: Federal Highway Administration;

GEAFA: Air Force Aerodrome Engineering Group;

GPIAA: Portuguese State Aircraft Accident Prevention and Investigation Office;

HMAC: Hot-mix Asphalt Concrete;

HWD: Heavy Weight Deflectometer;

ICAO: International Civil Aviation Organization;

INAC: National Institute of Civil Aviation;

INE: National Institute of Statistics;

LCPC: French Central Laboratory of Roads and Bridges;

LED: Layered Elastic Design;

LEDFAA: FAA Layered Elastic Design;

LPVZ: ICAO Code for Viseu Aerodrome;

MGMU: Master in Urban Mobility Management;

PCA: Portland Cement Association;

PCASE: Pavement-Transportation Computer Assisted Structural Engineering;

PCC: Portland Cement Concrete;

PCI: Pavement Condition Index;

PCN: Pavement Classification Number;

PEP: Pavement Experimental Programme;

PORDATA: Database of Contemporary Portugal;

RWY: Runway;

SI: International System of Units;

STAC: French Civil Aviation Center;

STBA: Air Base Technical Department;

USA: United States of America;

USACE: US Army Corps of Engineers;

VFR: Visual Flight Rules.

TERMINOLOGY

Aerodrome: Infrastructure to be used for aircraft landing, takeoff and movement, which may include facilities and support equipment;

Airport: Infrastructure to be used for landing, taking off and moving aircraft includes publicly accessible facilities and services with passenger and cargo boarding, collection, refueling, maintenance, and repair of aircrafts;

Airside: Area for moving aircraft, authorized personnel, and passengers. With restricted access control;

Landside: Part of the airport whose access is not controlled (car parking lots, access roads, cargo areas, part of passenger buildings);

Runway: Paved area for landing and taking off aircrafts;

Taxiway: Paved airport paths for the movement of aircraft on the ground;

Apron: Paved areas of the airport intended to accommodate aircraft for the purpose of boarding and disembarking passengers and cargo, fueling and parking aircrafts;

Aircraft Classification Number (ACN): This is a number representing aircraft loading on the pavements, this value is defined based on the ICAO method (usually reported by the aircraft manufacturer);

Pavement Classification Number (PCN): This is a number that represents the ability of the pavement to withstand loading, this value is defined based on the ICAO method.

1. INTRODUCTION

1.1 Motivation

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 (Neufville and Odoni, 2013; Gillen, 2011; Laurino and Beria, 2014). Likewise, in this period, Portugal has had remarkable growth in tourism. Nevertheless, airport infrastructure is not keeping up with demand as the two main Portuguese airports, Lisbon (Humberto Delgado Airport) and Porto (Francisco Sá Carneiro Airport), operate almost to the limit.

Looking at the Portuguese case, we see that this lack exists, especially in the Central and Interior zones (Martins, 2018). In this scenario, small airports and aerodromes appear as alternatives for operating low-cost regional flights in locations where critical mass does not yet support large infrastructure (Kazda *et al.*, 2017). In this sense, recent studies indicate the viability of a regional or small airport in Viseu (Martins, 2018).

On the other hand, at regional airports, operating costs put pressure on the viability of the operation, and subsidies are required (Ferreira *et al.*, 2009; Grimme *et al.*, 2018; Kazda *et al.*, 2017). Another relevant point in the operation of regional airports is the use of smaller aircraft, which end up having higher fuel consumption per seat, losing competitiveness (Neufville and Odoni, 2013). Also, it must be assessed that air transport competes with other modes of transport such as rail and road (Gillen, 2011).

However, a good-sized regional airport benefits the economy in which it operates by generating direct and indirect jobs, increasing tourism, improving the business environment (Kazda *et al.*, 2017; Nõmmik, 2019).

In response to this demand, this study was developed to present best practices for airport pavement design. Also, a case study will be conducted for the Viseu Municipal Aerodrome (Gonçalves Lobato Aerodrome).

In conclusion, the choice of this aerodrome was based on the location, the dynamics of the region, the possibility of expansion and improvements of the existing runways.

1.2 Problem

The problem identified in this study is the lack of airport infrastructure in the Central and Interior zones of Portugal. As well as the deficiency of studies on best practices for airport pavements design in Portugal.

1.3 Objectives

This writing is conceived in two parts, consisting of a literature review and a case study. In this sense, this dissertation intends to fulfill the following objectives:

- Study of best practices for design airport pavements;
- Apply FAARFIELD software in version 1.42 to a real case in Portugal.

Therefore, in the literature review, it will be developed with attention to airport pavement design.

In a second moment, to materialize the knowledge, it is proposed a case study constituted by the Viseu Municipal Aerodrome. Focused on developing an airport pavement solution that can meet current and future demand.

1.4 Methodology

In this study, a qualitative case study methodology was applied. The first step was to understand the problem, and then a study proposal was developed. From this, a literature review was performed. Using the knowledge created in the previous chapter, a case study was developed. The flowchart of Figure 1 represents this procedure.

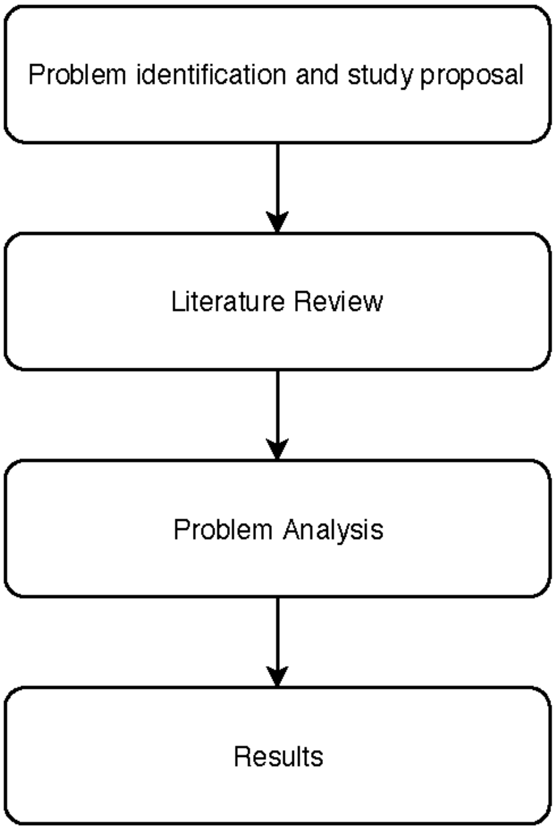


Figure 1 – Procedure developed

In each item represented, some topics must be explored to fulfill the objective of this dissertation (Figure 2). At this point, it is essential to emphasize that the developed topics have the function of answering the proposed problem.

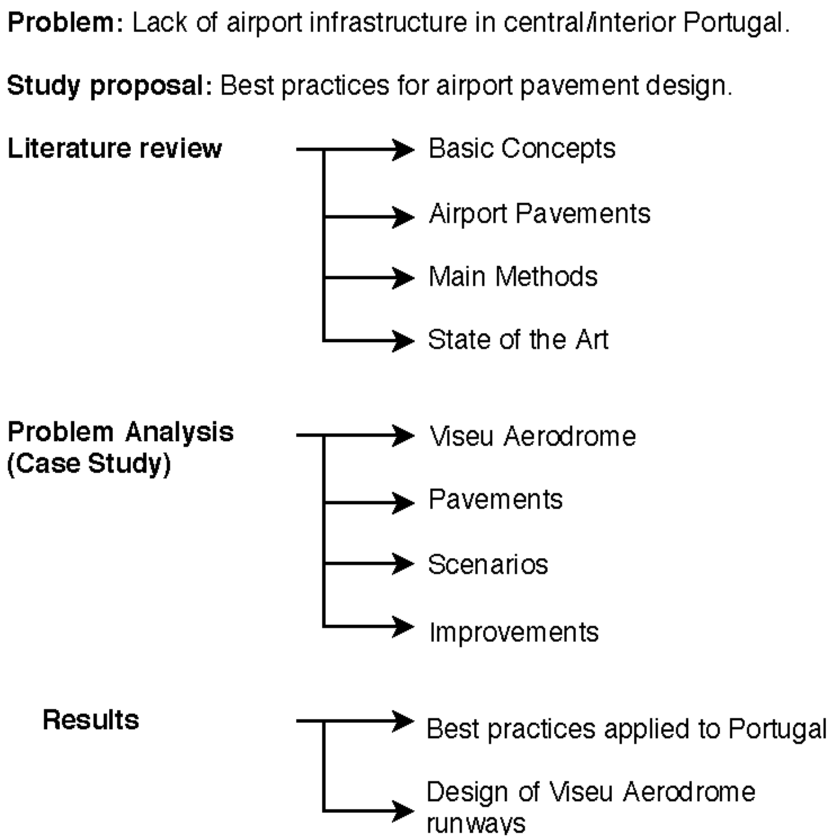


Figure 2 – Topics explored

As a final point, it is significant that it is not objective to create a guide about the design of airport pavements and should not use the information contained in this text as a standard or manual. Consequently, this work is a contribution to the application of best practices in Portugal, and the current regulations and informed sources should be consulted simultaneously with the reading of this work.

1.5 Text Structure

The first chapter, called Introduction, deals with the research context, as well as the problem, the objectives, and the applied methodology.

In the second chapter, the information necessary for the development of this dissertation was compiled, with attention to the state-of-the-art of airport pavement design methods. This chapter was used to prepare a paper already submitted to the 8th World Conference on

Information Systems and Technologies that will be held in Budva, Montenegro, from 7 to 10 April 2020 (Tamagusko and Ferreira, 2020a).

The third chapter focuses on the Viseu Aerodrome case study, which consists of a concise presentation of the existing infrastructure, its demand, and projections. Also, improvements are proposed. This chapter was used to prepare a paper already submitted to the 6th International Conference on Road and Rail Infrastructure that will be held in Pula, Croatia, from 20 to 22 May 2020 (Tamagusko and Ferreira, 2020b).

Lastly, the fourth chapter corresponds to the conclusion of the work and the suggestion of future studies.

2. LITERATURE REVIEW

2.1 Basic Concepts

This sub-chapter focuses on the basic concepts necessary for understanding this dissertation, from the airport areas, their nomenclature, to a brief summary of pavements. It is recommended to read this text together with the terminology (page xxi).

2.1.1 Airport areas

Usually, the airports are divided into two areas: airside and landside. Airside includes runways, taxiways, aprons, aircraft service areas, air control facilities, and all controlled access zones. On the airport landside are public access areas such as the passenger terminal (before security check), parking lots and other public service facilities (Belobaba *et al.*, 2009). Figure 3 shows a generic draft of an airport.

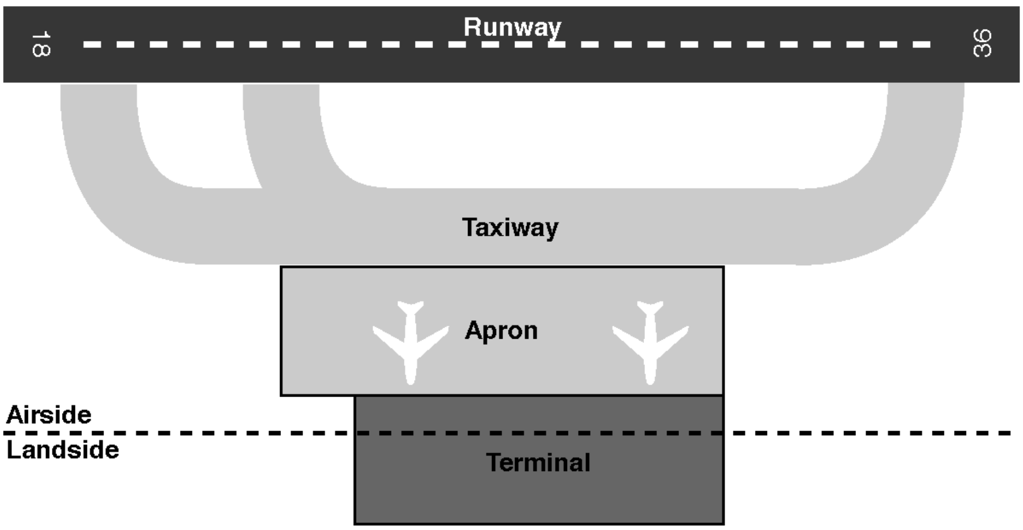


Figure 3 – Generic airport draft

Regarding pavements at an airport, there are three critical areas: the runway; the taxiway; and the apron. The runway takes place the landings and takeoffs. The taxiway has the function of connecting the runway to the apron. An apron is a place where the aircraft "parks", in this place, the aircraft are loaded and unloaded (with passengers, luggage, and cargo), and it is also the place where the aircraft is refueled (Mallick and El-Korchi, 2013).

2.1.2 Runway nomenclature

Runway (RWY) is identified by a 2-digit number indicating the angle to magnetic north (in the direction of landing or take-off) more straightforward value is rounded to the nearest multiple of 10°. Also, the value of one end of the runway differs by 18 values (180º) from the other end. Therefore, a runway named "09" receives the value "27" on the other side. Hence, the runway is called RWY 09/27 (Figure 4). In the case of two parallel runways, the letters R (right) and L (left) is used to distinguish the runways. Finally, if there are three parallel runways, their names are given the letters R, C (center), and L.

Figure 4 – Example for RWY 09/27

Typically, the runways are oriented to ensure no obstacles during takeoff and landing and based on the wind conditions of the area. In this regard, both the International Civil Aviation Organization (ICAO) and the Federal Aviation Administration (FAA) recommends that the runways be oriented so that the aircraft can land at least 95% of the time with allowable crosswind components (Horonjeff, 2010).

2.1.3 Pavements

Traditionally pavements are classified into two types: rigid; and flexible (Branco *et al.*, 2005; Fwa, 2006; Mallick and El-Korchi, 2013). There may eventually be composite pavements, with a flexible layer over a rigid layer. Usually, these "hybrid" pavements are applied solutions as an alternative to extending the service life of rigid pavements.

In the same way, according to Fwa (2006): "There are two primary types of pavement surfaces — Portland cement concrete (PCC) and hot-mix asphalt concrete (HMAC). Below this wearing course are material layers that provide structural support for the pavement system. These may include either the aggregate base and subbase layers, or treated base and subbase layers, and the underlying natural or treated subgrade. The treated layers may be cement-treated, asphalt-treated or lime-treated for additional structural support."

Figure 5 shows the traditional structures and this "hybrid" composition.

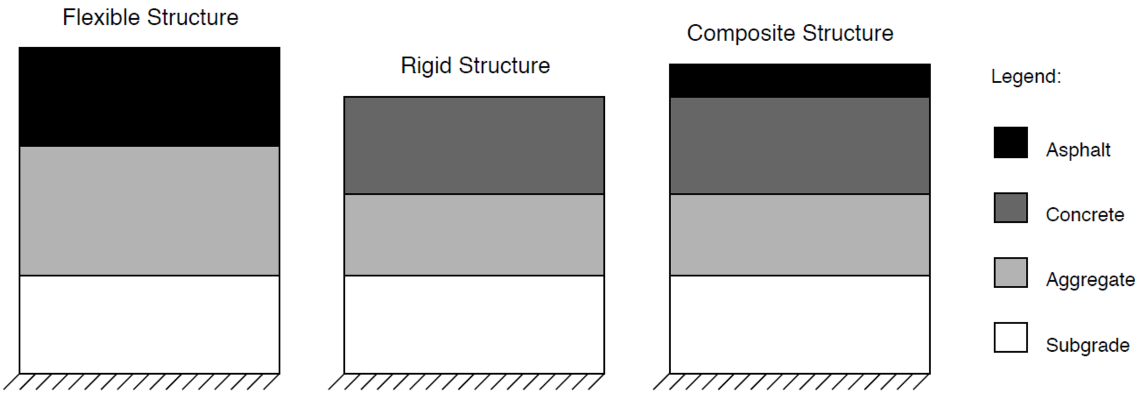


Figure 5 – Typical pavement structures

There are several methods for dimensioning the mixtures used on road pavements. For example, flexible pavements can be designed based on Marshall (AASTHO T 245; ASTM D 1559), Hveem (AASTHO T 246; ASTM D 1560), Superpave (FHWA, 2001), or LCPC (LCPC, 2007). Rigid pavements can be designed using the ACI (ACI, 2000) or the PCA (PCA, 1984) method (Fwa, 2006; Pereira and Pais, 2017). Likewise, it is interesting to note that due to the application of different materials in their layers, the structural response to load application is different (Figure 6). Also, it should be noted that usually flexible pavements are designed for 20 years, and rigid pavements for 40 years (Fwa, 2006).

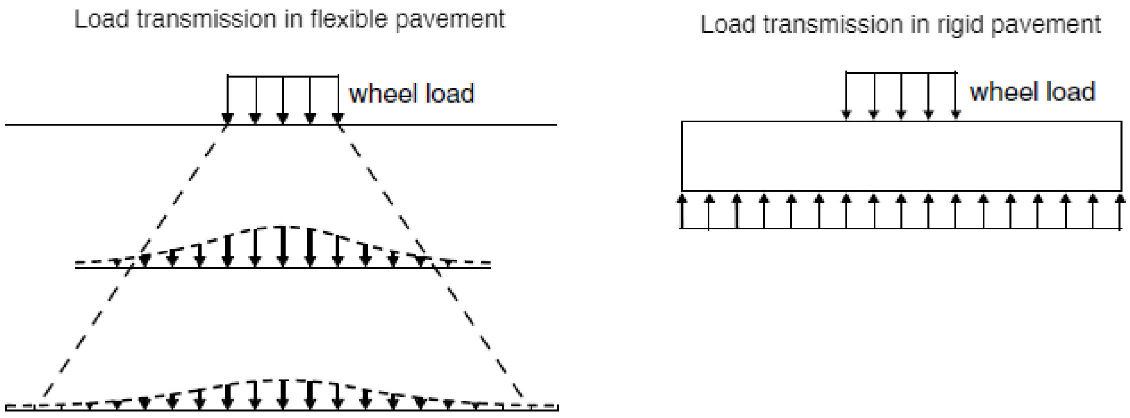


Figure 6 – Load transmission on flexible and rigid pavements (Fwa, 2006)

For flexible pavements when the load is applied to the top of the surface layer, a deformation occurs under the tire contact area (Figure 6), with most of that deformation recovered, and a minimal quantity is permanent. That said, the stress is higher on the surface and decreases with depth, so the highest quality materials need to be close to the surface, the most requested area. Therefore, the name flexible pavement is due to this deformation and recovery effect that occurs at the time of load application (Fwa, 2006).

Also, it is essential to note that the "required thickness of each layer of the flexible pavement varies widely depending on the materials used, magnitude and number of repetitions traffic load, environmental conditions, and the desired service life of the pavement" (Fwa, 2006).

For rigid pavements, unlike flexible pavements, the applied load is spread over a large area (Figure 6). Consequently, failure of pavement fatigue due to repeated loads caused by daily traffic is one of the primary considerations of rigid pavement design (Fwa, 2006).

Regarding the thickness of the rigid layer, it is designed to withstand design traffic and temperature changes. In this sense, steel reinforcements can be used to resist tensile stresses caused by temperature variation. Another relevant point for rigid pavements is the failure of joints, an item that should be considered in the design step (Fwa, 2006).

Concerning pavement design, it is possible to create a generic design methodology, which is replicable in several cases, FAA (1993) presents the following elements:

- Loading characterization;
- Material characterization;
- Start with a trial design;
- Calculation of structural response (deflection, stress, or strain) caused by loading using a mathematical model;
- Comparison of structural response with material failure criteria;
- Design improvement to meet failure criteria.

An adaptation of the methodology created by the FAA for airport pavement design is presented in Figure 7.

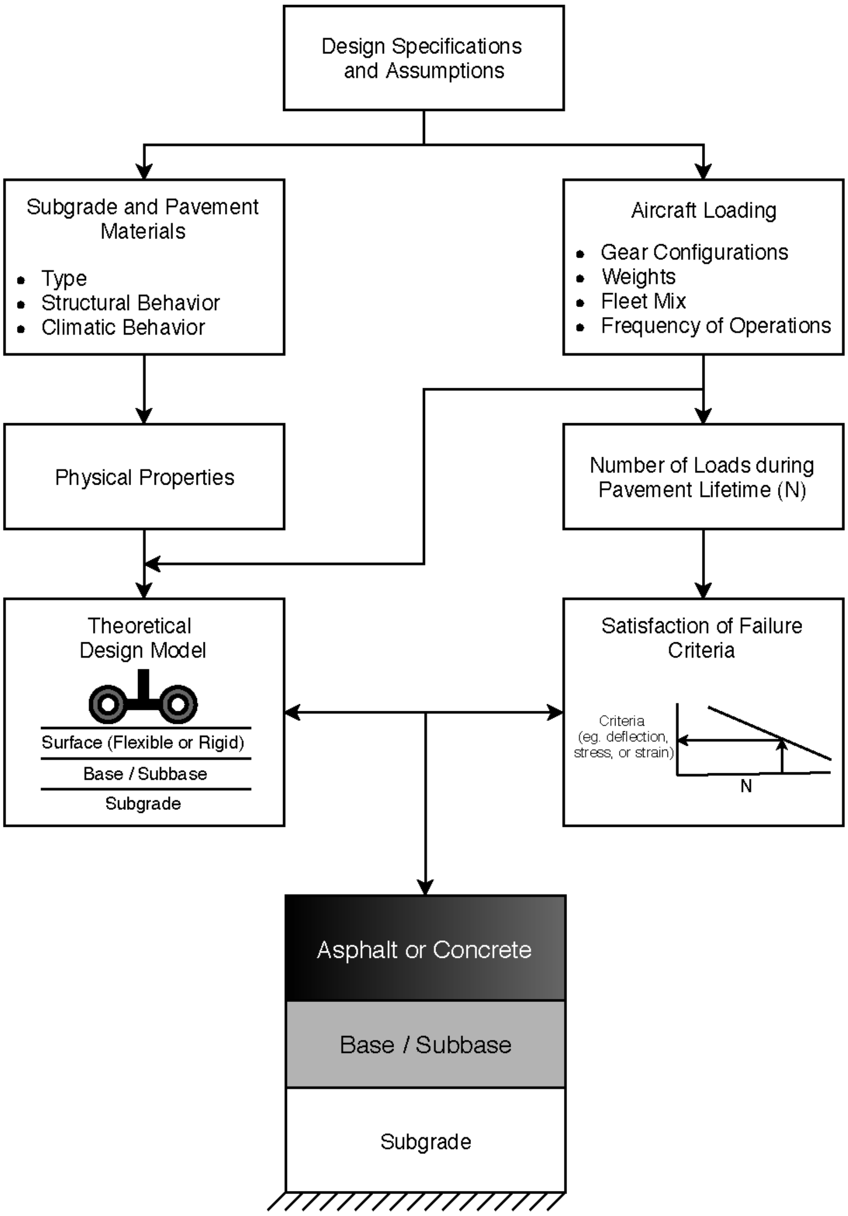


Figure 7 – Generic airport design methodology (adapted from FAA, 1993)

Finally, after this brief introduction to basic concepts, the next sub-chapter will cover more specifically airport pavements.

2.2 Airport Pavements

In Horonjeff (2010), two sources are considered the most important for the design of airport pavements: Federal Aviation Administration (FAA, 2014a, 2016) and International Civil Aviation Organization (ICAO, 1983, 2018). 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.

In Mallick and El-Korchi (2013), the authors point out that airport pavements must be built following strict guidelines and specifications (basically from FAA and ICAO), the aim is to ensure maximum safety. 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. Accordingly, AAA (2017), states that 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 (Branco et al., 2005).

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 (AAA, 2017). 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 (AAA, 2017; Heymsfield and Tingle, 2019).

As mentioned, airport pavements follow these same principles (AAA, 2017). In this sense, Table 1 presents a comparison of aircraft pavements and road pavements.

Table 1 – Comparison of aircraft pavements and road pavements (adapted from AAA, 2017)

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 Horonjeff (2010): "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 8, these distances are presented.

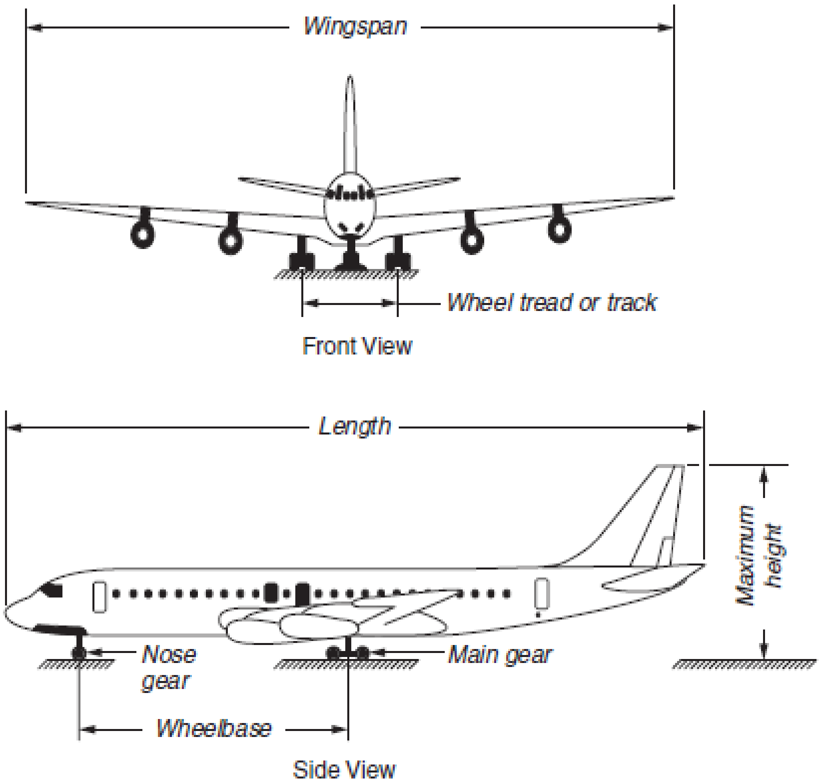


Figure 8 – Aircraft dimensions (Horonjeff, 2010)

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 (Horonjeff, 2010), as observed in Figure 9.

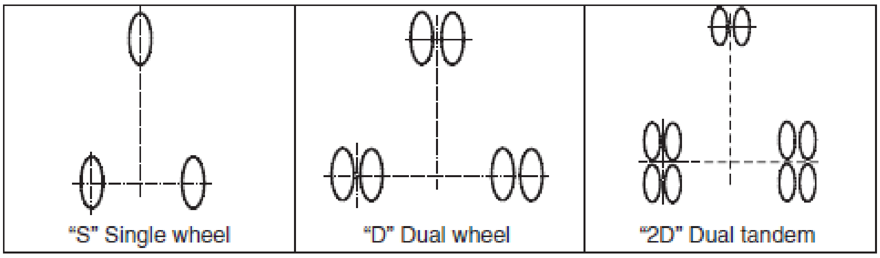


Figure 9 – Traditional landing gear configurations (Horonjeff, 2010)

There are even more complex configurations (Figure 10) like those used on Boeing 747, Boeing 777, and Airbus A-380 aircraft (Horonjeff, 2010).

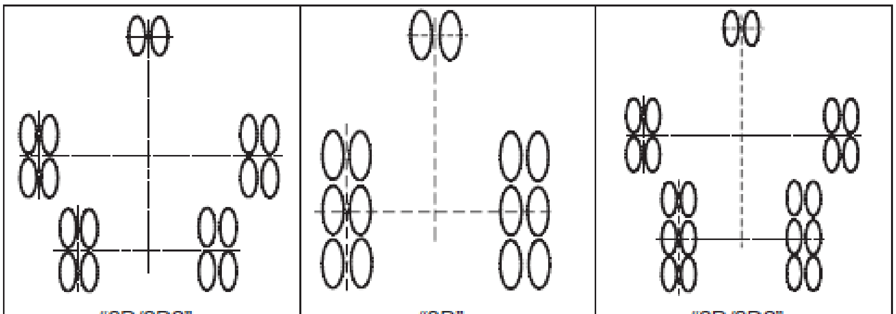


Figure 10 – Complex landing gear configurations (Horonjeff, 2010)

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 (Horonjeff, 2010). 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 – ICAO aerodrome reference codes (adapted from Horonjeff, 2010)

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."

After presenting these concepts related to airport pavements, the next sub-chapter to be presented will be related to the ACN-PCN Method.

2.2.1 ACN-PCN Method

ACN-PCN is an airport pavement resistance rating system developed by ICAO. The purpose of this method is to classify the pavement resistance according to the aircraft and pavement characteristics. It is formulated so that the structure of pavement can support, without restriction, an aircraft having a maximum allowable load and maximum tire pressure. However, some operators use this rating for taxiways and aprons (AAA, 2017). Also, it should be noted that this method was developed to specify the resistance of the pavements for aircraft with a mass exceeding 5,700 kg.

Therefore, according to the ICAO method, the Pavement Classification Number (PCN) must be equal to or greater than the Aircraft Classification Number (ACN), so it is ensured that the load caused by the aircraft theoretically is equal to or less than the designed pavement resistance (ICAO, 2018). According to ICAO (2018) in the ACN-PCN method, the following information is presented:

- The pavement classification number (PCN);
- Pavement type for ACN-PCN determination (rigid or flexible);
- Subgrade strength category (4 categories);
- The maximum allowable tire pressure category or the maximum allowable tire pressure value (4 categories);
- The evaluation method used (technical or empirical).

Thus, the codes used can be seen in Table 3.

Table 3 –PCN determination codes (adapted from ICAO, 2018)

Code	Pavement type		
R	Rigid pavement		
F	Flexible pavement		
Code	Subgrade strength category	Representative CBR	CBR Range
A	High strength	15	13 >
B	Medium strength	10	8 – 13
C	Low strength	6	4 – 8
D	Ultra low strength	3	< 4
Code	Tire pressure category		Pressure limits
W	Unlimited		No limit
X	High		1.75 MPa
Y	Medium		1.25 MPa
Z	Low		0.50 MPa
Code	Evaluation method		Definition
T	Technical evaluation		see in terminology
U	Empirical Evaluation		see in terminology

An excellent example of using this code was presented by ICAO (2018): “Example 1 - If the bearing strength of rigid pavement, resting on a medium strength subgrade, has been assessed by technical evaluation to be PCN 80 and there is no tire pressure limitation, then the reported information would be: PCN 80 / R / B / W / T”

Also, this example is again explained in Figure 11.

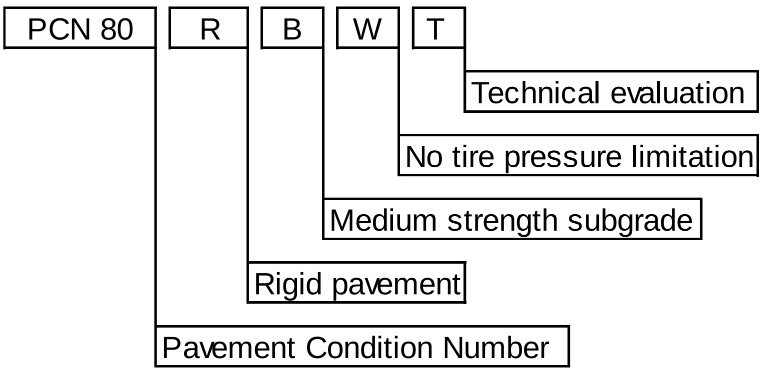


Figure 11 –PCN example code (adapted from ICAO, 2018)

As seen, the ACN-PCN rating system is simple and presents much information. Consequently, the ACN-PCN rating system created by ICAO is the standard adopted in the civil aviation area.

In the next sub-chapter, the main methods of airport pavement design will be presented.

2.3 Evolution of Design Methods

As mentioned in the previous sub-chapter, one of the main sources 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. Mallick (2015) 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 Vieira (2015), 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 4.

Table 4 – Evolution of main methods for design airport pavements (adapted from Brill 2014; DGAC, 2016; Vieira, 2015; and Wardle, 2019)

Method	Designation	Approach/Event	Year	Reference
FAA (USA)	AC 150/5320-6	- Critical Aircraft. - Charts Design.	1964	[1]
	AC 150/5320-6A		1967	[2]
	AC 150/5320-6B		1974	[3]
	AC 150/5320-6C		1978	[4]
	AC 150/5320-6D	- Transition: Chart design to software design.	1995	[5]
	AC 150/5320-16		1995	[6]
	AC 150/5320-6E	- CDF[a] for airplane mix.	2009	[7]
	AC 150/5320-6F	- Software Design.	2016	[8]
APSDS[b] (Australia)	Paper	- Concept.	1987	[9]
	Prototype	- Based on CIRCLY.	1993	[10]
	APSDS	- Software release[c].	1995	[11]
DGAC[d] (France)	Research Start	- Method Development.	1998	
	Tests[e]	- Research.	1998	[12]
	Validation	- Methodology.	2011	
	Alize-airfield	- Software release.	2016	[13,14]

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 Programme (PEP), 1998-2003.

Ref.: [1] FAA (1964); [2] FAA (1967); [3] FAA (1974); [4] FAA (1978); [5] FAA (1995a); [6] FAA (1995b); [7] FAA (2009); [8] FAA (2016); [9] Monismith et al. (1987); [10] Wardle (2010); [11] Mincad Systems (2019); [12] Airbus (2005); [13] Blanchard (2017); [14] Fabre and Vaurs (2017).

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 agents 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 (Heymsfield and Tingle, 2019; Vieira, 2015).

Table 5 – Main applications for airport pavement design (developed with data from Heymsfield and Tingle, 2019; Brill, 2017; Blanchard, 2017; Fabre and Vaurs, 2017; Mincad Systems, 2019; and USACE, 2010)

Software	Calculation Method	Design Life	Developer	Last Update
FAARFIELD	Flexible: LED. Rigid: LED + FEM.	20-year	FAA	Sep/2017 (v. 1.42)
ALIZE	Flexible: LED. Rigid: LED.	10-year	STAC	Nov/2016 (v. 1.51)
APSDS	Flexible: LED.	20-year	Mincad Systems	Oct/2019 (v. 5.0t)
PCASE	Flexible: CBR or LED. Rigid: Westergaard or LED.	20-year	USACE	Sep/2010 (v. 2.09.06)

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 (Heymsfield and Tingle, 2019). 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.

2.3.1 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 (White, 2018).

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 (FAA, 2008; Horonjeff, 2010; ICAO, 1983).

In Mallick and El-Korchi (2013) it was presented the Equation (1) that relates CBR to pavement thickness:

$$t = \propto (A_c)^{\frac{1}{2}} \left[-0.0481 - 1.1562 \left(\log \frac{CBR}{P} \right) - 0.6414 \left(\log \frac{CBR}{P} \right)^2 0.473 \left(\log \frac{CBR}{P} \right)^3 \right] \quad (1)$$

Where:
$\propto$ is the load repetition factor;
A_c is the tire contact area, in²;
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 (Mallick and El-Korchi, 2013). 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 (Mallick and El-Korchi, 2013).

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 (Horonjeff, 2010; Mallick and El-Korchi, 2013). These theories were first developed in the 1920s and were focused on calculating stresses and deflections in concrete pavements due to applied loading (Mallick and El-Korchi, 2013).

According to Mallick and El-Korchi (2013), in 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 (Horonjeff, 2010; Vieira, 2015).

The remaining aircraft from the traffic mix were converted to the critical aircraft according to Equation (2).

$$\mathrm{Log}\ \mathrm{R}_1 = \log \mathrm{R}_2 \left(\frac{\mathrm{W}_2}{\mathrm{W}_1}\right)^{\frac{1}{2}} \tag{2}$$

Where:
R_1 is the equivalent annual departures by the design aircraft;
R_2 is the annual number of departures by an aircraft in terms of design aircraft landing gear configuration;
W_1 is the wheel load of the design aircraft;
W_2 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 6.

Table 6 – Factors for converting annual departures by aircraft to equivalent annual departures by design aircraft (adapted from Horonjeff, 2010)

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

More information on these methods developed during this period can be viewed at FAA (1964, 1967, 1974, 1978).

2.3.2 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 Heymsfield and Tingle (2019), 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 (Horonjeff, 2010).

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

Table 7 – 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. Rigid: Westergaard's solution.	Flexible: LED. Rigid: FEM.
Thickness Design	Flexible: CBR. Rigid: Percent of thickness to basic design for 5000 coverages.	Failure model relates coverages to structural failure to a suitable response. Flexible: Subgrade strain. 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 i can be determined by Equation (3).

$$\mathrm{CDF_i} = \sum \frac{\mathrm{ni}}{\mathrm{Ni}} \tag{3}$$

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 Equations (4) or (5):

$$\mathrm{CDF_{total}} = \sum_{i=1}^{Na} \mathrm{CDF_i} \tag{4}$$

or

$$\mathrm{CDF_{total}} = \sum_{k=1}^{M} \sum_{j=1}^{Nk} \mathrm{CDF_{kj}} \tag{5}$$

Where:
CDF_i 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.

An example of the calculation of CDF was developed by Fabre (2017), as observed in Table 8.

Table 8 – CDF calculation example (adapted from Fabre, 2017)

Aircraft	Equivalent Damage
A321-200 NEO	0.013
A350-900	0.172
A380-800	0.138
B737-900	0.001
B787-9	0.208
B777-300ER	0.326
CDF	0.858

In this example, six aircraft make up the fleet operating on the runway, and the aircrafts that caused the most damage to the pavement are the A350-900 (17%), A380-800 (14%), B787-9 (21%) and B777 -300ER (33%). Therefore, this pavement has reached a project life of 86%.

Also, these values are shown in Figure 12.

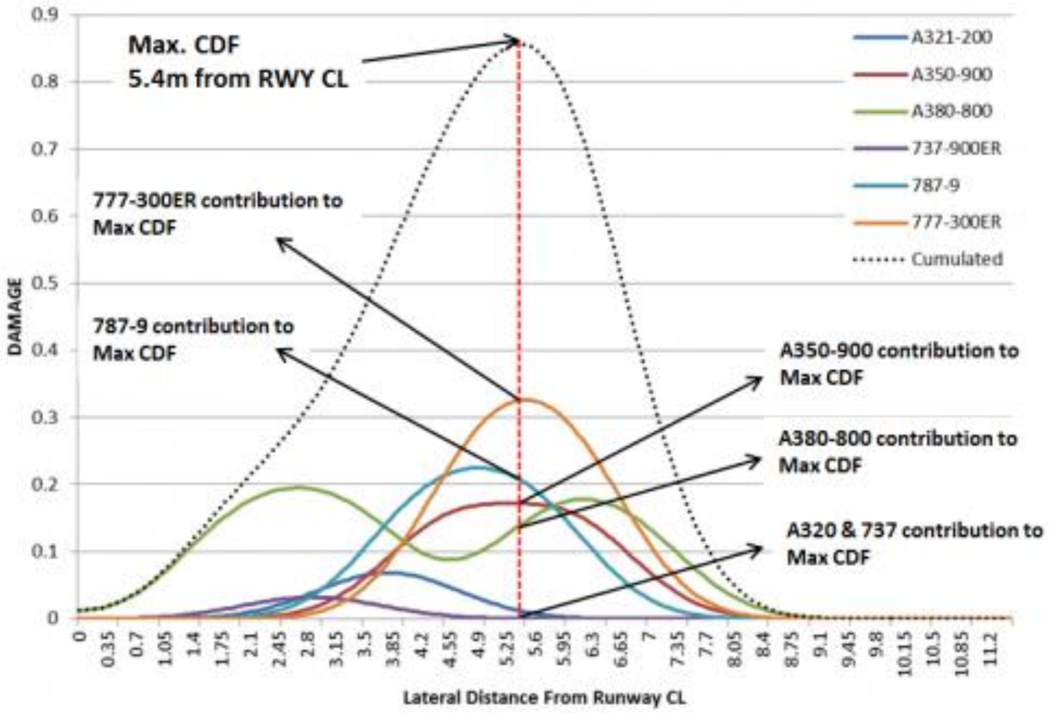


Figure 12 – Example of resulting CDF curves of an aircraft mix (Fabre, 2017)

Therefore, the design of airport pavements evolved with the adoption of the CDF concept and the implementation of LED (flexible pavements) and FEM (rigid pavements). Also, it is interesting to note that in the design of rigid pavements, due to the long processing time, the FAA adopted a mixed solution in its software, at the beginning of the design LED is used, and FEM is applied to final steps (Heymsfield and Tingle, 2019).

Finally, after this introduction on the evolution and the main methods applied for the design of airport pavements, the next subchapters will discuss the most used software for the design of airport pavements.

2.3.3 FAARFIELD (FAA Rigid and Flexible Iterative Elastic Layered Design)

In Brill and Kawa (2017), it is described that the acronym FAARFIELD (FAA Rigid and Flexible Iterative Elastic Layered Design) is a short description of the software, so it is an application developed for the design of airport pavements (rigid and flexible), which applies LED. Because the FAA supports it, the software is under continuous development, and its new version (1.42) was released in September 2017. As the FAA is a most respected organization in this area, its publications have a global impact, so FAARFIELD 1.42 and the AC 150/5320-6F are the airport industry standards. Also, in Brill and Kawa (2017), the authors explain that: “FAARFIELD belongs to the category of mechanistic-empirical pavement design procedures, meaning that it combines continuum-mechanics based analysis of stresses and strains within a layered pavement structure with empirically-derived failure models to produce a design. In the case of FAARFIELD, the failure models are based on analysis of full-scale traffic tests, including the most recent series of full-scale tests performed by the FAA…”

Therefore, it can be stated that the software developed by the FAA is based on a mechanistic-empirical formulation. Still, the core of the program is based on two subprograms, which are "LEAF for flexible pavement design and NIKE3D for rigid pavement design" (Heymsfield and Tingle, 2019).

In Heymsfield and Tingle (2019), the LEAF is defined as a computational layered elastic application program initially developed for the LEDFAA (Implemented to service the B777 dual tridem main landing gear). NIKE3D is based on a 3-D finite element analysis implementation. However, due to the high processing time required to use a 3-D FEM approach, the rigid airport pavement design is first developed with LED, and then 3-D FEM is applied to the final design (Heymsfield and Tingle, 2019; Wang *et al.*, 2018).

According to Heymsfield and Tingle (2019), the input information for the software are:

- Pavement layer properties;
- Aircraft types;
- Aircraft gross loads;
- Aircraft departure growth rate;
- Annual aircraft departures for each aircraft type.

Usually, the design life of the pavement is 20 years using CDF (see sub-chapter 2.3.2). This value is calculated based on an iterative process until the CDF value reaches 1. Also, by default, FAARFIELD values use a tolerance of ± 0.005 for CDF and ± 0.40 years for design life (Heymsfield and Tingle, 2019).

In Kawa (2017), the flexible failure model used in FAARFIELD is defined according to Equations (6) and (7).
For C > 1000 coverages:

$$\log_{10}(C) = (-\,0.1638\ + 185.19\mathcal{E}_{v})^{-0.60586} \quad (6)$$

For $C \leq$ 1000 coverages:

$$\mathrm{C} = \left(\frac{0.004141}{\mathcal{E}_{\mathrm{v}}}\right)^{8.1} \quad (7)$$

Where:
C is the coverage level (computed at the top of the subgrade);
$\mathcal{E}v$ is the vertical strain (also at the top of the subgrade).

This formulation was introduced in FAARFIELD 1.41. The current failure model is generally less conservative than previous ones, especially in the higher traffic range (Brill and Kawa, 2017).

FAARFIELD uses an iterative calculation process, where the thickness of the layers is defined based on the CDF and design life. The procedure consists of four steps: input, mechanistic calculations, total annual aircraft departures, and pavement distress (Heymsfield and Tingle, 2019). Therefore, the method developed by FAARFIELD can be summarized according to the diagram shown in Figure 13.

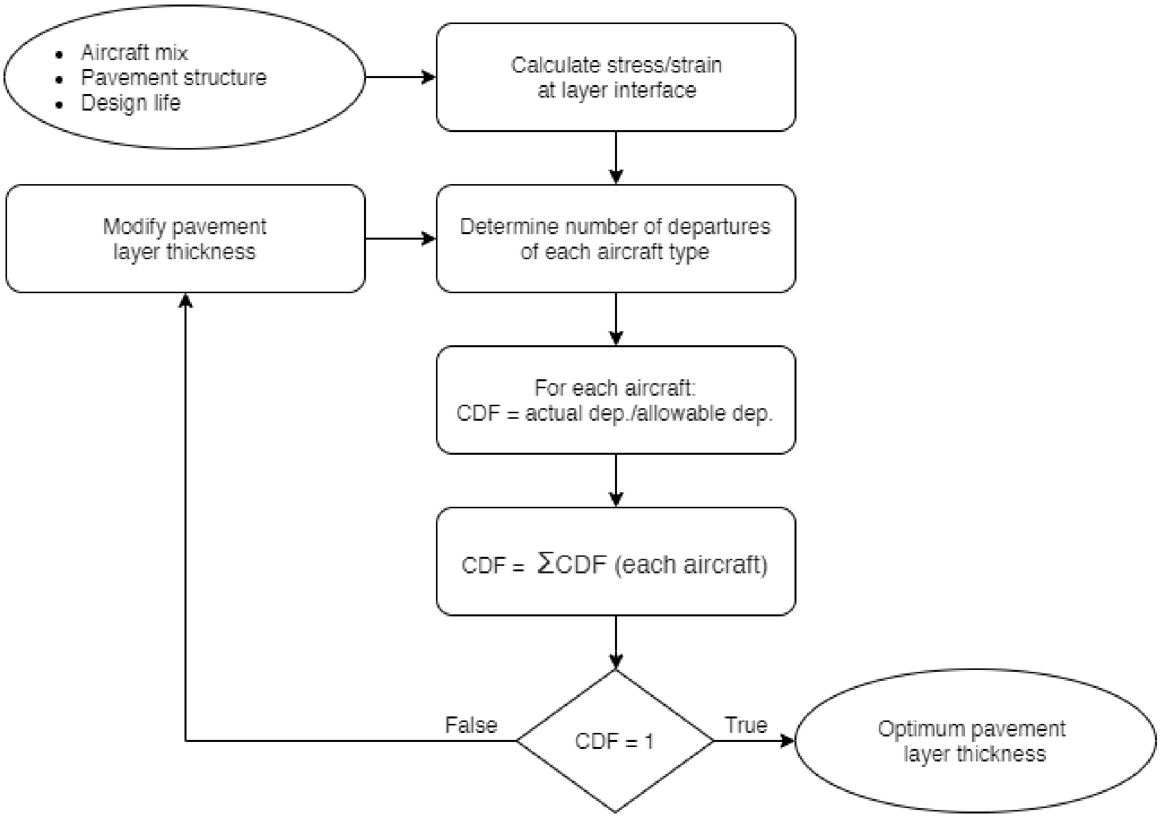


Figure 13 – FAARFIELD calculation process (adapted from Heymsfield and Tingle, 2019)

Finally, the final design provides the final thickness of all pavement layers. Also, design can be done for new rigid pavements, new flexible pavements, and overlays (Brill and Kawa, 2017; Heymsfield and Tingle, 2019).

2.3.4 Alize-Airfield

For airport pavement design, France has historically adopted an empirical methodology, using the CBR for flexible pavements and PCA for rigid pavements. With the increase in the number of flights and the weight of the aircraft, the pavements began to present problems ahead of the predicted time of their design. Therefore, it was concluded that the methodology used until then was not adequate. Thus, the French Civil Aviation Technical Center (STAC) developed a new methodology for the Rational Design Method for Flexible Airfield Pavements (STAC, 2014) and further developed dedicated software to apply this methodology (Heymsfield and Tingle, 2019; Mounier *et al*., 2015). This software is a modification of Alize-LCPC, which is used for road pavement design, for use on airport pavements.

The procedure adopted is based on the computation of resilient stresses and strains in the pavement structure, applying the multi-layer linear elastic model. For this purpose, the damage applied by each aircraft belonging to the pavement traffic composition (like CDF but with the acronym D) is considered, based on this loading the permanent deformation in the subgrade and the fatigue of the asphalt layers are computed. These calculations are added an empirical component based on laboratory testing of materials, observation of airport pavements, and an experimental program conducted in the early 2000s in Toulouse-Blagnac Airport with a full-scale heavy simulator (Mounier *et al*., 2015).

For flexible pavements, Alize-Airfield considers two failure models, the tensile stress at the bottom of the asphalt layer (fatigue failure) and vertical strain at the top of the subgrade (subgrade failure, i.e., rutting) (Heymsfield and Tingle, 2019). Equation (8) is used by this method.

$$\Delta D = \frac{1}{N(\varepsilon_{max})} = \left(\frac{\varepsilon_{max}}{K}\right)^{\beta} \tag{8}$$

Where:
ΔD is the incremental change in damage;
ε_{max} is the maximum strain induced by the aircraft wheel load;
N is the number of load applications at ε_{max} to cause failure;
β and K are damage parameters.

The method developed by Alize-Airfield is like that used by FAARFIELD and can be summarized according to the diagram shown in Figure 14.

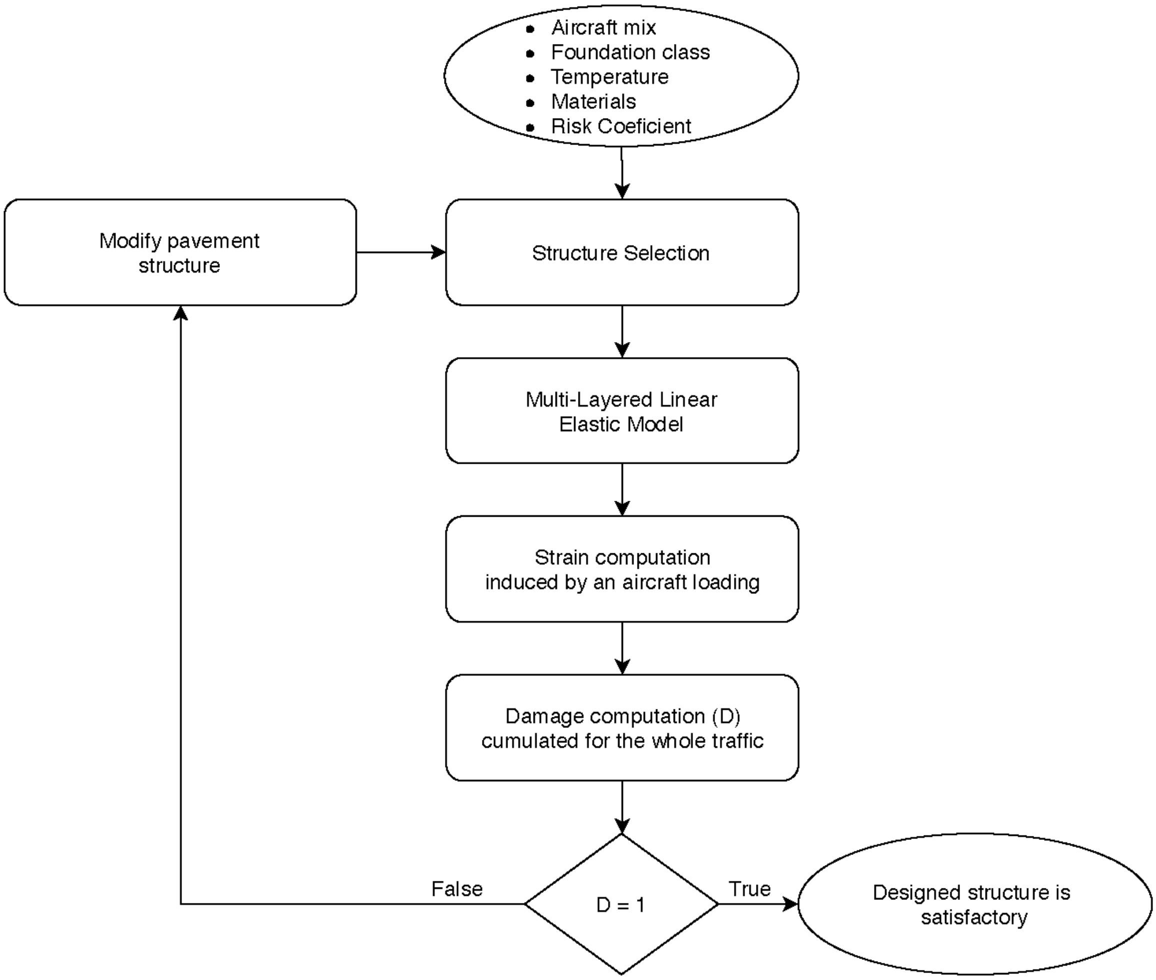


Figure 14 – Alize-Airfield calculation process (adapted from Mounier *et al.*, 2015)

As stated, the formulation used in Alize is similar to that of FAARFIELD, adjustments are made to the French rational methodology, the CDF is named D, but mainly the programs use multi-layered linear elastic models to calculate the stress generated by each aircraft in the pavement structure, from this the risk of pavement failure is calculated.

2.3.5 APSDS (Airport Pavement Structural Design System)

It is a software developed in Australia specifically for designing flexible pavements for airports, being a modification of software CIRCLY that was initially developed for road design. As presented in Table 4, the concept used in APSDS is based on the article by Monismith *et al.* (1987).

The APSDS uses a mechanistic-empirical model for the calculation of pavement damage. This statement is made due to the introduction of the applied methodology based on the layered elastic analysis. The empirical part is due to the parameters used, obtained in limited full-scale tests (Wardle and Rodway, 1998). The problem with this type of calibration is that the values obtained are limited to a few tests and are extrapolated to other situations. These approximations often may not best represent the structural damage to the pavements. This process is performed from the deformations, which is related to pavement life, that is, strain repetitions (Wardle, 2010).

Also, in Wardle and Rodway (1998), the authors explain that:"...subgrade strains, or alternative indicators of the rate at which deformation develops at the pavement surface, are computed for all points across the pavement in order to capture all damage contributions from all the aircraft wheels in all their wandering positions. This contrasts with previous methods that computed single maximum values of the damage indicators. It is this feature that eliminates the need for the pass-to-coverage concept and allows the designer to specify any degree of wander. Successive aircraft movements have been observed to be normally distributed about the pavement centerline.”

The mechanistic-empirical Equation (9) is used for the failure criteria.

$$N = \left[\frac{K}{\varepsilon}\right]^{b} \tag{9}$$

Where:
N is the predicted life (repetitions of ε);
Ɛ is the load-induced strain;
K is a material constant;
b is the damage exponent of the material.

In this formulation, the parameters K and b are empirical values determined from field testing or observation of pavements in service.

Such as in FAARFIELD and ALIZE, APSDS also uses the cumulative damage factor concept, so the actual wheel configurations and loads of all aircraft in the design mix are considered (see Equation (3)). Thus, this treats the level of the stress response of the aircraft load as a direct indicator of damage over the life of the airport pavement. Accumulated damage from all aircraft contributes to pavement failure according to the stress imposed by each aircraft (Wardle, 2010).

2.3.6 PCASE (Pavement-Transportation Computer Assisted Structural Engineering)

It is a software developed by the USACE for designing pavements of airfields, roads, and railroads (USACE, 2010). More specifically, it is supported by the Engineer Research and Development Center (ERDC) (Heymsfield and Tingle, 2019).

According to USACE (2010), concerning PCASE applications, it was developed to fulfill several functions, such as:

- Pavement Design for Roads, Streets, Walks, and Open Storage Areas;
- Aggregate Surfaced Roads and Airfields Areas;
- Airfield and Heliport Planning and Design;
- Pavement Design for Airfields;
- Airfield Pavement Evaluation.

Therefore, for airports, PCASE can be used to design various areas, including those not intended for aircraft traffic. Another added value is its backcalculation module, which serves to evaluate the life of the airport pavement structure (Heymsfield and Tingle, 2019).

Another interesting feature of the software is the possibility to choose the CBR-based or LED design as the calculation methodology for flexible pavements, while for rigid pavements, it is possible to choose between Westergaard solution and LED (Heymsfield and Tingle, 2019). This feature of the software opens the possibility of comparing the two approaches and performing some types of different analyses.

Finally, among the evaluated software, PCASE is the oldest software as its latest version (2.09.06) was released in September 2010. However, the aircraft database is continuously updating. The last update was in November 2019, this demonstrates that USACE maintains support for PCASE.

2.4 Final Considerations

This chapter provided a brief overview of the basic concepts that support the general understanding of airport pavements. Still, it focused on design methods, their evolution, and state-of-the-art. It was concluded that the appropriate software for the case study is FAARFIELD version 1.42. This computer application is supported by the FAA, is continuously evolving, and can be considered a reference in the design of airport pavements.

The software evaluated in the study was FAARFIELD, Alize-Airfield, APSDS, and PCASE. These computer applications are supported by government agencies and have been developed to meet the specifications and standards of each agency to which they belong. Therefore, FAARFIELD applies the concepts of the FAA, Alize-Airfield applies the concepts of the DGAC, and so on.

Regarding the calculation methodologies, the LED method is the most used for flexible pavements, being also applied to rigid pavements. In the FAA software, a more elegant solution is considered, with the use of the LED at the beginning and the application of a finite element method in the final design. This effort makes it possible to obtain more accurate results. Although inelastic approaches have the potential to provide more accurate predictions, the downside is an increase in the number of input parameters and the required computational processing time.

It is interesting to note that the studied methodologies follow the evolution of the FAA. This is another reason to choose FAARFIELD in this study, since it is the reference in the area, and other software usually adapts the concepts for each country/region. This is also one of the disadvantages of the application of FAARFIELD in Portugal, since it is specially formatted for the American reality, with materials and units used in the United States. A clear example is a final thickness of the dimensioned layers (using SI as a definition in FAARFIELD), which are dimensioned in inches, with results of 5.08 cm (2 in), 7.62 cm (3 in). Finally, in the next chapter, the Viseu Aerodrome case study will be discussed.

3. CASE STUDY

3.1 Case Study Choice

Until the 1970s, the air transport market was highly regulated, relying heavily on tax incentives and political decisions. From the opening of the aviation market (started in 1978 in the USA), airport operators had to focus on efficiency, operation, profitability, i.e., the economic and financial viability of the projects. This scenario led to a growth of 5% per year in the civil aviation market until 2009 (Belobaba *et al*., 2009). Also, in Europe, the air transport market has been growing, with the creation of new routes, improving the connectivity of the European continent, and contributing to the economic and social development of its cities and regions (Calzada and Fageda, 2019).

In Calzada and Fageda (2019) the authors point out that in Europe, in addition to the liberalization of the aviation market (in Europe it was fully liberated only in 1997), the emergence of low-cost airlines and the development of new regional jets in the 1990s, made it possible to open new routes that would previously have been uneconomical.

Regarding mainland Portugal, it can be said that the three main international airports (Lisbon, Porto, and Faro) in operation are located on the coast (Figure 15), leaving the interior with some isolation, there is still a gap in the Centro region (Martins, 2018). Since Portugal's two largest housing hubs are Greater Lisbon and Greater Porto, however, the Centro region also has a considerable population.

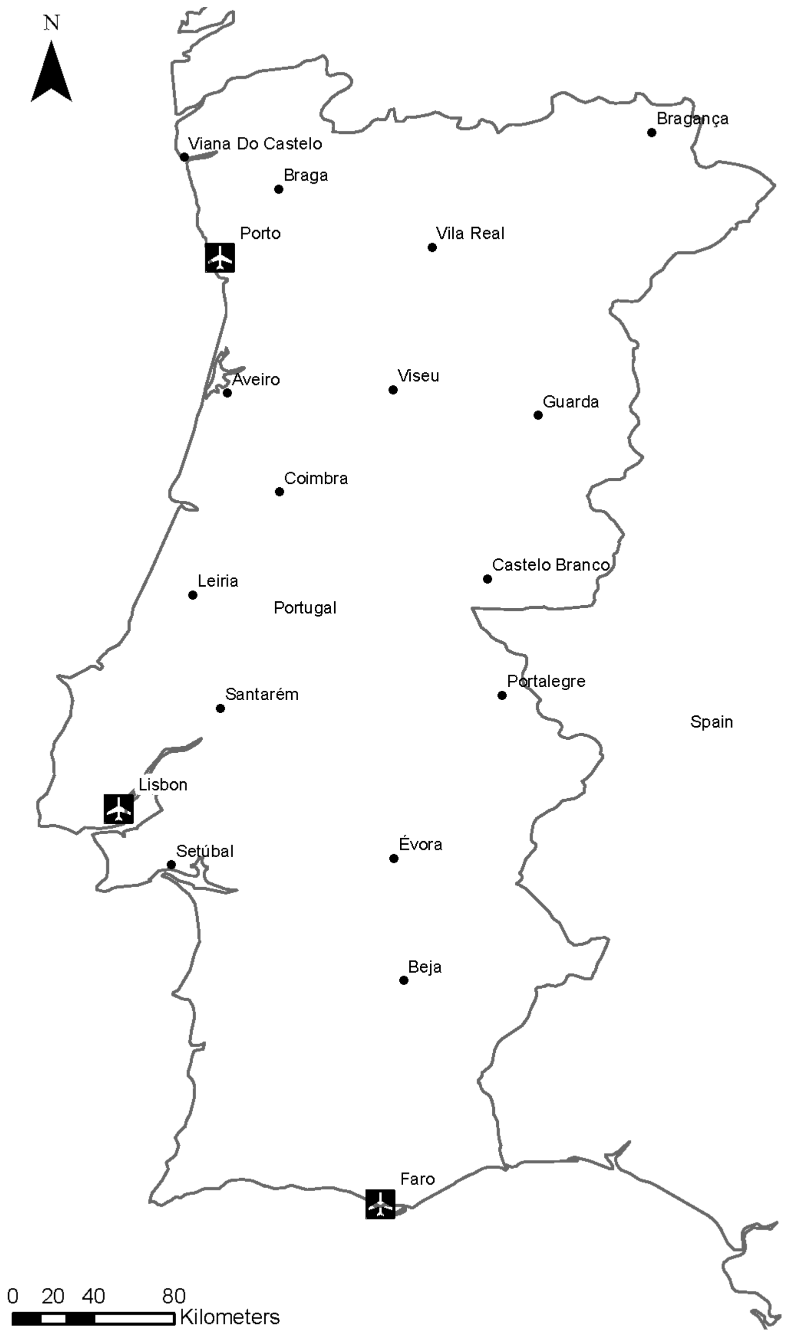


Figure 15 – International airports operating in Portugal

Recent studies indicate that there is a demand for an airport that serves the Central and Interior regions of Portugal. This idea is supported by various stakeholders (Martins, 2018). In this same study, the Viseu Aerodrome was described as the best alternative, for its strategic location, dynamics of the region's economy, population served, and for the capacity for infrastructure expansion (especially runways). Therefore, looking at the Portuguese scenario and the existing options, the case study to be addressed in this case study will be the Viseu Aerodrome.

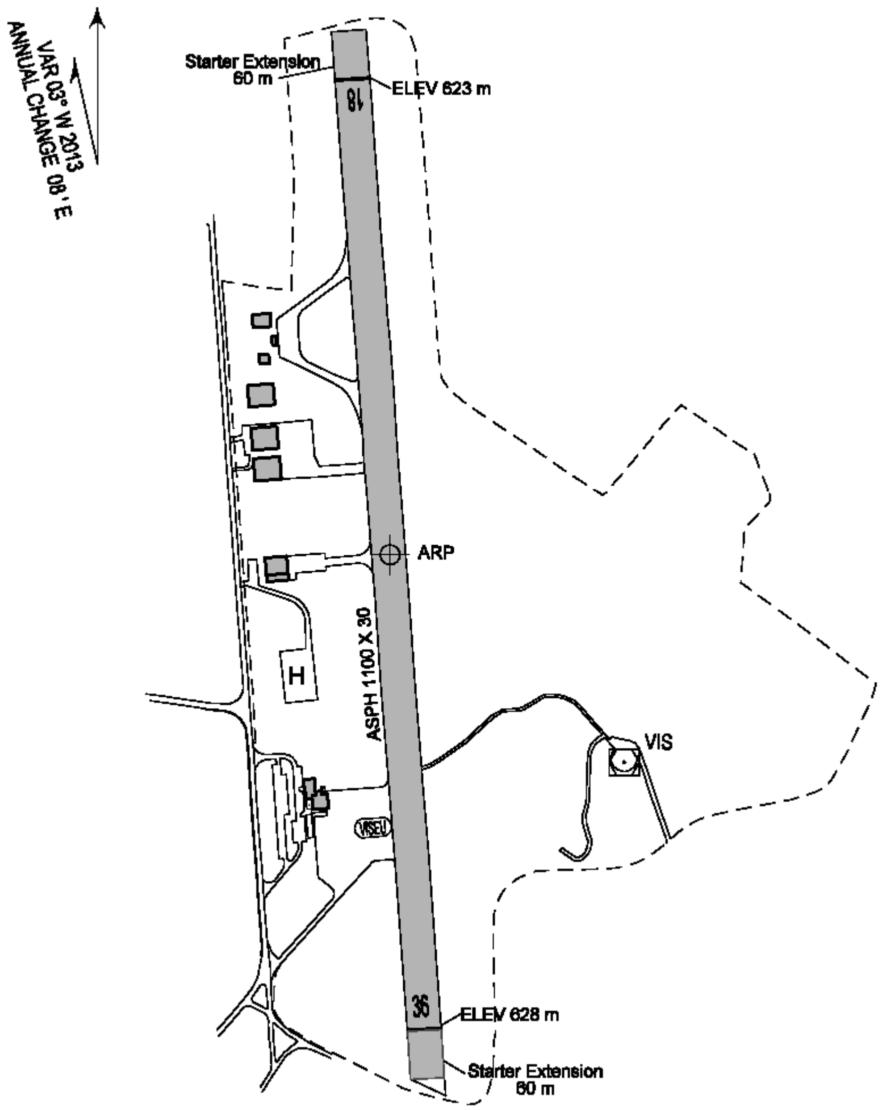
3.2 Viseu Aerodrome

Viseu Municipal Aerodrome (ICAO: LPVZ) is located at an altitude of 628 m and 7 km north of the city of Viseu (LPVZ, 2019). Also, it is located 87 km from Porto Airport (141 km by highways), 242 km from Lisbon Airport (295 km by highways), and 412 km from Faro Airport (538 km by highways). The following geographical coordinates give the exact position: latitude 40°43'22.5"N and longitude 7°53'25.0"W.

Regarding its operation, it has authorized traffic for visual flight procedures and rules with general aviation operations and scheduled and non-scheduled passenger air services. Also, the use of ultralight is allowed (LPVZ, 2019). It is still a relevant factor that the Aerodrome is equipped and duly certified to perform night flights (CMV, 2019a).

Concerning the runway, it has a North-South orientation (18/36) with 1160 m length (60 m extension on both sides) and 30 m wide. The pavement is flexible and has the code PCN 6/F/C/W/U (Figure 16). The prevailing wind is East (E), so, unlike the best engineering practices for airport infrastructures, the orientation of the current runway is perpendicular to the prevailing winds and may cause the phenomenon of crosswind.

As of June 2014, Viseu Aerodrome has been receiving commercial flights and aeronautical operations, complying with all safety protocols of the National Institute of Civil Aviation (INAC). At the aerodrome, there are also the services of the Portuguese State Aircraft Accident Prevention and Investigation Office (GPIAA) and the civil protection district air services. The Aero Clube de Viseu has maintained a pilot training school since the 1960s (AC Viseu, 2019), ensuring the dynamization of this infrastructure.



RWY	DIRECTION	THR	BEARING STRENGTH
18	179°	40° 43' 50" N 007° 53' 22" W	PCN 6/F/C/W/U
36	359°	40° 43' 14" N 007° 53' 19" W	

Figure 16 – Viseu Municipal Aerodrome chart (LPVZ, 2019)

Finally, according to Viseu City Hall (CMV,2019b) since 23 December 2015, it has been providing a regular public service with the regional airline that connects Bragança, Vila Real, Viseu, Cascais, and Portimão (Figure 17).

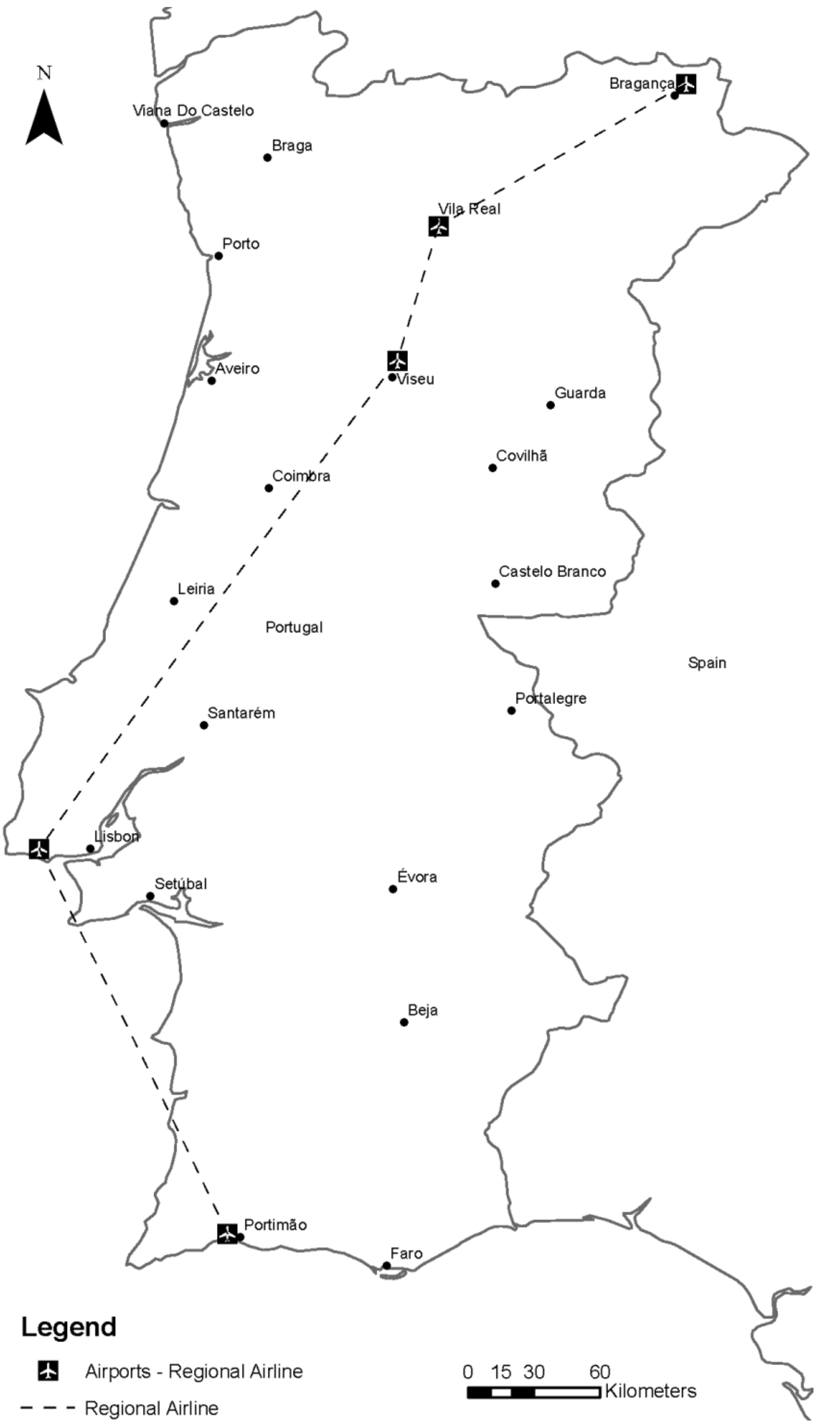


Figure 17 – Regional airline connecting Bragança, Vila Real, Viseu, Cascais and Portimão

This operation is an asset to the region. However, it loses capillarity because it does not connect to any aeronautical hub in the region. In this sense, it would be interesting to operate some route that connects the city of Viseu to the airports of Porto, Lisbon, or even Madrid.

3.3 Pavements

The Gonçalves Lobato Aerodrome runway was built in the 1950s. On July 18, 1989, the Portuguese Air Force Aerodrome Engineering Group conducted a study for the application of a runway reinforcement. In this study, it was recommended to correct the surface irregularities through the localized application of a bitumen binder for the regularization layer, and for the surface layer, it was proposed to apply a 7.6 cm (3 in) bituminous concrete layer (GEAFA, 1989).

For this study, a prospecting campaign was conducted with the nine drill holes in the road for the coring test, with the locations indicated in Figure 18.

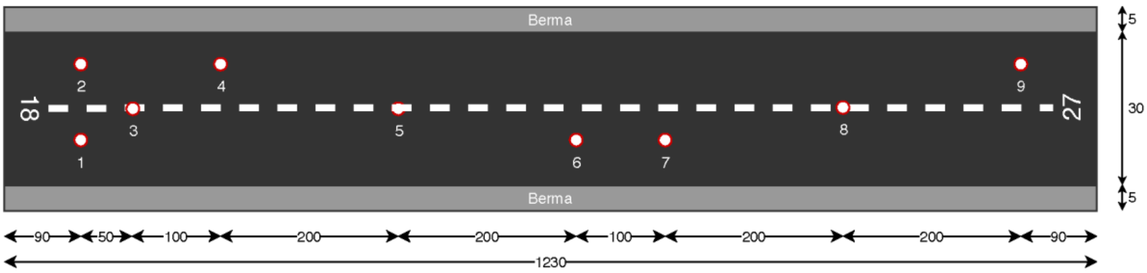


Figure 18 – Location of test points (GEAFA, 1989)

The results of the surveys which were performed are presented in Table 9.

Table 9 – Result of studies conducted in 1989 (GEAFA, 1989)

Test hole	Base layer thickness (m)	Foundation Soil Type	CBR of foundation soil	In-situ moisture content (%)	Foundation Soil Color
1	0.18	A-4 (3)	16.2	10.7	Red
2	0.20	A-4 (3)	13.5	17.0	Red
3	0.25	A-4 (3)	10.6	16.7	Red
4	0.20	A-4 (2)	24.6	14.3	Brow
5	0.20	A-4 (2)	19.4	13.2	Brow
6	0.19	A-4 (2)	21.4	15.5	Brow
7	0.20	A-4 (2)	21.6	15.7	Brow
8	0.23	A-4 (2)	49.2	11.2	Brow
9	0.17	A-4 (2)	42.8	11.2	Brow

Table 10 shows the results of laboratory tests for both identified soil types (GEAFA, 1989).

Table 10 – Result of studies conducted in 1989

Foundation Soil Type	Maximum dry density (g/cm³)	Optimum moisture content (%)	LL (%)	LP (%)	IP (%)
A-4 (3)	1.960	11.5	31.6	29.6	2.0
A-4 (2)	1.875	12.5	32.3	28.2	4.1

As a result of this study, a year later (1990), the pavement was reinforced, and the runway had the pavement structure shown in Figure 19.

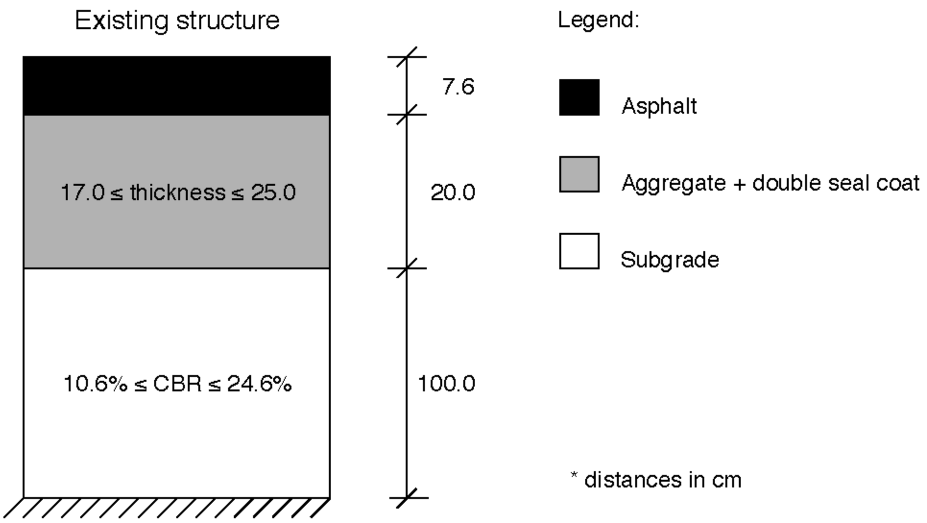


Figure 19 – Runway pavement structure

Existing pavement load capacity was determined based on a Heavy Weight Deflectometer (HWD) load testing campaign along three alignments (centerline, 2.00 m to the left, and 2.00 m to the right) on the Viseu Aerodrome runway (values in Attachment 1). At each test point, two temperature measurements were taken: air temperature and surface temperature. It should be noted that the temperature at which the load tests are performed can have a significant influence on the results obtained, namely on the determination of the deformability modules of the bituminous mixtures. The tests were performed in periods with pavement temperatures were always between 5ºC and 30ºC. The results of the tests performed can be seen in Figure 20. The maximum deflection is verified at km 0+126 and has a value of 2884 µm.

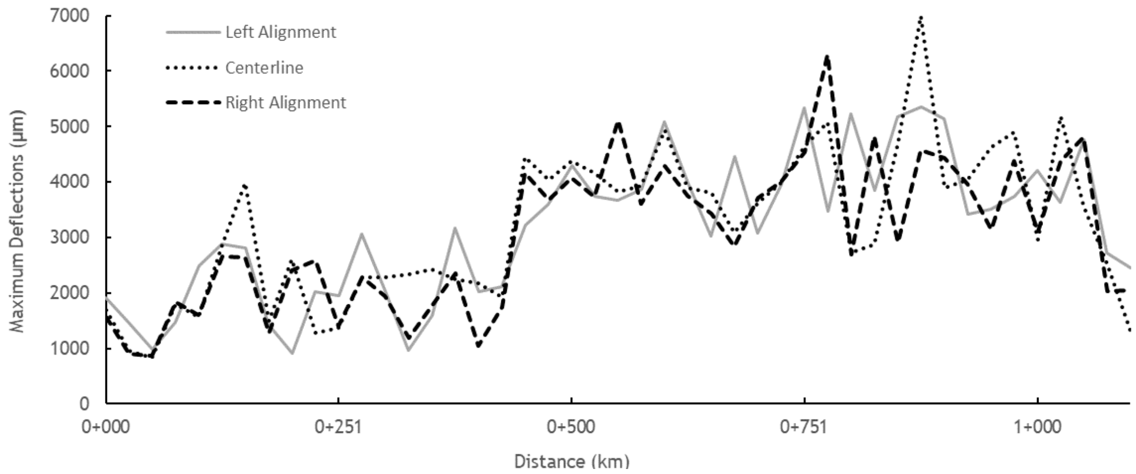


Figure 20 – Maximum deflections at each alignment

Therefore, the characteristic soil type for design will be the same as tested in 1989, the pavement layers will be the current layers, and the pavement strength will be typified by the HWD test performed on July 23, 2019.

Applying the accumulated difference method (AASHTO) to the values shown in Figure 20, it was concluded that the runway could be separated into two sections with "similar" characteristics. In addition, the percentile 85 was considered in the design, so Figure 21 presents the values for Section 1.

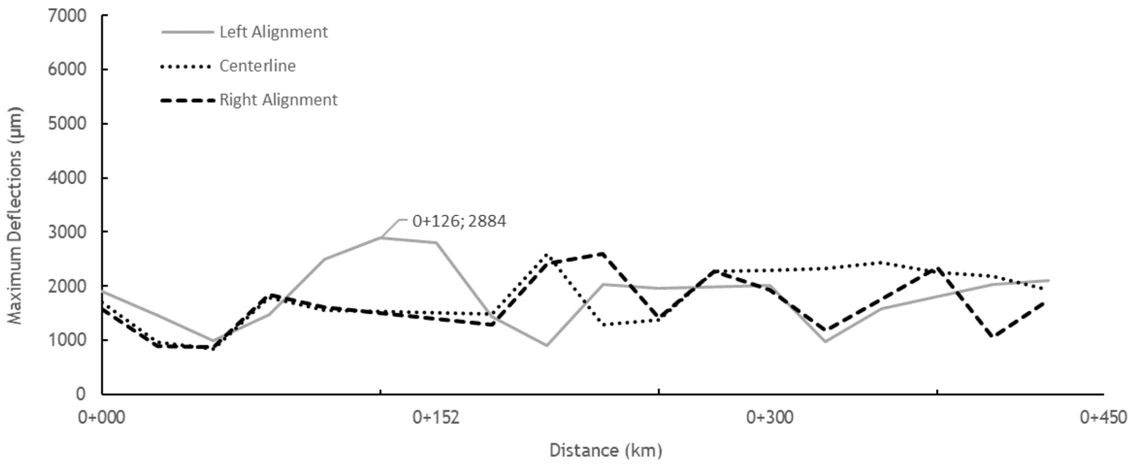


Figure 21 – Maximum deflections at each alignment (Section 1 - 0+000 to 0+450)

Similarly, Figure 22 shows the values for Section 2 (considering the percentile 85). The maximum deflection is verified at km 0+900 and has a value of 5147 µm.

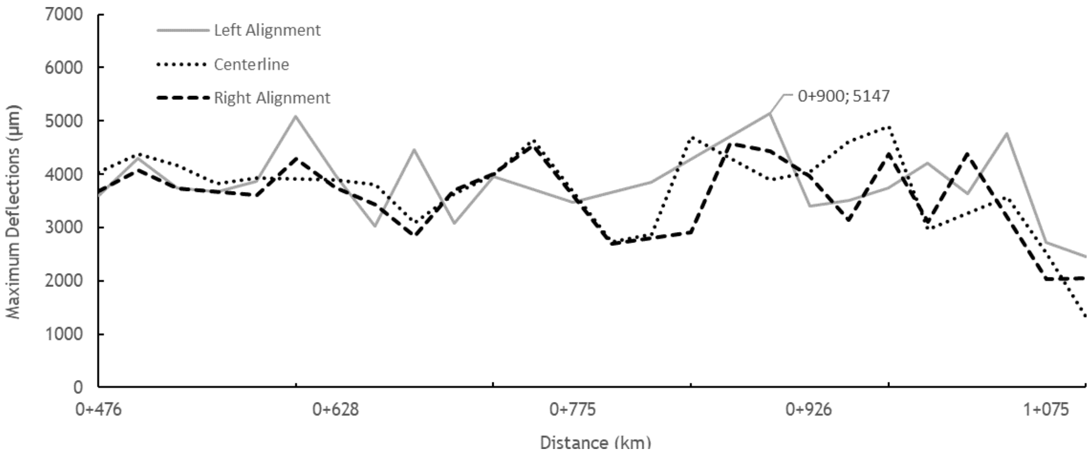


Figure 22 – Maximum deflections at each alignment (Section 2 - 0+476 to 1+100)

In the next sub-chapter, it will be presented the backcalculation developed to estimate the elastic modulus of each pavement layer.

3.3.1 Backcalculation

As shown before, the Viseu Aerodrome runway was divided into two sections. In Section 1, the maximum deflection is located at km 0+126 and has a value of 2884 µm. So, the backcalculation will be performed for this point for the first section. Table 11 shows the calculated values supported by the software's BAKFAA (initial calculation) and KenPave (final module adjustment).

Table 11 – Modulus of elasticity calculated for Section 1

Distance (m)	Measured Deflection	E (MPa) (Try 1)	Calculated Deflection (Try 1)	E (MPa) (Try 2)	Calculated Deflection (Try 2)	E (MPa) (Final)	Calculated Deflection (Final)
0.00	2884	1400	1755	1400	2966	1400	2824
0.30	1718	500	1159	200	1853	170	1668
0.45	1123	60	841	40	1262	50	1083
0.60	749	400	615	400	872	400	721
0.90	353		310		394		316
1.20	196		150		164		134
1.50	138		72		62		58
1.80	108		38		23		29
2.10	91		27		13		21

Notes: Deflections in µm/m.

All these values are represented in Figure 23.

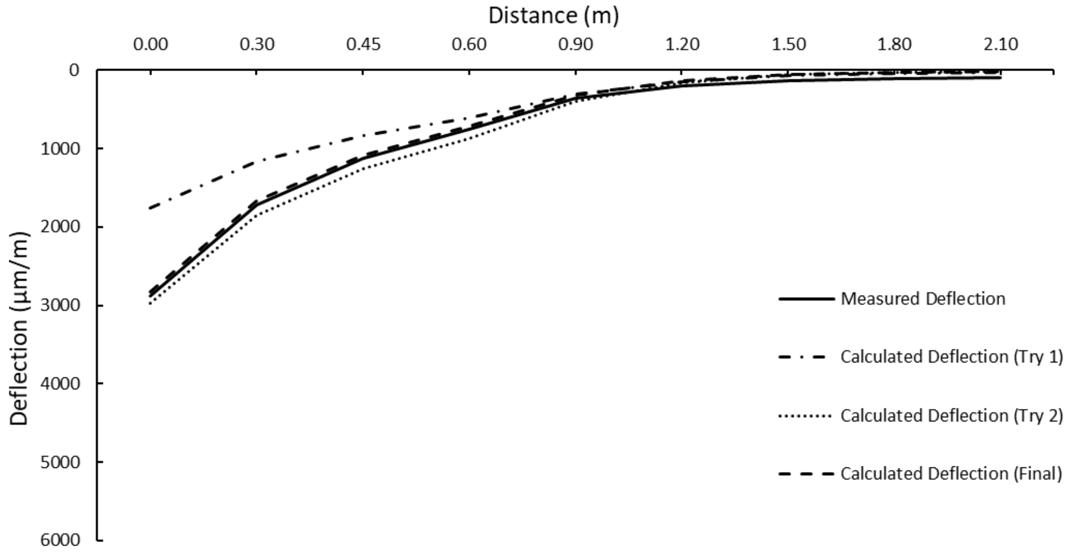


Figure 23 – Deflections for Section 1

Following the same procedure as for Section 1, for Section 2, the maximum deflection is located at km 0+900 and has a value of 5147 µm. Table 13 shows the calculated values.

Table 12 – Modulus of elasticity calculated for Section 2

Distance (m)	Measured Deflection	E (MPa) (Try 1)	Calculated Deflection (Try 1)	E (MPa) (Try 2)	Calculated Deflection (Try 2)	E (MPa) (Final)	Calculated Deflection (Final)
0.00	5147	1000	2520	1000	5561	1000	5057
0.30	3724	200	1438	100	3520	130	3286
0.45	2487	60	926	20	2386	20	2294
0.60	1672	400	619	400	1622	400	1602
0.90	722		274		691		717
1.20	379		122		245		270
1.50	277		58		53		67
1.80	222		34		15		10
2.10	199		27		0		0

Notes: Deflections in µm/m.

Additionally, all these values are represented in Figure 24.

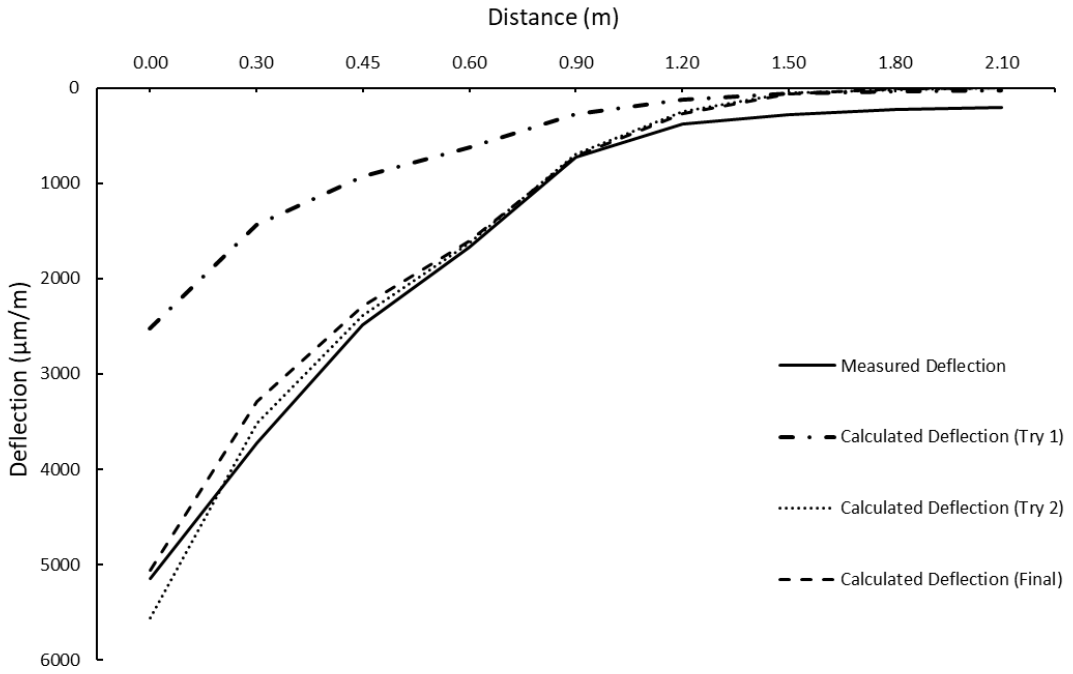


Figure 24 – Deflections for Section 2

Finally, the calculated values for bituminous layers must be adjusted to a working temperature of 26ºC (values for the region of Viseu based on Ferreira, 2018), and this correction was possible using the Equation (10) (Ullidtz and Peattie, 1982).

$$\frac{S_T}{S_{15}} = 1\text{- }1.384\log\left(\frac{T}{15}\right) \tag{10}$$

Where:

S_T is the asphalt moduli at the temperature of T (ºC);

S_{15} is the asphalt moduli at the temperature of 15ºC.

Equation (10) was reformulated in order to be applied to 26ºC of temperature, resulting in equation (11).

$$E_{T_s} = E_{T_t}\frac{1\text{- }1.384\log\left(\frac{T_s}{15}\right)}{1\text{- }1.384\log\left(\frac{T_t}{15}\right)} \tag{11}$$

Where:

E_{Ts} is the asphalt moduli at service temperature T_s;

E_{Tt} is the asphalt moduli at test temperature T_t.

The corrected values supported by Equation (11) are presented in Table 13.

Table 13 – Correction of bituminous layer modules for working temperature (26ºC)

Layer	Thickness (cm)	E (MPa) 17.0ºC	E (MPa) 26.0ºC	E (MPa) 17.5ºC	E (MPa) 26.0ºC
			Section 1		Section 2
Asphalt	7.6	1400	1013	1000	738
Agregate + Double Seal Coat	20.0	170	170	130	130
Subgrade	100.0	50	50	20	20
Rigid	inf	400	400	400	400

In addition to data relating to existing pavement layers, FAARFIELD must provide the entire mix of aircraft operating in the airport infrastructure. This will be discussed in the following sub-chapter.

3.4 Scenarios

A computer application was built in Python to understand the scenarios for this study. This analysis is based on the possible coverage from the design of the Viseu Aerodrome runway. In this sense, a simple strategy was adopted, where the only input parameters are the structural resistance of the pavement (based on the PCN) and the length of the runway for landings and takeoffs. FAARFIELD software does not embrace this concept. However, this approach was useful in the pre-design phase, so this will be the first step to runway pavement design, understanding what coverage will be possible based on simple input data.

According to data from the LPVZ (2019), the Viseu Aerodrome (LPVZ) runway has a PCN 6 and a length of 1160 m. In this sense, it is an infrastructure for regional use. To create the scenarios, an application was developed in Python. This software calculates the coverage of the Viseu Aerodrome based on two input parameters for the runway: PCN; and runway length.

With the support of this computer application, it was possible to develop three scenarios for Viseu Aerodrome operation. These were created to enable the operation of the Dornier

228, ATR 72-600, and Boeing 737-800 aircrafts. Each aircraft made it possible to create a scenario to meet the runway length and PCN. The first would be just to reinforce the pavement to the point of maintaining the characteristics of PCN 6.4 and runway length of 1160 m (Figure 25).

Figure 25 – First scenario (PCN 6.4 and 1160 m runway length)

Therefore, maintaining the current characteristics of the pavement, it was possible to serve mainland Portugal, Spain, and southern France. But the aircraft in operation is limited to the use of the Dornier 228, which carries only 19 passengers.

This Viseu Aerodrome operating scenario is already used on a smaller scale for daily regional flights (see Figure 17 and sub-chapter 3.2). However, it does not operate regular flights to Spain or Southern France.

Two more possible scenarios were created. The second scenario is based on a pavement with PCN 23 and a length with 1800 m. Finally, the third scenario adopts PCN 82.2 and 2500 m runway length. All scenarios can be seen in Figure 26.

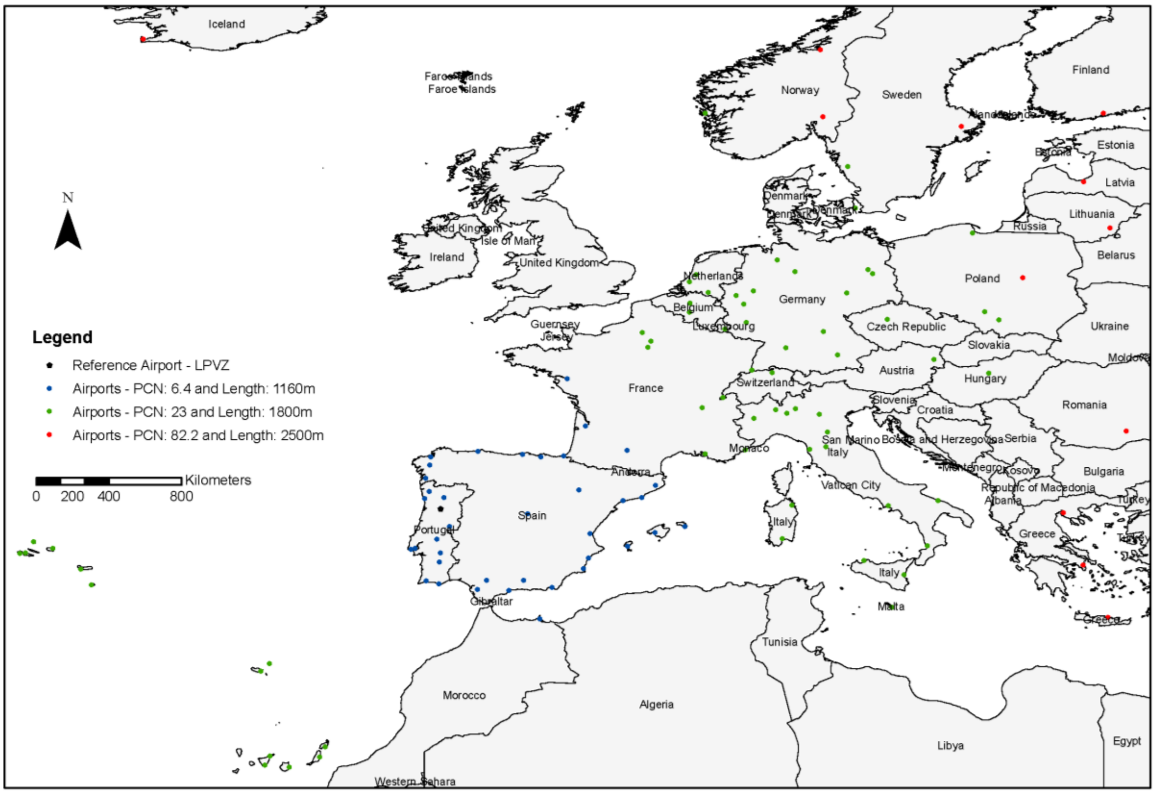


Figure 26 – Viseu Aerodrome coverage study

On the other hand, with PCN 23 and runway length of 1800 m, the Schengen space is almost served. However, it is limited to use on aircrafts such as CRJ200 and ATR72-600. These aircrafts carry between 50 and 70 passengers.

Finally, with PCN 82.2 and runway length of 2500 m, you get little coverage, but larger aircraft (up to 200 passengers) can be used. For example, low-cost airline Ryanair only operates B737-800 aircraft (within these parameters).

3.5 Pavement Design

The design of the pavement was performed with the FAARFIELD software, which corresponds to the state-of-the-art in this area. For the existing pavement, the values obtained in the backcalculation were used as the base (rounded values to multiples of 10; therefore, 1010 and 730 MPa were adopted). Therefore, the backcalculation values developed in sub-chapter 3.3.1 were used as characteristics of the existing pavement (Figure 27).

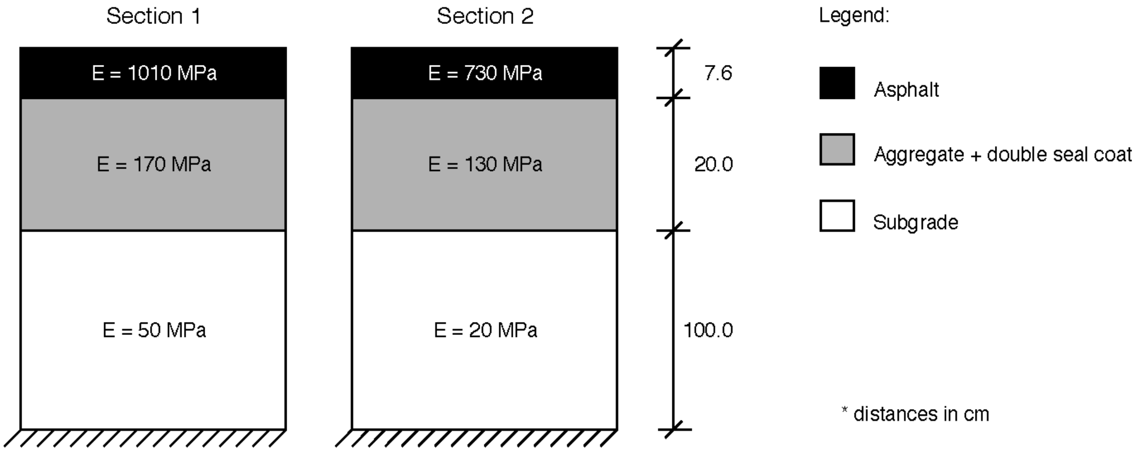


Figure 27 – Parameters adopted for existing pavement

This existing pavement structure will only be used in the scenario where the current runway length can be maintained, so it is an overlay of the existing runway. If a runway longer than 1160 m is required, the option adopted will be the construction of a new runway, which will be addressed in sub-chapter 3.5.2.

Therefore, three operation scenarios were created for the Viseu Aerodrome. The first scenario considers only the overlay of the current layer with a focus on keeping the operation limited to the Dornier 228-200 aircraft. In the second scenario, it was also considered to use turboprop aircraft for regional flights. For the third scenario, the 737-800 aircraft was added, which is a cost-effective option for medium-range flights.

Following the methodology developed by the FAA, the design life considered for the structure of the design pavement is 20 years, and the annual growth of 3%. Therefore, the aircrafts used for the design of the Viseu Aerodrome pavement are presented in Table 14.

Table 14 – Main aircrafts used for design

Group	Typical Aircraft	Equivalent (generic) Aircraft	Maximum take-off weight kg	Annual Departures		
				Overlay on existing pavement	New Pavement PCN 23	New Pavement PCN 82.2
Small Regional airliner	Dornier 228-200	S-15	6800	1460[b]	800[c]	800
Medium turboprop airliner	ATR 72-600	S-50	22680	0	1460	1460
Medium jet airliner	Boeing 737-800[a]		79243	0	0	2200[d]

Notes: a. Not considered a 3% growth for this aircraft;
b. Four flights a day;
c. A little more than two flights a day;
d. About six flights a day.

As seen before, the typical aircrafts considered are different from the aircrafts used in the project, where equivalent generic aircraft were considered. This approach was taken only because there is not all the necessary information for the FAARFIELD software. Thus, similar aircraft in weight and landing gear configuration were adopted.

For the overlay on the existing pavement, layers with custom configurations were used (Figure 28), according to the calculated values in the backcalculation.

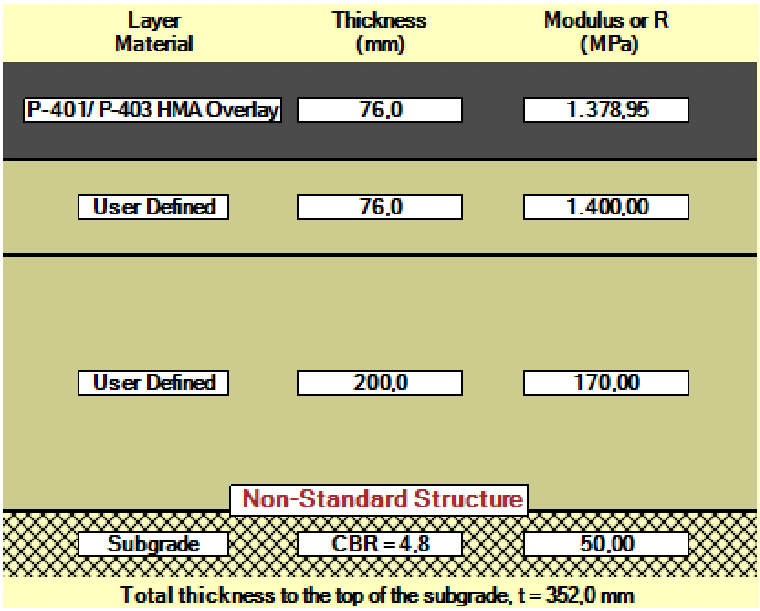


Figure 28 – Overlay design on the existing runway (example)

The following sub-chapter will cover the overlay design of the existing runway.

3.5.1 Existing runway (18/36)

As shown in 3.3.1 (backcalculation), the existing pavement (orientation 18/36) can be divided into two sections in relation to its structural capacity. Therefore, in the option to maintain the current operation (2 daily scheduled flights with the Dornier 228-200 aircraft), the pavement must be reinforced with an overlay. The pavement is designed for a project life of 20 years, with a traffic growth of 3% per year. Figure 29 shows the layers calculated for Section 1.

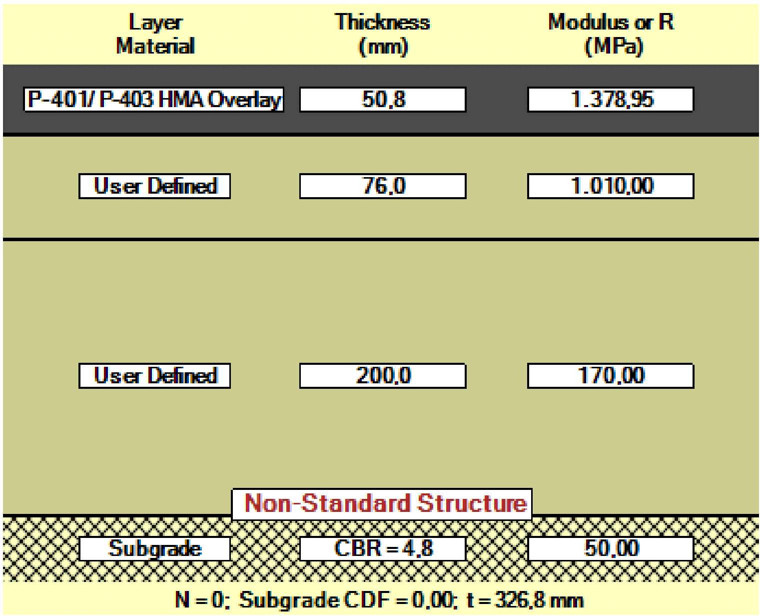


Figure 29 – Reinforcement of existing pavement - Section 1

In this scenario, for the proposed loading the runway CDF does not reach 1, however, the FAARFIELD 1.42 software measures the minimum reinforcement recommended by the FAA which is 5.08 cm (2 in).

The same does not happen in section 2 (Figure 30), in this section according to backcalculation the structural results are worse.

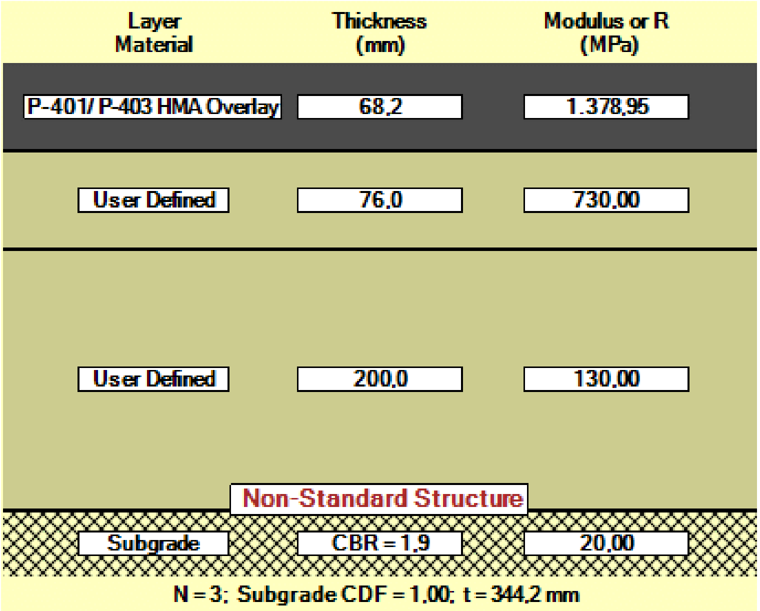


Figure 30 – Reinforcement of existing pavement - Section 2

Therefore, if the option is to keep the current operation, a 5.1 cm overlay between 0+000 to 0+450 (Section 1) and a 6.8 cm overlay between 0+476 to 1+100 (Section 2) should be performed. For practical purposes, the overlays must be rounded for 5.5 cm (section 1) and 7,0 cm (section 2). In the space between 0+450 and 0+476, a transition must be made to compensate for this difference of 1.5 cm.

As a result of the design for the existing runway 18/36, the final thickness is shown in Figure 31.

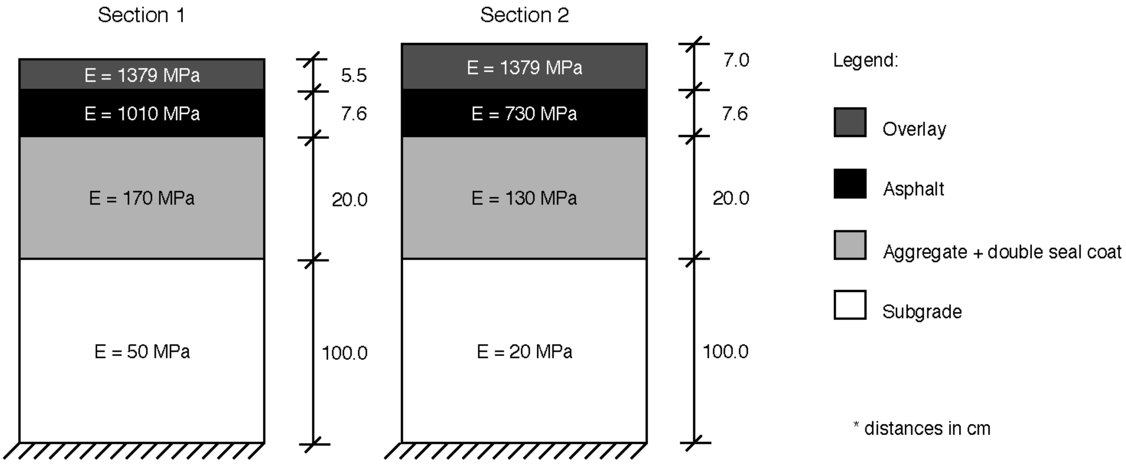


Figure 31 – Final structure dimensioned for Sections 1 and 2

For scenarios that support Medium Turboprop Airliners (ATR 72-600) and Medium Jet Airliners (Boeing 737-800), it is necessary to build a new runway (item discussed in the next sub-chapter).

3.5.2 New runway (04/22)

The current pavement length (18/36) is close to the space limit. So, the option adopted in this study is the construction of a new pavement with orientation 04/22 (oriented according to prevailing wind). The orientation and position proposed for this new runway can be seen in Figure 32.

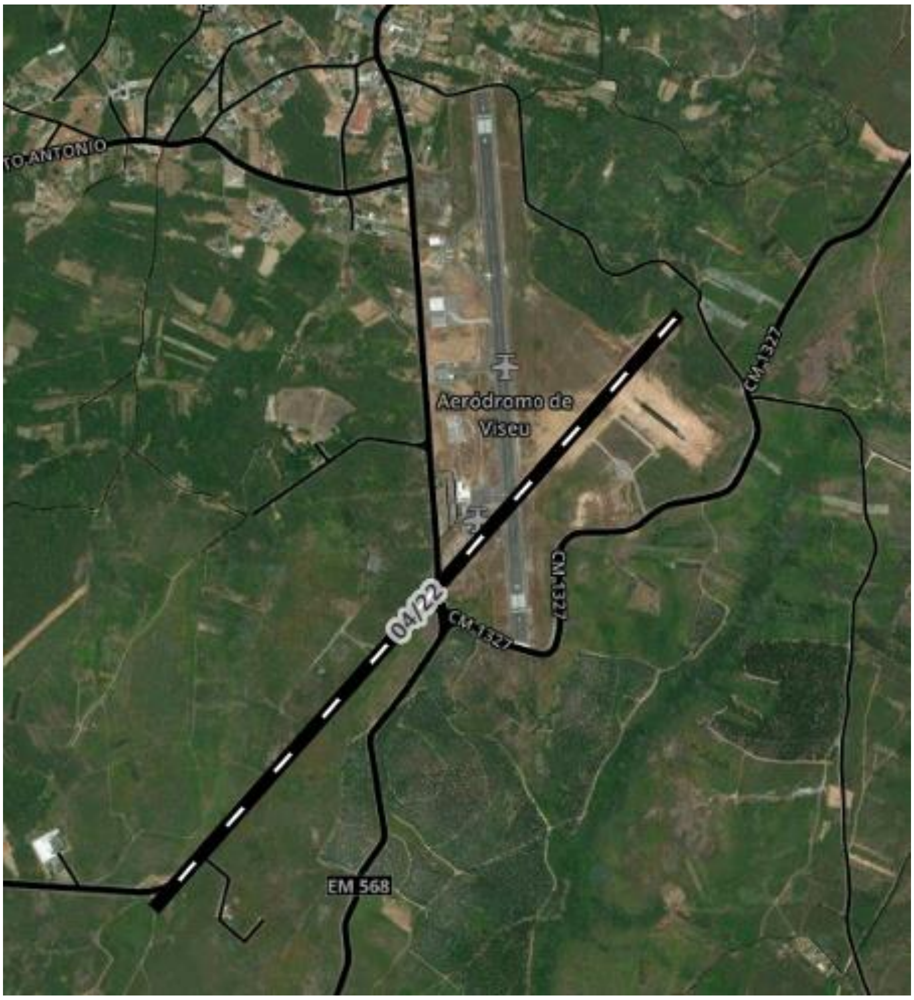


Figure 32 – Segment of a new runway with 04/22 orientation (no real scales)

For both design scenarios, the runway length shall be 1800 m (Medium Turboprop Airliners) and 2500 m (Medium Jet Airliners). Building a new runway has two clear advantages: build a pavement using the latest aircraft engineering techniques; and avoid crosswind, opting for a parallel orientation to the prevailing winds in the region.

The new runway, with orientation 04/22, was calculated with the same soil characteristics of the existing runway. It is expected that there are no significant changes about soils in the same zone. Therefore, the structure of the new pavement designed for Medium Turboprop Airliners is shown in Figure 33.

Layer Material	Thickness (mm)	Modulus or R (MPa)
P-401/ P-403 HMA Surface	101,6	1.378,95
P-401/ P-403 St (flex)	127,0	2.757,90
P-209 Cr Ag	150,0	276,34
Subgrade	CBR = 10,0	103,42

Total thickness to the top of the subgrade, t = 378,6 mm

Figure 33 – New pavement, intermediate loading - Medium Turboprop Airliners

This runway must have a usable length of 1800 m for landings and takeoffs and must follow FAA guidelines for the other geometric elements. In this scenario, the new runway has a total thickness of 37.9 cm with 15.0 cm of the granular layer, 12.7 cm of bituminous layer, and 10.2 cm of wear layer. For practical purposes, the new runway (Figure 34) must have a total thickness of 38.5 cm with 15.0 cm of the granular layer, 13.0 cm of bituminous layer, and 10.5 cm of wear layer.

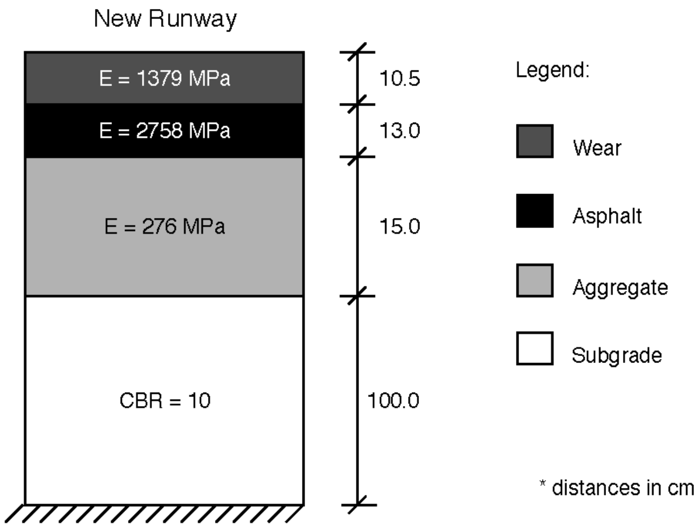
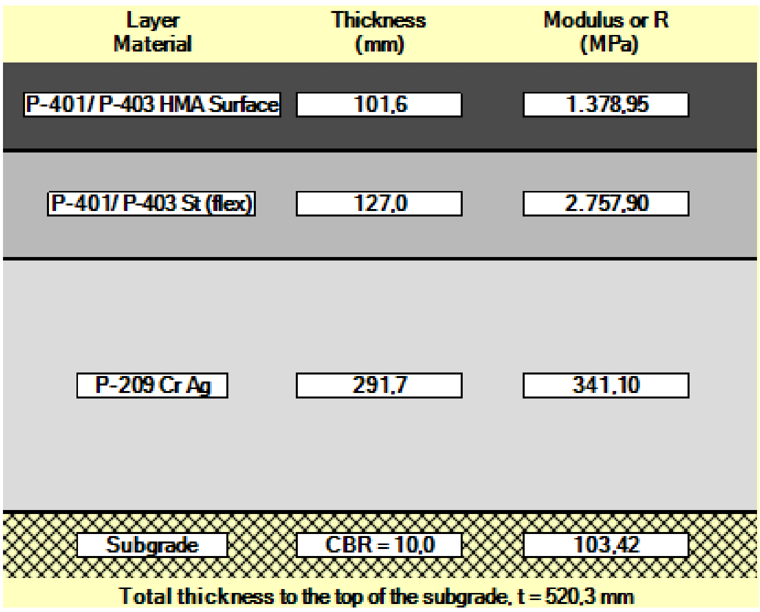


Figure 34 – Final structure dimensioned - Medium Turboprop Airliners

For a sturdy design (Medium Jet Airliners), the new runway should be 2500 m, being a runway with a standard for medium-haul regional and even international flights. This structure has been calculated, and its result can be seen in Figure 35.



Layer Material	Thickness (mm)	Modulus or R (MPa)
P-401/ P-403 HMA Surface	101,6	1.378,95
P-401/ P-403 St (flex)	127,0	2.757,90
P-209 Cr Ag	291,7	341,10
Subgrade	CBR = 10,0	103,42

Total thickness to the top of the subgrade, t = 520,3 mm

Figure 35 – New pavement, larger loading - Medium Jet Airliners

This pavement to receive the robust scenario has approximately 52.0 cm, with 29.2 cm of the granular layer, 12.7 cm of bituminous layer, and 10.2 cm of the wear layer. For practical purposes, the new runway (Figure 36) must have a total thickness of 53.0 cm with 29.5 cm of the granular layer, 13.0 cm of bituminous layer, and 10.5 cm of wear layer.

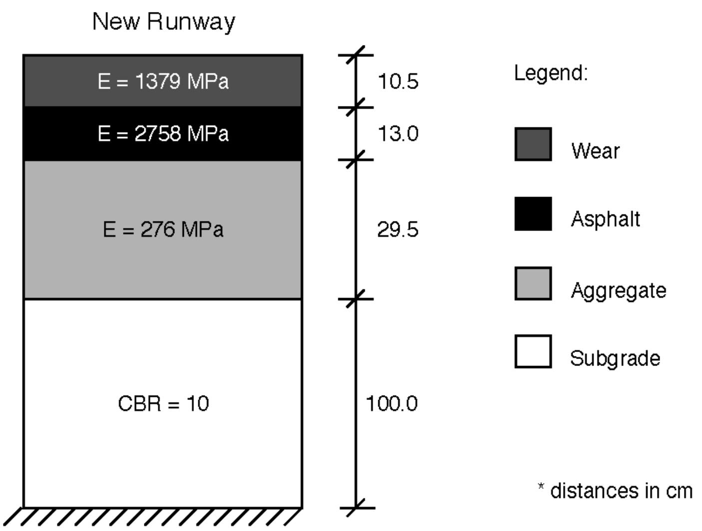


Figure 36 – Final structure dimensioned - Medium Jet Airliners

In addition to the plan to build a new 2500 m runway with a total layer thickness of 53.0 cm (all layers on top of the subgrade), another option has been devised, which is to build a runway at two different times. Initially, an 1800 m runway would be built capable of receiving Medium Turboprop Airliners. In a later stage, the pavement would be extended up to 2500 m and receive an overlay, as shown in Figure 37.

Layer Material	Thickness (mm)	Modulus or R (MPa)
P-401/ P-403 HMA Overlay	84,3	1.378,95
P-401/ P-403 HMA Surface	101,6	1.378,95
P-401/ P-403 St (flex)	127,0	2.757,90
P-209 Cr Ag	150,0	276,34
Subgrade	CBR = 10,0	103,42
Total thickness to the top of the subgrade, t = 462,9 mm		

Figure 37 – New pavement built in two steps, larger loading - Medium Jet Airliners

For practical purposes, the new runway (Figure 38) must have a total thickness of 47.0 cm with 15.0 cm of the granular layer, 13.0 cm of bituminous layer, 10.5 cm of wear layer, and 8.5 cm of overlay.

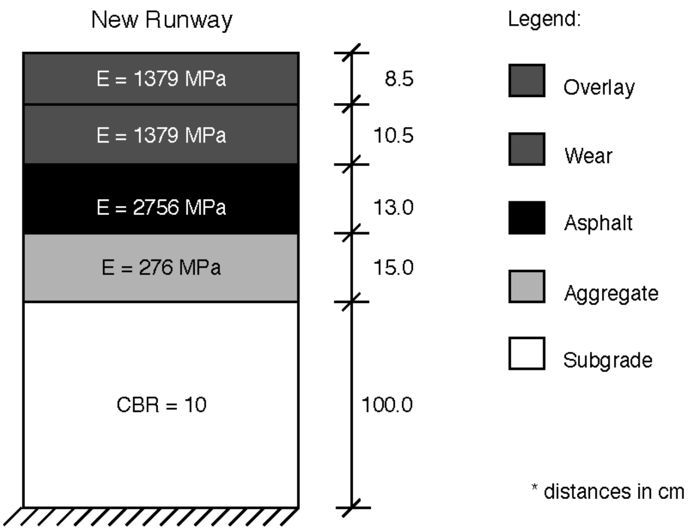


Figure 38 – Final structure dimensioned (overlay) - Medium Jet Airliners

This is a hypothetical design since, at the time of overlay, the pavement should probably not have the same structural design characteristics. So, a loss of structural capacity was simulated as shown in Figure 39.

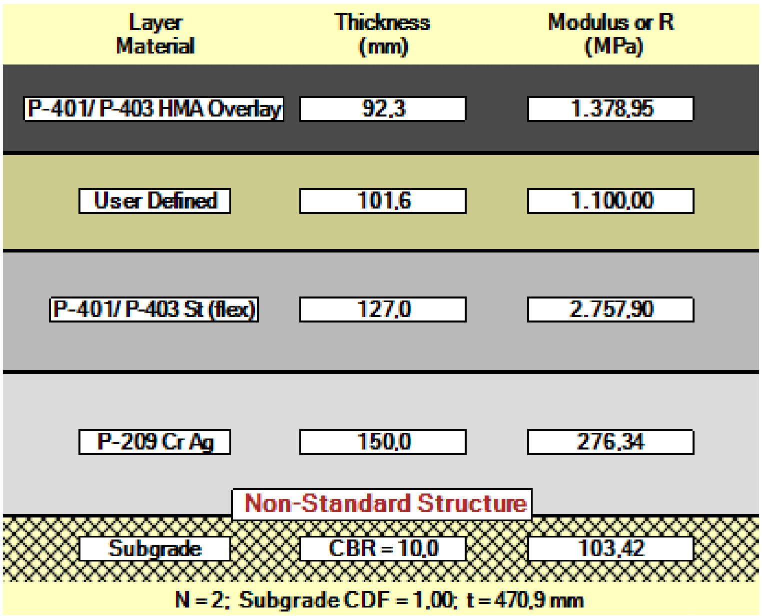


Figure 39 – New pavement built in two steps (loss of structural capacity), larger loading - Medium Jet Airliners

This pavement designed in two steps has a total of 47.1 cm, with 15.0 cm of the granular layer, 12.7 cm of bituminous layer, 10.2 cm of the wear layer and a 9.2 cm overlay.
For practical purposes, the new runway (Figure 40) must have a total thickness of 48.0 cm with 15.0 cm of the granular layer, 13.0 cm of bituminous layer, 10.5 cm of wear layer (loss of structural capacity), and 9.5 cm of overlay.

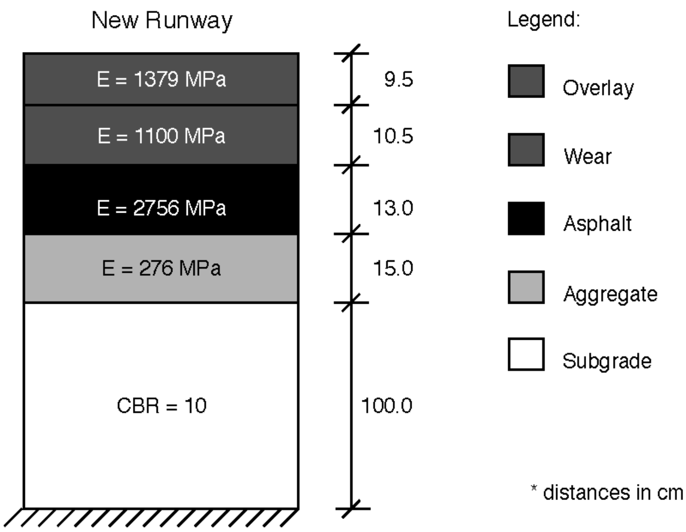


Figure 40 – Final structure dimensioned (loss of structural capacity) - Medium Jet Airliners

In this option, the layer was designed to receive Medium Turboprop Airliners (approximately PCN 23) and lost structural capacity. This drop was made possible by lowering the module from 1,378.95 MPa (FAA standard) to 1,100 MPa. In this scenario, the overlay grew from 8.5 cm to 9.5 cm.

3.6 Final Considerations

The Viseu Aerodrome (LPVZ) has the potential to strengthen the Central Portugal region and may also serve the Interior region and even as a low-cost alternative to Porto Airport.

In the scenario maintaining the current infrastructure, the possible coverage of the LPVZ would be from mainland Portugal, Spain, and a portion of southern France (Figure 25). However, the aircrafts would be limited to the Dornier 228-200 (19 passengers) or smaller aircrafts. This limitation imposes a cost-benefit ratio that is difficult to maintain without the state subsidy, as it is currently the case with Seven Air's operation.

Two scenarios were created where the current infrastructure improved with the construction of a new runway with orientation 04/22, in this orientation, there is already a 500 m runway built on compacted soil (Ferreira et al., 2009).In this option, the pavement is designed to support Medium Turboprop Airliners (intermediate scenario) and Medium Jet Airliners (robust scenario), which already allows flights to almost all Shengen space (Figure 26). With smaller aircrafts (50 to 70 passengers) in the intermediate scenario and larger aircrafts (up to 200 passengers) in the robust scenario. In this alternative, the existing runway would be used for Viseu Aero Clube, Civil Protection, and other flights, and the new runway would be used for commercial flights.

Also, for the robust scenario, the construction of the new runway was phased out, with an initial stage where the LPVZ would operate in the intermediate scenario and then would go for the robust option. This possibility is very promising and depends on complementary studies of the economic and market order.

It should be noted that for engineering work at this time, it is advisable to re-evaluate the current runway condition, as well as the existing soil and auxiliary infrastructures, this being a preliminary study and not a guide for the design of the Aerodrome runways.

4. CONCLUSIONS

The pursuit for the sustainability of the airport infrastructure operation is an engineering challenge, in this sense, the runway pavements are of vital importance. This dissertation offers a simple and straightforward approach with best practices for airport pavement design. Finally, it focused on the application of a case study for Viseu Aerodrome. This aerodrome is operating at a reduced scale with the daily operation of a Regional Airline connecting Bragança, Vila Real, Viseu, Cascais, and Portimão. This is an asset to the region and proves that there is a demand for more significant airport infrastructure.

The Portuguese Airline Industry is under pressure from the increase in demand, as well as the Central and Inland regions of Portugal need investment to avoid being left between the two major poles that are Lisbon and Porto. In response, this study focused on upgrading the Viseu Aerodrome (LPVZ) to operate larger aircrafts that enable new routes to be opened and cost-effective operation.

Therefore, to improve the LPVZ runway, three scenarios were created. The first scenario is to maintain the current operation, ensuring the pavement quality for the next 20 years. The second scenario focuses on the operation of Medium Turboprop Airliners, which are aircrafts that carry between 50 and 70 passengers and have a range of 1500 kilometers. In the third scenario, we seek to operate Medium Jet Airliners, which are aircrafts that carry up to 200 passengers and have a range of over 6000 kilometers.

To maintain the current operation, the existing runway (orientation 18/36) must be reinforced. Based on the backcalculation developed in this dissertation, it was concluded that the existing pavement presents two distinct behaviors in relation to its structural capacity. Therefore, the designing for this scenario was 5.5 cm overlay between 0+000 to 0+450 and 7.0 cm overlay between 0+476 to 1+100.

In the scenario for the operation of Medium Turboprop Airliners, it is necessary to build a new 1800 m runway. So, it is suggested that this runway be 04/22 oriented. In this design, the new runway has a total thickness of 38.5 cm with 15.0 cm of the granular layer, 13.0 cm of bituminous layer, and a 10.5 cm wear layer.

Finally, a third scenario was created, named robust scenario, in which the pavement was designed to receive Medium Jet Airliners. In this case, the pavement has a structure of approximately 53.0 cm, with 29.5 cm of the granular layer, 13.0 cm of bituminous layer, and 10.5 cm of the wear layer.

However, the construction of this runway was also designed in two stages, with the first stage being precisely the same as the previous design (1800 m in length and a total thickness of 38.5 cm). Later, the runway should reach the final characteristic, with 2500 m and structural capacity for aircraft up to 82.2 tons. This pavement designed in two steps has a total of 48.0 cm, with 15.0 cm of the granular layer, 13.0 cm of bituminous layer, 10.5 cm of the wear layer and a 9.5 cm overlay.

To develop this study, the most modern airport pavement design techniques were applied. In this sense, the contribution of this dissertation was the study of the best practices for the design of airport pavements and the application of these practices to a case study in Portugal.

There are several directions for future research. This work focused only on the design of the pavement, and it is necessary to analyze all economic and market issues, as well as the actual impacts on the Central and Interior regions of Portugal. Similarly, other elements of airport infrastructure can be addressed. Finally, it would be interesting to study possible connections to newly created routes, generating a network with larger and denser coverage.

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Attachments 1 - HWD (2m Left)

Identification	
Aerodrome	Viseu
Runway	18/36
Alignment	2m Left

Load	
Force	150 kN
Plate Diameter	450 mm
Pressure	943 kPa

Legend	
Above the percentile 85	Value
Value considered for section	Value

Geophones	D1	D2	D3	D4	D5	D6	D7	D8	D9
Distance (m)	0.00	0.30	0.45	0.60	0.90	1.20	1.50	1.80	2.10

	Normalized Deflections (µm)									Temperatures (°C)			
Pk	D1	D2	D3	D4	D5	D6	D7	D8	D9	Air	Surface	Depth	Hour
0+000	1906	1226	881	643	337	167	94	62	48	19.2	16.9	24.6	07:42
0+025	1465	892	647	455	229	109	57	34	26	19.2	16.9	24.6	07:42
0+050	987	517	331	211	88	40	29	25	22	19.3	16.8	24.6	07:43
0+075	1470	675	396	234	96	69	67	64	58	19.2	16.7	24.6	07:44
0+100	2489	1310	837	546	236	119	85	70	63	19.6	16.9	24.6	07:44
0+126	2884	1718	1123	749	353	196	138	108	91	19.9	17,0	24.6	07:45
0+152	2804	1610	1059	724	373	227	169	139	110	19.8	17.2	24.6	07:45
0+177	1439	701	411	243	88	50	43	39	33	19.9	17.3	24.6	07:46
0+202	910	277	125	64	32	32	31	29	25	20.1	17.4	24.6	07:47
0+227	2029	1248	820	546	259	137	95	67	60	20.1	17.5	24.6	07:47
0+251	1952	1019	620	379	152	88	72	60	54	20.4	17.5	24.6	07:48
0+276	3062	1817	1178	778	330	141	80	58	47	19.7	17.6	24.6	07:48
0+300	2017	1093	675	419	157	58	31	26	23	18.7	17.4	24.6	07:49
0+326	973	350	181	101	54	46	42	36	31	19.2	17.5	24.6	07:50
0+350	1590	810	463	268	93	41	29	24	21	19,0	17.5	24.6	07:50
0+378	3174	2357	1742	1308	754	442	293	209	165	19,0	17.6	24.6	07:51
0+400	2029	988	575	334	113	46	29	20	19	18.9	17.7	24.6	07:51
0+426	2105	1027	600	344	111	44	28	22	17	19.1	17.7	24.6	07:52
0+450	3217	2184	1579	1179	679	402	259	188	134	19.1	17.7	24.6	07:52
0+476	3602	2746	1999	1497	909	577	403	307	239	19,0	17.8	24.6	07:53
0+500	4290	2655	1823	1290	682	386	257	195	152	19.1	17.7	24.6	07:54
0+525	3735	2216	1467	987	479	277	198	149	132	19.3	17.8	24.6	07:54
0+552	3665	2207	1476	1014	504	295	211	159	144	19.5	17.8	24.6	07:55
0+578	3864	2291	1495	993	465	260	186	147	138	19.9	17.9	24.6	07:55
0+601	5078	2710	1767	1195	539	280	193	157	136	20.2	18,0	24.6	07:56
0+628	3983	2179	1478	1027	513	291	202	150	143	20.6	17.9	24.6	07:56
0+655	3019	2099	1407	973	500	308	233	204	170	20.7	17.9	24.6	07:57
0+675	4459	2339	1531	1031	511	311	239	192	154	20.7	17.8	24.6	07:57
0+700	3077	2811	1805	1203	587	347	256	221	167	21.1	17.8	24.6	07:58
0+725	3962	2771	1809	1223	607	359	249	203	174	20.8	17.7	24.6	07:59
0+751	5331	3650	2517	1798	928	510	357	265	202	21.1	17.6	24.6	07:59
0+775	3478	3697	2567	1840	929	503	333	251	220	21.2	17.6	24.6	08:00
0+801	5227	2059	1187	683	239	137	105	65	70	20.8	17.6	24.6	08:00
0+828	3856	1984	1203	755	334	192	140	112	86	20.6	17.7	24.6	08:01
0+850	5181	3328	2149	1429	626	294	172	107	81	20.6	17.5	24.6	08:01
0+877	5352	2558	1579	967	317	113	86	87	64	20.4	17.5	24.6	08:02
0+900	5147	3724	2487	1672	722	379	277	222	199	20.3	17.5	24.6	08:03
0+926	3410	2977	2020	1416	681	371	263	221	175	20.3	17.4	24.6	08:03
0+951	3503	2781	1971	1407	755	410	282	223	187	20.2	17.4	24.6	08:04
0+975	3745	3627	2500	1718	683	359	231	182	145	20.4	17.6	24.6	08:04
1+000	4210	2950	2068	1480	742	380	243	181	157	20.6	17.7	24.6	08:05
1+025	3628	3290	2340	1715	910	490	305	224	155	20.9	17.8	24.6	08:05
1+050	4771	2993	2152	1576	857	455	290	213	179	20.7	17.5	24.6	08:06
1+075	2723	1915	1457	1122	673	397	255	176	136	20.7	17.3	24.6	08:07
1+100	2451	1749	1321	1028	615	375	263	205	169	20.3	17.1	24.6	08:07

Attachments 1 - HWD (Centerline)

Identification	
Aerodrome	Viseu
Runway	18/36
Alignment	Centerline

Load	
Force	150 kN
Plate Diameter	450 mm
Pressure	943 kPa

Legend	
Above the percentile 85	Value
Value considered for section	Value

Geophones	D1	D2	D3	D4	D5	D6	D7	D8	D9
Distance (m)	0.00	0.30	0.45	0.60	0.90	1.20	1.50	1.80	2.10

	Normalized Deflections (µm)									Temperatures (°C)			
Pk	**D1**	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**	**D9**	**Air**	**Surface**	**Depth**	**Hour**
0+000	1698	1111	798	579	312	161	92	62	47	17.6	17.6	24.6	06:39
0+026	962	533	357	238	105	45	27	20	17	17.7	17.7	24.6	06:40
0+050	832	413	264	166	69	32	22	16	14	17.8	17.6	24.6	06:40
0+075	1790	1120	774	535	260	129	80	58	46	18,0	17.4	24.6	06:41
0+101	1562	941	632	421	187	88	59	49	45	8.2	17.4	24.6	06:42
0+125	2879	1754	1168	798	380	202	138	112	98	18.4	17.4	24.6	06:42
0+150	3975	2170	1453	1001	504	291	212	169	133	18,0	17.5	24.6	06:44
0+175	1490	677	387	231	96	57	49	47	42	8.2	17.6	24.6	06:44
0+200	2603	1565	1021	682	306	150	97	70	54	17.3	17.4	24.6	06:45
0+226	1285	561	306	173	69	43	39	37	32	16.9	17.4	24.6	06:46
0+252	1370	616	349	200	78	52	49	47	41	16.7	17.4	24.6	06:46
0+275	2279	1381	907	601	260	112	61	38	35	16.8	17.4	24.6	06:47
0+301	2286	1417	928	609	239	87	43	34	28	17.4	17.4	24.6	06:47
0+326	2326	1383	867	534	183	64	39	32	28	18.1	17.3	24.6	06:48
0+351	2426	1191	697	417	154	64	45	38	32	18.1	17.1	24.6	06:49
0+375	2253	1312	857	573	253	116	69	46	37	18.5	17.2	24.6	06:49
0+401	2179	1087	609	340	91	28	23	23	21	18.2	17,0	24.6	06:50
0+427	1924	989	573	335	108	36	22	20	15	18.2	17,0	24.6	06:50
0+450	4453	2441	1782	1335	770	455	305	231	166	18.1	7.2	24.6	06:51
0+475	4042	2900	2116	1614	989	617	425	305	223	17.7	17.4	24.6	06:52
0+500	4373	2892	2061	1498	815	453	292	216	158	17.3	17.4	24.6	06:52
0+526	4166	2313	1526	1049	525	298	208	162	129	17.3	17.4	24.6	06:53
0+550	3816	2303	1479	978	459	255	178	133	113	17.5	17.5	24.6	06:53
0+575	3929	2436	1605	1086	520	291	201	157	116	18.1	17.5	24.6	06:54
0+602	4938	2713	1782	1192	532	279	197	154	128	18.5	17.6	24.6	06:55
0+625	3900	2332	1581	1096	538	286	198	145	127	18.2	17.6	24.6	06:55
0+650	3809	2192	1436	974	502	310	237	193	149	18,0	17.6	24.6	06:56
0+675	3092	2088	1474	1062	564	320	225	177	143	8.1	17.5	24.6	06:57
0+700	3626	2318	1586	1106	577	339	246	193	157	18.1	17.2	24.6	06:57
0+726	3982	2753	1831	1257	646	372	262	194	155	18.2	17.1	24.6	06:58
0+750	4640	3396	2401	1742	903	494	328	260	195	18.3	17.1	24.6	06:59
0+775	5081	3546	2426	1707	858	468	315	230	203	18.5	17.1	24.6	06:59
0+801	2722	1526	909	541	214	116	86	74	65	18.6	17.1	24.6	07:00
0+825	2879	1703	1138	775	379	212	145	105	91	18.6	17.1	24.6	07:00
0+850	4704	2929	1960	1321	602	287	177	129	100	18.7	17.1	24.6	07:01
0+876	6990	3410	2215	1457	580	279	206	150	144	18.8	17.2	24.6	07:02
0+900	3890	3781	2604	1833	904	467	303	220	188	19,0	17.1	24.6	07:02
0+926	4032	2981	2077	1479	752	409	279	214	190	8.9	16.9	24.6	07:03
0+950	4620	2950	2111	1548	844	470	311	241	200	18.8	16.8	24.6	07:03
0+975	4904	3612	2562	1819	833	454	285	224	170	18.8	16.8	24.6	07:04
1+000	2955	2161	1611	1211	684	376	238	182	143	18.8	16.7	24.6	07:05
1+025	5184	3282	2298	1664	861	458	293	211	160	18.6	16.8	24.6	07:05
1+050	3566	3288	2404	1803	1013	543	340	216	173	18.5	16.7	24.6	07:06
1+075	2507	1784	1364	1069	663	406	269	194	149	18.6	16.7	24.6	07:06
1+100	1331	1473	1153	920	599	387	267	195	149	18.5	16.8	24.6	07:07

Attachments 1 - HWD (2m Right)

Identification	
Aerodrome	Viseu
Runway	18/36
Alignment	2m Right

Load	
Force	150 kN
Plate Diameter	450 mm
Pressure	943 kPa

Legend	
Above the percentile 85	Value
Value considered for section	Value

Geophones	D1	D2	D3	D4	D5	D6	D7	D8	D9
Distance (m)	0.00	0.30	0.45	0.60	0.90	1.20	1.50	1.80	2.10

	Normalized Deflections (µm)									Temperatures (°C)			
Pk	**D1**	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**	**D9**	**Air**	**Surface**	**Depth**	**Hour**
0+000	1570	1107	820	612	331	167	93	61	49	18.4	16.6	24.6	07:12
0+025	902	526	366	250	109	44	24	19	17	18.5	16.7	24.6	07:12
0+050	872	472	316	210	97	41	23	18	14	18.5	16.7	24.6	07:13
0+076	1836	1232	881	629	307	143	84	64	55	18.4	16.7	24.6	07:14
0+100	1607	908	613	412	180	86	59	51	46	18.2	16.8	24.6	07:14
0+126	2665	1589	1055	712	343	192	136	102	92	18.3	16.8	24.6	07:15
0+152	2634	1698	1164	817	422	241	174	138	112	18.3	16.7	24.6	07:15
0+177	1286	648	397	250	111	67	55	51	45	18.2	16.5	24.6	07:16
0+200	2412	1305	818	528	246	136	94	69	60	18.2	16.5	24.6	07:17
0+225	2587	1708	1178	822	383	177	100	71	51	18.2	16.5	24.6	07:17
0+251	1409	713	430	259	102	59	50	44	39	18.1	16.4	24.6	07:18
0+275	2281	1422	947	629	266	103	44	28	18	18.1	16.4	24.6	07:18
0+301	1932	1009	570	319	91	43	42	42	39	18.1	16.4	24.6	07:19
0+325	1180	498	269	148	59	40	34	30	26	18.2	16.6	24.6	07:20
0+351	1761	961	578	340	119	52	33	25	25	18.1	16.7	24.6	07:20
0+376	2347	1381	877	549	210	89	54	46	34	18.2	16.7	24.6	07:21
0+400	1051	472	259	137	53	37	32	26	23	18.1	16.8	24.6	07:21
0+425	1737	913	541	315	94	28	19	18	17	18.1	16.7	24.6	07:22
0+452	4165	2510	1883	1457	877	540	357	251	199	18.2	16.8	24.6	07:23
0+478	3673	2781	2013	1516	910	560	378	276	229	18.4	16.8	24.6	07:23
0+500	4072	2739	1930	1424	774	444	291	197	177	18.3	16.8	24.6	07:24
0+526	3730	2188	1496	1049	532	294	205	161	133	18.2	16.7	24.6	07:24
0+550	5118	2495	1580	1004	411	209	137	89	62	18.2	16.7	24.6	07:25
0+576	3602	2325	1511	1014	469	254	184	149	132	18.2	16.8	24.6	07:26
0+600	4295	2516	1635	1091	497	274	188	152	120	18.2	16.9	24.6	07:26
0+626	3757	2145	1459	1007	500	277	196	155	134	18.3	17.1	24.6	07:27
0+650	3433	2265	1509	1036	530	308	225	182	169	18.4	17,0	24.6	07:27
0+676	2845	2427	1631	1130	572	348	251	210	171	18.6	17,0	24.6	07:28
0+701	3706	2311	1555	1087	559	328	234	183	163	19.3	17,0	24.6	07:28
0+726	3997	2854	1782	1187	575	346	258	202	156	19.5	17.1	24.6	07:29
0+750	4534	3441	2319	1616	776	418	265	206	178	19.4	17.1	24.6	07:30
0+775	6288	3372	2271	1566	777	435	297	249	185	19.8	17.1	24.6	07:30
0+801	2698	1538	963	617	285	174	129	94	79	19.6	17.3	24.6	07:31
0+826	4819	2748	1657	1116	489	240	151	115	92	19.9	17.2	24.6	07:31
0+851	2903	1876	1090	635	227	113	87	69	56	20,0	17.3	24.6	07:32
0+877	4580	3753	2424	1609	666	334	233	190	150	19.9	17.3	24.6	07:33
0+901	4438	3833	2585	1808	923	501	311	224	194	19.6	17.3	24.6	07:34
0+925	3972	2809	1909	1330	680	383	267	205	183	19.7	17.3	24.6	07:34
0+950	3150	2497	1895	1465	860	491	314	226	168	19.5	17.2	24.6	07:35
0+975	4371	3478	2410	1693	868	438	257	190	158	19.3	17.2	24.6	07:35
1+000	3111	2333	1728	1300	722	392	237	164	145	19.1	17.3	24.6	07:36
1+026	4380	3195	2270	1662	878	464	284	192	156	18.7	17.4	24.6	07:37
1+050	4807	3219	2324	1703	867	462	288	222	171	18.3	17.3	24.6	07:37
1+076	2032	1539	1218	980	637	400	265	187	145	18,0	17.3	24.6	07:38
1+100	2052	1512	1182	944	604	391	276	194	143	17.7	17.2	24.6	07:39