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REDUCTION OF SUBGRADE VERTICAL DEFORMATION IN RUNWAYS WITH THE USE OF SEMI-RIGID PAVEMENT

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ABSTRACT

The degradation of airfield pavements, which is commonly attributed to vertical deformation at the top of the subgrade, can be influenced by factors such as aircraft operation, climate variation, and soil characteristics. Cement incorporation in base or subbase layers tends to increase the resistance and the durability of these pavements but can also lead to the emergence of distresses such as block cracking. In this sense, this technical paper analyzed whether the cement incorporation, when applied in the base or in the subbase layers, results in a reduction of vertical deformation at the top of the subgrade, and an increase in the service life of runways. To this end, five runways with distinct combinations of layer thicknesses and materials were studied. Among these structures are included semi-rigid and flexible pavements with various compositions of base and subbase layers. Six aircraft models with different maximum takeoff weights, landing gear types, and tire pressures were selected aiming to simulate the airport operations. The results indicated that semi-rigid pavements constructed with Cement Treated Crushed Stone or Soil-Cement subbases were more effective in reducing vertical deformation and in the assurance of service life when compared to the flexible structure or to the other semi-rigid combinations. It is concluded that the use of base or subbase layers constructed with cement-added materials leads to reduction in vertical deformations. Thus, it is indicated that semi-rigid pavements could be an option for runways, improving their performance in terms of resistance to vertical deformations when compared to flexible structures.

Keywords: Airfield pavement, Structural performance, Service life, Hydraulic binders.

GENERATIVE AI USAGE STATEMENT

The authors declare that the use of generative AI tools was restricted to technical support activities, without compromising the originality, analysis, or conclusions presented in the work. All information obtained through these resources was carefully evaluated and integrated into the study, ensuring methodological rigor and academic integrity. ChatGPT was used to review English grammar and improve sentence clarity.

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1 INTRODUCTION

One of the main factors which contribute to degradation and service life reduction of an airfield pavement is the vertical deformation at the top of the subgrade. Many factors can cause these deformations, including the aircraft operations and associated cargo loads, climate variations, and soil characteristics (Yoder and Witczak, 1975). In this context, it is necessary to verify, using the vertical deformation at the top of the subgrade, whether the addition of cement in base and subbase layers influences the reduction of vertical deformation, which contributes to the increase of the service life of airfield pavements. This reduction of deformations is conditioned on the strict compliance with the constructive and dosage parameters (Balbo and Cargnin, 2023), thereby optimizing both the resistance and the durability of the pavement.

White (2019) confirmed this approach, showing that although fatigue cracking induced by the tensile stress at the bottom of the Asphalt Concrete (AC) surface layer being a worry, they rarely occur in airfield pavements. It is mainly due to the low load repetition these pavements are subjected to when compared to highway pavements. Thus, the use of appropriate hydraulic binders such as Portland cement, lime, or fly ashes in base or subbase granular layers is a strategy to mitigate the deformations in the structure, increasing the service life of airfield pavements.

The treatment of base or subbase layers using Portland cement can reduce vertical deformations at the top of the subgrade because the stabilization of aggregates or soils with Portland cement is an effective technique to increase the stiffness of base and subbase layers (Saxena *et al.*, 2010). Furthermore, the addition of cement to the granular material can improve the fatigue behavior of the asphalt layer and reduce vertical deformation at the top of the subgrade. Given the above, the present technical paper aims to evaluate if there are differences of vertical deformation at the top of the subgrade and of service life of runways whose base or subbase layers use Portland cement.

1.1 Literature Review

The semi-rigid pavements, as described by Balbo and Cintra (1993), are characterized by the inclusion of a layer constructed with hydraulic binder-stabilized material, presenting an intermediate structural behavior between flexible pavements and rigid pavements. Depending on the cement content used to stabilize the material, distinct nomenclatures can be adopted: the Cement Treated Crushed Stone (CTCS) and the Soil Cement are two materials whose main differences are their gradation and cement content.

According to Saxena *et al.* (2010), base and subbase layers may consist of cemented materials. These layers can be used in pavements that present both the asphalt hot mixes and the Portland cement concrete.

The stabilization, still according to Saxena et al. (2010), is one of the most efficient and widely adapted techniques for increasing the stiffness of layers of pavements because it promotes the reduction of stresses in upper layers, and of subgrade deformation. The Long-Term Pavement Performance counted a total of 143 stabilized sections when considering 29 states in the United States, the whole Puerto Rico, and 7 provinces in Canada, which characterizes the stabilization as a consolidated technique. In the United States this practice is particularly well known, having been recorded 1,050 km of semi-rigid pavements in the period from 2001 to 2003 according to the Louisiana Department of Transportation and Development.

A remarkable consequence of this addition of hydraulic binder is the tendency of the stabilized layer to contract (influenced by the moisture loss), to hydration processes, and to other environmental factors. This contraction can lead to the development of transverse cracks in stabilized base or subbase layers. These cracks present the potential to be reflected through thin asphalt surface layers. However, since airfield pavements tipically have more robust and thicker AC surface layers when compared to highway pavements, this situation of crack reflection is mitigated. (Deilami and White, 2018). Rabaiotti, Tsirantonaki, and Schnyder (2017) affirm that it is not possible to guarantee that cracks formed in stabilized layers can reach the top of the AC surface layer.

Another problem that can occur is when the stiffness of a stabilized base layer is higher than that of the AC surface layer (since it presents a thin thickness). This scenario can create a peculiar stress distribution significantly influenced by thermal effects, which can eventually enhance the disaggregation between layers with the appearance of block cracks (Saxena *et al.*, 2010).

Thereby, Majarrez (2013) affirms that cement treated layers, especially base layers, need to be protected by a specific AC surface layer thickness aiming to facilitate homogeneous distribution of traffic loads as well as to absorb part of the cracks that will inevitably appear. As said by Su *et al.* (2017), the daily thermal variation is the main cause of these cracks that reflect to the AC surface layer when the pavement presents chemical stabilized base layers. It was also verified that a cement-added layer is greatly responsible for the final stiffness of the pavement structure, being able to reduce the subgrade deformation by around 40%.

Through the advancement of computer technology, it has become possible to investigate and analyze the structural behavior of airfield pavements. According to Sun *et al.* (2024), the mechanistic methods, including layered elastic analysis and finite element modeling (FEM), are generally used in the design of highway and airfield pavements through the use of software working with linear-elastic model or FEM to evaluate stresses and deformations induced by loads applied in the pavement layers. Thus, the behavior of the pavements must be analyzed as a function of permanent deformation (controlled by the vertical deformation at the top of the subgrade), and of fatigue cracking determined by horizontal tension at the bottom of the AC surface layer.

It is worth highlighting that Kim and Tutumler (2008), applying FEM, studied the effects of the multiple wheel load interaction as the magnitude and direction of deflections in the pavement layers (including subgrade) of an airfield pavement subjected to the loading of real aircraft traffic. They found that the pavement deformations are mainly caused by vertical deformation of the subgrade which can be alleviated by building a thicker base layer.

The vertical deformations acting in a pavement structure are important in the verification of possible failure of granular layers since the occurrence of plastic deformation can compromise the structure. These failure criteria include tension deformation at the bottom of the AC surface layer, and compressive deformation at the top of the subgrade. Thereby, failure criteria for airfield pavement defined by FAA (2009) are the permanent deformation, and fatigue.

For AAA (2017), there are three pavement responses that must be monitored when an airfield pavement is subjected to a load application: (i) deflection – is the absolute displacement value presented by a given point of the pavement when the load is applied, generally about 1.0 mm to 2.0 mm; (ii) tension – is the force divided by the area and it is equivalent to the tire pressure. This tension changes gradually according to the pavement depth and present values about 0.01 MPa to 2.0 MPa; (iii) vertical deformation – is the change on the dimension of a material or layer expressed as a portion of the total length over which the change occurred. It is dimensionless and generally expressed as m/m. The deformation in an airfield pavement has a magnitude order of about 1.0×10^{-3} m/m to 2.0×10^{-3} m/m. Still according to AAA (2017), the pavement deformation is the base to the calculation of the damage caused by an aircraft load as well as of its service life.

In airfield pavements the aircraft used in civil aviation use various configurations of landing gear. In this sense, according to Horonjeff (2010), there are three basic configurations of landing gear:

single wheel, dual wheel, and dual tandem. Tamagusko and Ferreira (2020) affirmed that among the main factors influencing the design of airfield pavements is the way the aircraft applies the loads in the structure. That being said, it is fundamental to understand the geometry or configuration of the aircraft landing gears. In addition to the basic configurations, there are more complex arrangements such as: double dual tandem, triple tandem, and dual tandem plus triple tandem. Figure 1 presents the aforementioned configurations highlighting the dual wheel, dual tandem, and triple tandem arrangements which were used in the development of the present technical paper.

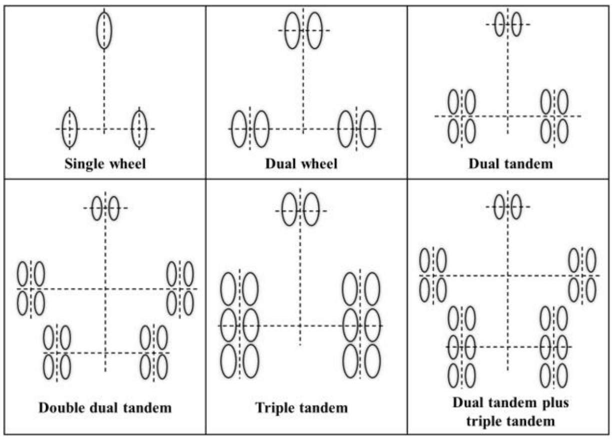


Figure 1: Types of landing gear.

According to Horonjeff (2010), depending on the number of wheels and the distribution of loads on these wheels, the impact of loading on the pavement can have a considerable magnitude that may interfere on the pavement structural design. For airfield pavements the tire pressure of aircraft wheels can commonly reach 1.4 MPa, and the wheel load is around 25.0 tons (AAA, 2017).

Still according to AAA (2017), higher wheel loads, as well as higher tire pressures, demand thicker pavements. Thereby, the airfield pavements are, generally, thicker and must have material of adequate quality. However, Almeida *et al.* (2022) noted that aircraft with higher Maximum Takeoff Weight (MTOW) do not always contribute the most to higher vertical deformations at the top of the subgrade mainly due to the distribution of the aircraft weight by the number of wheels on the landing gear.

Regarding tire pressure, Wesolowsky *et al.* (2020) said that the contact area between tire and pavement is important for the airport operations because the proper load transfer ensures the safety of operations. The contact area also affects the tensions appearing in the pavement structure which can impact its durability. The authors noted that equations commonly used to calculate the tire/pavement contact area generated results different from those obtained in laboratory tests.

Raposo (2017) also affirms that traditional analytical solutions only assume that loads imparted to the pavement have a circular shape. It is worth mentioning that, according to Garg *et al.* (2018), there is a propensity for the aeronautical industry to increase the aircraft range which results in an increase in MTOW and in tire pressure. This propensity influenced aircraft models as Airbus A-380 and A-350, and Boeing B 787, leading to tire pressures of about 1.75 MPa.

2 RESEARCH METHOD

In this technical paper, the structures of five runways were analyzed. The first structure is a typical semi-rigid pavement, composed for an Asphalt Concrete (AC) surface layer, a cement-stabilized base, and a granular subbase. The second pavement analyzed is also a semi-rigid structure whose difference from the first one is the use of a granular base and a cement-stabilized subbase with being kept the AC surface layer. The third pavement is a typical flexible pavement. The two remaining structures are variations of the two first pavements mentioned, with an inversion of the materials used in the base and subbase layers. A flowchart depicting methodological steps is presented in Figure 2.

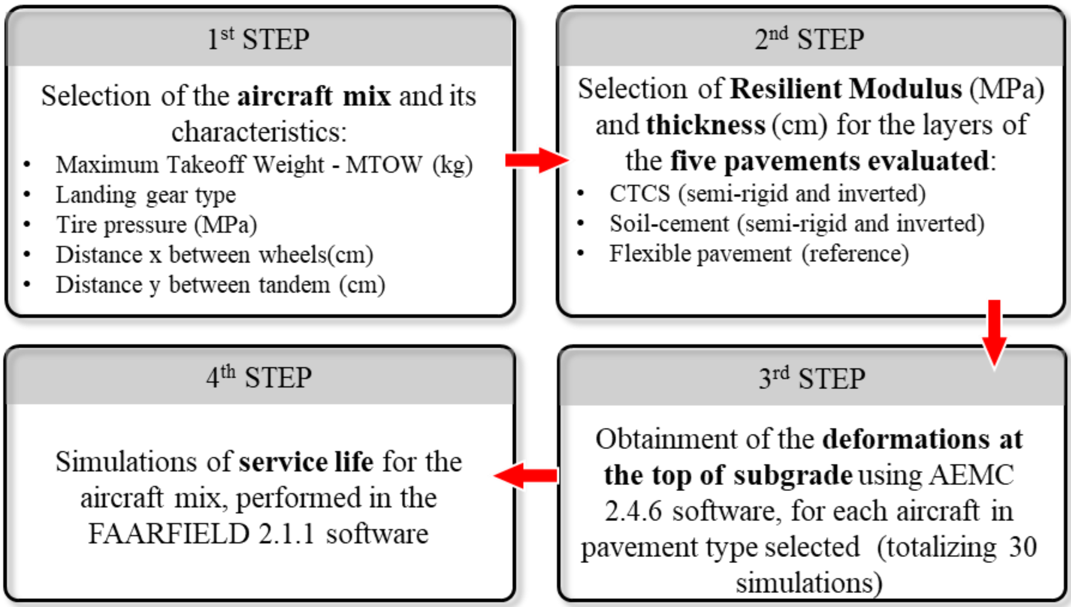


Figure 2: Methodological steps.

Six distinct types of aircraft were chosen, considering factors such as Maximum Takeoff Weights (MTOW), the type of landing gear (Dual Wheel – DW, Dual Tandem – DT, and Triple Tandem – TT), and tire pressure as decision criteria for selecting the aircraft models. From this selection, the vertical deformation at the top of the subgrade and the service life of the pavement structures proposed were analyzed. The characteristics of each aircraft model and the configuration of the five pavements analyzed were inserted in the software AEMC version 2.4.6 (2023) (Elastic Multilayered Analysis). The characteristics of each aircraft model can be seen in Table 1. For the simulation of the service life of the pavements, 1,200 annual departures were considered for each model, and the software FAARFIELD version 2.1.1 was used.

Table 1: Aircraft characteristics

Aircraft Model	MTOW (kg)	Landing Gear Type	Tire Pressure (MPa)	X* (cm)	Y* (cm)
EMB-195 (Embraer)	48,950	DW	1.06	86.40	0.00
A-320 (Airbus)	78,400	DW	1.44	92.70	0.00
B-737-800 (Boeing)	79,242	DW	1.40	86.40	0.00
A-321 (Airbus)	93,900	DW	1.50	92.70	0.00
B-767-400 (Boeing)	204,570	DT	1.48	116.30	137.20
B-777-200 (Boeing)	248,120	TT	1.26	139.70	144.80

* X – Distance between wheels; Y – Distance between tandem

Data for the runways were obtained using the FAARFIELD 2.1.1 software. The Resilient Modulus (RM) values for the surface layer, base, and subbase are standard values. The thicknesses assumed for each layer were 10.0 cm for the AC surface layer, 20.0 cm for the base layer, and 20.0 cm for the subbase layer. The subgrade strength was assumed to be 10% for all the simulations (Table 2). The order of the RM values of base and subbase layers varied according to the configuration of the semi-rigid pavement analyzed.

Table 2: Characteristics of the runways' pavement structures

CTCS (Cement Treated Crushed Stone)		
Layer	**Resilient Modulus (MPa)**	**Thickness (cm)**
Surface Layer (P-401 HMA Surface)	1,378.95	10.0
Base (P-304 Cement treated base)	3,447.38	20.0
Subbase (P-154 Uncrushed aggregate)	275.79	20.0
Subgrade	CBR = 10%	-
Soil-Cement		
Layer	**Resilient Modulus (MPa)**	**Thickness (cm)**
Surface Layer (P-401 HMA Surface)	1,378.95	10.0
Base (P-301 Soil Cement base)	1,723.69	20.0
Subbase (P-154 Uncrushed aggregate)	275.79	20.0
Subgrade	CBR = 10%	-
Flexible Pavement		
Layer	**Resilient Modulus (MPa)**	**Thickness (cm)**
Surface Layer (P-401 HMA Surface)	1,378.95	10.0
Base (P-209 Crushed Aggregate)	517.11	20.0
Subbase (P-154 Uncrushed aggregate)	275.79	20.0
Subgrade	CBR = 10%	-

3 RESULTS AND DISCUSSION

According to the simulations performed, it was observed that the vertical deformations at the top of the subgrade are, in general, lower for semi-rigid pavements that use granular base with subbase constructed with Cement Treated Crushed Stone (CTCS) or soil-cement. For example, for aircraft model EMB-195 the deformation measured was 6.04×10^{-4} m/m in a semi-rigid structure with CTCS subbase whilst the value obtained for a semi-rigid pavement using CTCS in the base layer was equal to 7.14×10^{-4} m/m (see Table 3). These deformations are smaller than those in semi rigid pavements with a combination of granular subbase and CTCS or soil cement base layer. Additionally, the vertical deformations were also lower than those calculated for flexible pavements, which presented vertical deformation of 1.07×10^{-3} m/m when the pavement response for the same aircraft model (EMB-195) was analyzed.

This fact suggests that the semi-rigid pavements (using cement-added subbase) provide surfaces more resistant to the vertical deformations at the top of the subgrade. The higher values of vertical deformation were verified for the flexible pavement (using only granular materials in its layers) because it is the one with the lowest Resilient Modulus (RM) values.

By comparing the values of vertical deformation induced by the aircraft models selected it was possible to perceive EMB-195 as the model creating the least deformations for the pavement structural configurations analyzed. This can be due to its lesser Maximum Takeoff Weight (MTOW) and tire pressure compared to the other models, requiring less mobilization of the pavement layers during the operations. On the other hand, the aircraft models A 321 and B-767-400 (although not presenting the highest MTWO among the six models used) tend to generate the highest deformations in the runways studied. Probably, it is because of the landing gear configuration of the two models, which influences the load distribution on the pavement.

Attention must be paid to tire pressure, as high tire pressures can result in concentrated loads in some parts of the pavement even if the aircraft model has a lower MTWO, leading to greater deformations (see Table 4, and Figures 3 and 4). However, in a general way, it was observed that lower deformations were induced when semi-rigid pavements with cement-added subbase layers were employed as structural solution. Table 3 shows the percentage reduction in vertical deformation generated by each aircraft model when using CTCS or soil-cement in the subbase layers, compared to using these materials in the base layer.

Table 3: Vertical deformations (m/m) at the top of the subgrade

	Scenario 1 CTCS		**Scenario 2 Soil cement**		**Scenario 3 Standard**
	Semi-rigid				**Flexible**
Aircraft	**base**	**subbase**	**base**	**subbase**	**granular**
EMB-195	7.14×10^{-4}	6.04×10^{-4}	8.39×10^{-4}	7.59×10^{-4}	1.07×10^{-3}
A-320	1.10×10^{-3}	9.38×10^{-4}	1.29×10^{-3}	1.18×10^{-3}	1.65×10^{-3}
B-737-800	1.13×10^{-3}	9.60×10^{-4}	1.33×10^{-3}	1.20×10^{-3}	1.68×10^{-3}
A-321	1.30×10^{-3}	1.10×10^{-3}	1.52×10^{-3}	1.38×10^{-3}	1.94×10^{-3}
B-767-400	1.34×10^{-3}	1.19×10^{-3}	1.56×10^{-3}	1.48×10^{-3}	1.99×10^{-3}
B-777-200	1.05×10^{-3}	9.67×10^{-4}	1.22×10^{-3}	1.19×10^{-3}	1.57×10^{-3}

Table 4: Percentual reduction in vertical deformation (m/m) at the top of the subgrade

Aircraft	**Percentual reduction CTCS (%)**	**Percentual reduction Soil-cement (%)**
EMB-195	15.41	9.54
A-320	14.73	8.53
B-737-800	15.04	9.77
A-321	15.38	9.21
B-767-400	11.19	5.13
B-777-200	7.90	2.46

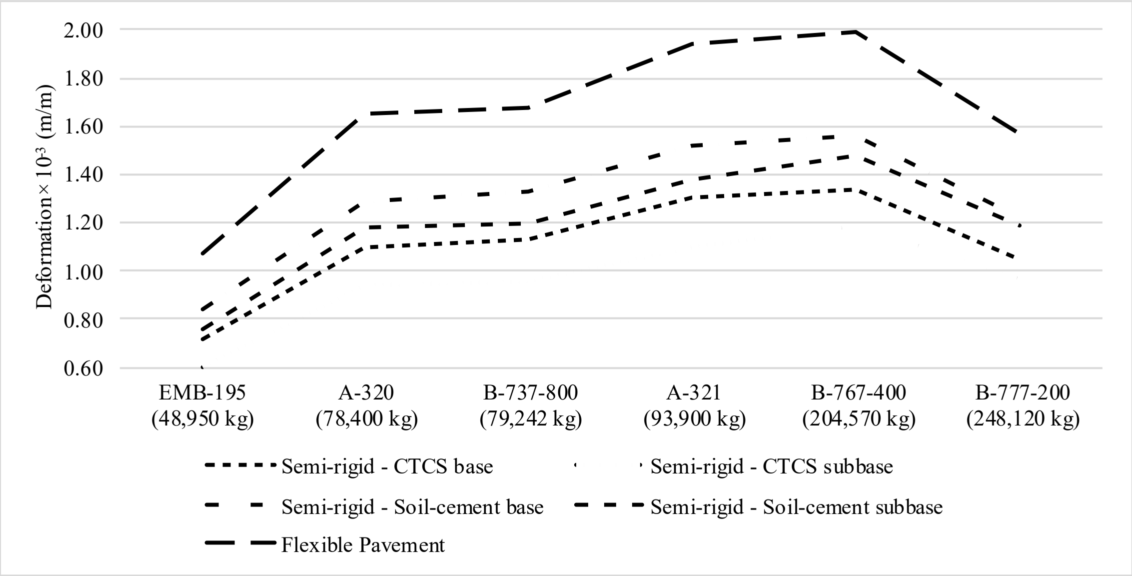
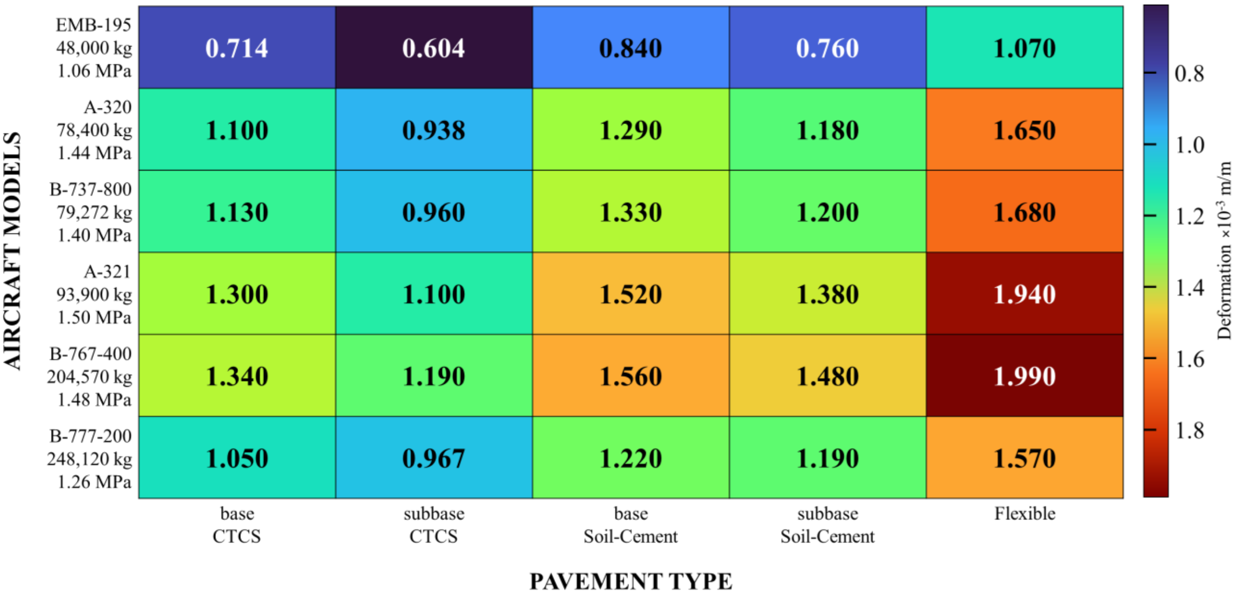


Figure 3: Values of vertical deformation at the top of the subgrade by aircraft model and by MTOW.



AIRCRAFT MODELS	base CTCS	subbase CTCS	base Soil-Cement	subbase Soil-Cement	Flexible
EMB-195 48,000 kg 1.06 MPa	0.714	0.604	0.840	0.760	1.070
A-320 78,400 kg 1.44 MPa	1.100	0.938	1.290	1.180	1.650
B-737-800 79,272 kg 1.40 MPa	1.130	0.960	1.330	1.200	1.680
A-321 93,900 kg 1.50 MPa	1.300	1.100	1.520	1.380	1.940
B-767-400 204,570 kg 1.48 MPa	1.340	1.190	1.560	1.480	1.990
B-777-200 248,120 kg 1.26 MPa	1.050	0.967	1.220	1.190	1.570

Figure 4: Values of deformation at the top of subgrade by aircraft model, MTOW, tire pressure, and pavement type.

It was observed that the aircraft model B-777-200, despite presenting the highest MTOW (268,120 kg), does not cause the highest vertical deformation on the top of the subgrade. This occurs because of its main landing gear type that has a TT configuration with 12 wheels. It provides a better weight distribution and, consequently, minimizes the pavement deformations. Regarding the pavement types, it was verified that there was a tendency for reduced vertical deformations at the top of the subgrade of semi-rigid structures with both the CTCS and the Soil-Cement subbase layers.

It was also found that the aircraft model A-320 induced the highest deformation in some of the pavements studied despite having a MTOW about three times lower than that of B-777-200. This phenomenon can be assigned to two factors: the distinct load distribution that exists for each aircraft's landing gear, and the pressure exerted by the tires on the pavement. The specific A-320 landing gear configuration can lead to intense load concentration in each wheel, which contributes to higher deformation despite the lower MTOW of this model. This fact suggests that, in addition to MTOW, the landing gear configuration and the load distribution are important factors influencing the vertical deformation at the top of the subgrade.

With respect to the relation between vertical deformation at the top of the subgrade and the tire pressure, it was observed that higher pressures, as on A-321 model, lead to higher deformations even if used a semi-rigid pavement. Thus, the need to consider the specific load per wheel distribution in the design of runway pavements should be highlighted.

For the service life simulations performed using FAARFIELD 2.1.1 software (Table 5), it was verified that the pavement with CTCS subbase presented a service life of 16 years, which is more durable than the pavement with the CTCS applied on the base layer (service life of about 6 years) under the same traffic conditions. The semi-rigid pavement with its more resilient material in the subbase can explain its higher resistance to vertical deformations at the top of the subgrade.

Table 5: Simulation for the service life calculation (measured in years)

Scenario 1 CTCS		Scenario 2 Soil-Cement		Scenario 3 Flexible
base	**subbase**	**base**	**subbase**	**granular**
5.94	16.00	1.10	1.10	0.10

Regarding the pavement with soil-cement, the service life (1.1 years) remained unchanged for both structures with soil-cement applied on the base and on the subbase layers. It was possible to verify that the service life did not change even with the reversal of the materials in the base and subbase layers, which is likely due to the difference in the RM between CTCS and soil cement (the difference is about 1,700 MPa). Even when the most resilient layer was positioned close to the subgrade, it was not sufficient to increase the pavement's service life (despite having minimized the vertical deformations at the top of the subgrade).

4 CONCLUSIONS

The analysis conducted pointed differences in the vertical deformations at the top of the subgrade and in the service lives for distinct airfield pavement types (semi-rigid and flexible pavements) when applying the load from six aircraft models with distinct physical characteristics (maximum takeoff weight and landing gear). It was found that pavements with Cement Treated Crushed Stone subbase layers or Soil-Cement subbase layers constructed under granular base layers presented the least values of vertical deformation at the top of the subgrade. This higher resistance is especially notable compared to the performance of the flexible pavement which demonstrated to be more susceptible to higher deformations due to its lower values of Resilient Modulus for base and subbase layers.

Depending on the placement of the granular and cement-treated layers in airfield pavements, distinct levels of vertical deformation at the top of the subgrade are observed. This information can inform the appropriate selection of aircraft and layer materials in the design of airfield pavements, especially the pavement structure of runways.

Relating to the service life, it was verified that the layer materials as well as their position in the pavement structure influences on its durability. The pavement's ability to resist vertical deformation at the top of the subgrade has a direct relation with its service life. In other words, pavement layers which are more effective in mitigating vertical deformation at the top of the subgrade tend to provide structures with extended service lives.

The technical paper highlighted the importance of choosing the appropriate pavement type for runways considering the loads under which they will be subjected to. The semi-rigid pavement can be an appropriate solution because it provides a more resistant and durable structure, minimizing potential vertical deformations at the top of the subgrade, increasing its service life, and consequently ensuring the safety of the operations in runways.

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