The significance of concrete slab flexural strength inference variation based on its compression strength characteristics in apron pavement analysis and design

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Abstract. Rigid pavement of apron in the airport is a complex structure which is designed based on the sense of balance of sub-grade strength, pavement aggregates, applied load characteristics, and climate. Various sub-grade condition and concrete slab flexural strength values results on the pavement design thickness that have a direct impact on the cost construction. In this study, the rigid pavement design of an apron with various sub-grade condition and concrete flexural strength values are presented. As a reference, the Federal Aviation and Administration (FAA) method is used. Dynamic Cone Penetration (DCP) test value is used to estimate California Bearing Ratio (CBR) values to determine the sub-grade reaction modulus (k). The flexural strength of concrete slab analyzed by several empirical models with constant values range of 0.72-0.9. The pavement structure analysis conducted by FAARFIELD. The CBR values from DCP's test vary between 6-10% which equal to k values between 31.4-46.8 MN/m^3. Concrete slab flexural strength of 4.6 MPa results on the concrete slab thickness of 550-510 mm. Based on k value of 46.8 MN/m^3 and K400 concrete strength, the calculated flexural strength varies between 4.15-5.17 MPa and the concrete slab thickness is 570-540 cm. The inference variation of flexural strength based on the same value of concrete compression strength characteristics will produce different concrete slab thickness. The concrete slab thickness tends to increase with the smaller values of inference of flexural strength.

1 Introduction

Airport pavements are designed and built to provide sufficient bearing capacity for aircraft. The pavements should strong enough and stable, endow with acceptable surface friction, and the surface is free from debris and fragments that may obstruct aircraft operations (jet blast). The apron is commonly designed with rigid pavement to make available stiffness support for aircraft and its loads during parking, loading and unloading cargo, refueling and passengers movements.

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Rigid pavement consists of a surface layer such as slabs of Portland Cement Concrete (PCC), base (un-stabilized or stabilized crushed aggregate), sub-base (un-stabilized and stabilized granular), and prepared sub-grades (natural or modified soils). Federal Aviation Administration (FAA) had developed a computer-based software FAA Rigid Flexible Interactive Elastic Layer Design (FAARFIELD) to assist the design process. In which, the FAARFIELD method defines the pavement's layers and materials for the surface, base and sub-base according to the larger designed-aircraft loads.

The bearing capacity of the entire pavement thickness is obtained from the balance sub-grade bearing capacity and layers' materials of the pavement. The sub-grade and pavement's materials strength are measured base on elasticity modulus according to standards for Specifying Construction of Airports [1, 2]. In FAARFIELD, the elasticity modulus of material base and sub-base are predetermined as constant, on the other hand, the sub-grade and PCC slabs are adjusted accordingly. The bearing capacity of the sub-grade is obtained from field tests and the selected values should able to represent the tested area. The strength of PCC slabs are determined from its flexural strength, and the flexural strength values are between a certain range of 4.14-5.17 MPa. Preferably, the flexural strength of the PCC slabs should be taken from test results. The test is conducted following procedures from a standard method, i.e. ASTM C78/C78M-18, Standard Test Method for Flexural Strength of Concrete Using Simple Beam with Third-Point Loading [3]. In a circumstance where the lack of data and limited resources for the materials testing, the value of the flexural strength could be estimated by using empirical approaches. An empirical model such as $fck = K(fc')^{0.5}$ is a relation model of flexural (*fck*) and compressive (*fc'*) strengths. The constant values of K are vary based on some studies. Some references set the *K* value of a normal concrete as K = 0.7-0.75 [3], K = 0.6-0.62 [4], K = 0.81-0.83 [4], therefore the empirical model may generate variation in flexural strengths and cause difference thickness of the PCC slab design.

This study is conducted to investigate and analyze sub-grade strength variation incorporated with the estimation of PCC slab flexural strength. Therefore, the influence of sub-grade and flexural strength variations can be incarcerated in the thickness structural design.

2 Methodology

2.1 Soil investigation and evaluation

The accuracy of foundation bearing capacity is mainly needed in apron pavement design. Investigation of sub-grade bearing capacity is conducted by performing a field test of Dynamic Cone Penetration (DCP). The required test follows ASTM D 6951 Standard Test Method for Use of the Dynamic Cone Penetrometer in Shallow Pavement Applications [5] Fig. 1 shows the application of the DCP test on the field. The tests are conducted in two different depth from original existing level to obtain the sub-grade CBR values for the apron pavement design. The DCP test results are the simplest way to determine the sub-grade bearing capacity by using DCP-CBR correlation values.

The test results provide CBR value of the sub-grade in range of 6-10%, therefore, the sub-grade reaction modulus (*k*) can be estimated by $k = 28.6929*CBR^{0.7788}$ (pci) and the expected elasticity modulus value can be generated by $Esg = 20.15*k^{1.284}$ (psi) [2]. The sub-grade values of *k* and *Esg* are presented in Table 1.

Fig. 1. Dynamic Cone Penetration Test: depth -1m and -2m from existing surface.

Table 1. CBR, *k*, and *Esg* subgrade value.

CBR (%)	***K* (pci)**		***Esg***	
	pci	*MN/M*³	psi	MPa
6	115.8	31.4	9436.8	61.95
7	130.6	35.4	11,022.8	72.26
8	144.9	39.3	12,610.5	82.64
9	158.8	43.1	14,199.8	93.04
10	172.4	46.8	15,790.5	103.41

2.2 Pavement layers materials

The apron pavement materials are selected following the code of Advisory Circular (AC) 150/5310-10G [1] incorporated with Standards for Specifying Construction of Airports (e.g. P-501 Portland Cement Concrete (PCC) pavement, P-306 Lean Concrete Base Course, P-209 Crushed Aggregate Base Course, P-201 Lime Rock Base Course, etc) [2]. Layer types and required minimum layer thickness of the rigid pavements are given in Table 2.

Some limitations in using the material types and required thickness are as follow: 1) Pavement thickness to be up rounded to the closest 0.5 inches (10 mm), 2) Pavements for aircraft greater than 30,000 lbs (13,610 kg), the base may be replaced with sub-base, 3) Sub-base layer is required for pavements designed for gross loads of 12,500 pounds (5670 kg) or less only when the following soil types are present: OL, MH, CH, or OH, and 4) The following specific items may also be used as sub-base: P-208 Aggregate Base Course, P-209 Crushed Aggregate Base Course, P-211 Lime Rock Base Course, P-219 Recycled Concrete Aggregate Base Course, and P-301 Soil-Cement Base Course. If more than one layer of sub-base is used, each layer should meet the minimum thickness requirement in this table.

Table 2. Minimum layer thickness for rigid pavement structures [1].

Layer type	**FAA specification item**	**Maximum airplane gross weight operating on pavement, lbs (kg)**		
		<12,500 (5670)	**< 100,000 (45,360)**	**= 100,000 (45,360)**
PCC Surface	P-501, Portland Cement Concrete (PCC) Pavements	5 in. (125 mm)	6 in. (150 mm)[1]	6 in. (150 mm)[1]
Stabilized Base	P-401 or P-403, P304, P-306	Not Required	Not Required	5 in. (125 mm)[1]
Base	P-208, P-209, P-211, P-301	Not Required	6 in. (150 mm)[2]	6 in. (150 mm)[1]
Sub-grade	P-154, Sub-base Course	-	As needed for frost or to create working platform	As needed for frost or to create working platform

2.3 PCC slab strength

The required PCC slab thickness in supporting repetition aircraft loads is affected by 28 days PCC flexural strength obtained from tests according to ASTM C 78, Standard Test Method for Flexural Strength of Concrete. The most recommended values of flexural strength are in the range of 4.14-5.17 MPa (AC 150-5320-6F). Other than mechanical test, the PCC flexural strength can be obtained from empirical models, and the suggested values are in the range 8-15% of its compressive strength. The followings are empirical correlation stated in flexural and compressive strengths [3, 4]:

$$fck = K\left(fc'\right)^{0.5} \text{ (MPa)} \tag{1}$$

where fc' = Characteristics compressive strength in 28 days (kg/cm^2, MPa), fck = Flexural strength in 28 days (Mpa), K = Constant.

Table 3. K and fck values.

K	fck (MPa)
0.72	4.15
0.75	4.32
0.80	4.60
0.85	4.90
0.90	5.17

For a normal concrete, the constant are the ratio of fck to $(fc')^{0.5}$ directly depends on material and available applied technology. The Standard Nasional Indonesia (SNI) provides K value range of 0.7-0.75 [4], meanwhile ACI stated K = 0.6 [4]. Other studied elsewhere gave K = 0.81-0.83 [4]. In Table 3, *fck* values are required for variation of K = 0.7-0.9 with concrete compressive strength K400 kg/cm^2 or equivalent to *fc'* 33.2 Mpa.

2.4 FAA method

Engineering procedures both FAA's mechanical and empirical are implemented in FAARFIELD and using the three-dimensional finite element as basic procedures in rigid pavement design. FAARFIELD applies maximum horizontal stress under PCC slab to predict the pavement structure lifetime by taking into account the load position relative to the center and edges of the PCC slab simultaneously. The results, FAARFIELD provides the required thickness of the PCC slab to support the traffic of various aircraft during rigid pavement structure lifetime [2].

2.4.1 Structure lifetime

Structure life time is identical to life time of pavement structure representing its ability in serving the number of repetition loads. The FAA recommended the pavement structure lifetime of 20 years [2].

2.4.2 Aircrafts traffic

Table 4. Annual departures of aircrafts.

Aircraft type	Gross Taxi Weight (Tns)	Annual Departures				
		2013	2014	2015	2016	2017
A322	85,400	28,030	35,904	31,475	37,497	41,216
A333	233,90	11,969	13,835	14,412	18,285	19,106
A346	381,200	55	55	58	90	10
ATR72	22,680	12,717	14,869	11,186	12,679	13,363
B737	70,307	4221	3866	3487	5249	4394
B739ER	85,366	33,886	40,271	38,273	49,656	54,088
B777-300	352,441	5869	7587	4602	4500	6211
B788	228,384	225	1641	2417	2533	2758
F100	45,813	732	620	403	429	379
GLF5	41,232	477	375	303	314	311
H25B	12,483	129	84	106	103	62
LR35A	8165	150	86	79	101	114
MD83	73,028	358	406	329	352	111

Several issues to be considered regarding aircrafts traffic in rigid pavement design by FAARFIELD are as follows [2] a) Aircraft Loads, the pavement are designed to anticipate the regularly operated aircraft's takeoff weight. In the design procedure, aircraft's main gears and nose gears are loaded with 95% and 5% of take off weight loads; b) The pavements are designed base on number of annually departure. Typically, the weight of departure aircrafts are heavier than when they are landed. Table 4 presents annually departures aircrafts in year 2013-2017 which selected by aircraft types and the highest frequency criterion. The annual growth number of departure aircrafts (annual growth) based on data time series annual departure for 5 years (2013-2017).

2.4.2 Cumulative Damage Factor (CDF)

Cumulative Damage Factor (CDF) is defined as:

$$CFD = \frac{number\ of\ applied\ load\ repetitions}{number\ of\ allowable\ repetitions\ to\ failure} \tag{2}$$

The basic concept of FAARFIELD is based on Cumulative Damage Factor (CDF). The contributed damage due to each of aircrafts movements are considered in the determination of total cumulative damage. Then, the pavement thickness is determined by CDF. Fatigue failure which is the number of used pavement structure also can be represented by CDF. CDF is a ratio of a number of applied repetition loads to allowable repetition loads before failure state occurs [2].

3 Results and discussion

The assortment of type and material of pavement layer are determined base on the heavier design aircraft. In this study, the heavier aircraft is B777-300ER with gross taxi-weight 352.441 tons. The selected pavement layers above the sub-grade are sub-base with minimum thickness of 150 mm (P-209 crushed aggregate), stabilized base with minimum thickness of 125 mm (P-306 lean concrete) and surface (P-501 PCC).

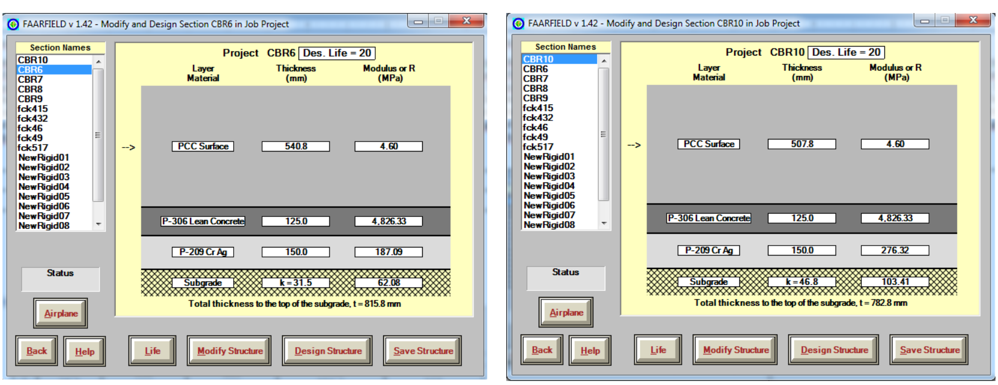

Fig. 2. FAARFIELD Output (k sub-grade 31.5. and 46.8 KN/M^3)

Fig. 2 present the output of FAAFIELD design structure surface with *f'ck* 4,6 Mpa at k sub-grade 31.5 and 46.8 MN/M^3 completed by detail design of structure at range of k sub-grade value of 31.5-46.8 MN/M^3. The detail design of the pavement structures is presented in Table 5.

Table 5. Apron Pavement Design with various k sub-grade values

Sub-grade *k* (MN/M^3)	Sub/base P-209 crushed aggregate (mm)	Stabilized base P-306 lean concrete (mm)	Surface PCC slab (*fck* 4.6 MPa) (mm)	Applied surface PCC slab (*fck* 4.6 MPa) (mm)
31.5	150	125	540.8	550
35.5	150	125	530.2	540
39.3	150	125	521.4	530
43.1	150	125	514.0	520
46.8	150	125	507.8	510

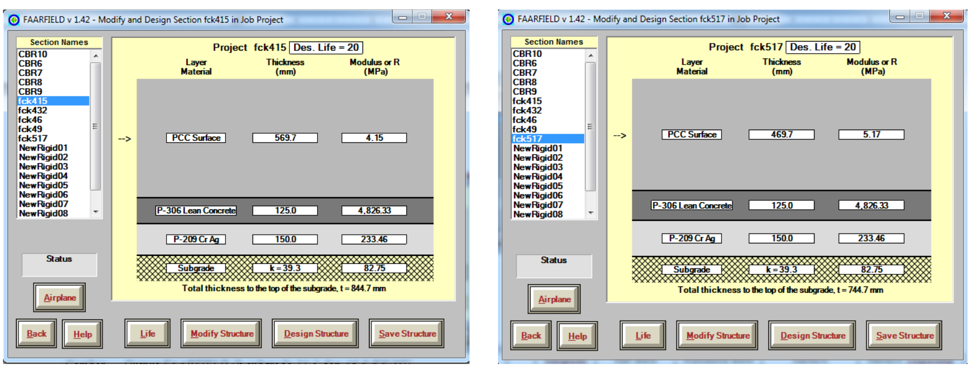

Fig. 3. FAARFIELD Output (*fck* 4.15 and 5.17 MPa).

Table 6. Apron pavement design with various PCC slab.

Sub-grade *k* (MN/M^3)	Sub/base P-209 crushed aggregate (mm)	Stabilized base P-306 lean concrete (mm)	Surface report PCC slab (mm)		Surface design PCC slab (mm)	
			fck (MPa)	mm	*fck* (MPa)	mm
39.3	150	125	4.15	569.7	4.15	570
39.3	150	125	4.32	550.5	4.32	560
39.3	150	125	4.60	521.4	4.60	530
39.3	150	125	4.90	493.1	4.90	500
39.3	150	125	5.17	469.7	5.17	470

The variation of k sub-grade value in range 31.5-46.8 KN/M^3 or CBR values of 6-10% generate the various thickness of PCC slab 550-510 mm at *fck* 4.6 MPa. The various result also occur on the variation of *fck* 4.15-5.17 MPa which cause the decrease of PCC slab thickness of 570-470 mm at *k* sub-grade value 39.3 MN/M^3 or CBR 8%. PCC slab thickness interval is employed to balance the whole structural strength of pavement as a result of sub-grade and PCC slab variation in anticipated the repetition loads during structure lifetime of 20 years. The pavement design balance can be indicated by the ratio of CDF = 1.The design structure FAARFIELD output with *fck* 4.15 and 5.17 MPa is presented in Fig. 3. The detail design of the pavement structures with required *fck* 4.15-5.17 MPa is presented in Table 6.

4 Conclusions

The thickness of apron pavement design is profoundly affected by the balance of pavement layers strength. The increase in sub-grade strength at a condition of constant bearing capacity of its overlain layers will decrease the thickness of the PCC slab. The same results also mimic for the upper layers, i.e., the increase in the required range of PCC slab (4.14-4.17 MPa) will also decrease the PCC slab thickness. To obtain the economics design based on the available sub-grade, a simulation of combined layers thickness need to be exercised. Further study can be conducted for inclusive analyze of the influence of pavement bearing capacity variation to the thickness of the PCC slab using an available statistical approach. Advance research on evaluating of total pavement bearing capacity with an indication of Pavement Classification Number (PCN) value which describes the extent of pavement bearing capacity generated by Aircraft Classification Number (ACN) is recommended.

References

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